POLLUTION MANAGEMENT & ENVIRONMENTAL HEALTH

THE WORLD BANK
IBRD • IDA | WORLD BANK GROUP

AIR QUALITY MANAGEMENT PLANNING FOR LAGOS STATE

Joseph Akpokodje; Christopher Weaver; Mofoluso Fagbeja; Francesco Forastiere; Joseph V. Spadaro; Todd M. Johnson; Obi Ugochuku; Oluwakemi Osunderu and Sarath Guttikunda.

AUGUST 2022
TASK TEAM LEADER: JOSEPH AKPOKODJE

POLLUTION MANAGEMENT & ENVIRONMENTAL HEALTH

THE WORLD BANK
IBRD • IDA | WORLD BANK GROUP

AIR QUALITY MANAGEMENT PLANNING FOR LAGOS STATE

Joseph Akpokodje; Christopher Weaver; Mofoluso Fagbeja; Francesco Forastiere; Joseph V. Spadaro; Todd M. Johnson; Obi Ugochuku; Oluwakemi Osunderu and Sarath Guttikunda

1818 H Street NW
Washington DC 20433
Telephone: 202-473-1000
Internet: www.worldbank.org
Email: feedback@worldbank.org

Cover photos credit: Elohor Egbane / SmartEdge.

CONTENTS

FIGURES

TABLES

BOXES

ACKNOWLEDGMENTS (REVISED OCTOBER 2022)

This report was prepared by a team led by Joseph Akpokodje and comprising Christopher Weaver (Air Resources Engineer, California Air Resources Board), Mofoluso A. Fagbeja (Space Applications and Environmental Scientist, Centre for Space Science and Technology Education, Ile-Ife, Nigeria), Francesco Forastiere (Environmental Epidemiologist, National Research Council, Italy), Joseph V. Spadaro (Senior Environmental Research Scientist, Spadaro Environmental Research Consultants, USA and WHO Consultant, Bonn, Germany), Todd M. Johnson (Environmental Economist, former World Bank Group staff), Obi Ugochuku (Climate Finance Expert, former World Bank Group staff), Oluwakemi Osunderu (Principal Research Fellow, Forestry Research Institute of Nigeria), and Sarath Guttikunda (Director, Urban Emissions, India).The opinion expressed in this report are those of the authors and should not be attributed to their respective employer or affiliated organizations.

The team would like to acknowledge, with thanks, the valuable support and advice from Jostein Nygard, Yewande Awe, Steve Baillie, Max Klotz, Urvashi Narain, Özgül Calicioglu, Oznur Oguz Kuntasal, Iguniwari Thomas Ekeu-Wei, Omezikam Onuoha, Jayne Kwengwere, Rohan Selvaratnam, and Abiodun Elufioye. This report benefited from contributions and inputs provided by the following colleagues: Silvia Calderon, Felix Ukeh, and Andrew Kelly.

The team would like to acknowledge comments provided by the peer reviewers: Sameer Akbar – Senior Environmental Specialist (SCAEN); Craig Meisner – Senior Economist (SCCDR); Roger Gorham - Senior Transport Economist (ILCT1); Jian Xie – Senior Environmental Specialist (SAEE2); and Gary Kleiman – Senior Environmental Specialist Consultant (SCAEN).

Editorial support was provided by Akashee Mehdi.

The team would like to acknowledge the valuable support of His Excellency, Mr. Babajide Sanwo-Olu, Executive Governor of Lagos State and the following Lagos State Government officials: Mr. Tunji Bello, Honorable Commissioner for Environment and Water Resources; Prof Akin Abayomi, Honorable Commissioner for Health, Lagos State Ministry of Health; Mr. Sam Egube, Honorable Commissioner, Lagos State Ministry of Economic Planning and Budget.; Dr. Frederic Abimbola Oladeinde, Honorable Commissioner, Lagos State Ministry of Transportation; Engr. Olalere Odusote, Honorable Commissioner for Energy and Mineral Resources; Mrs. Abisola Olusanya, Honorable Commissioner for Agriculture; Dr. Dolapo Fasawe, General Manager, Lagos State Environmental Protection Agency (LASEPA); Mr.

Olajide Oduyoye, General Manager, Lagos State Metropolitan Transport Agency (LAMATA); Mr. Ibrahim Adejuwon Odumboni, General Manager, Lagos Waste Management Agency (LAWMA); Mr. Tayo Oseni-Ope (Director), Mr. Peter Kehinde Olowu (Deputy Director), and Mrs. Bolanle Pemede (Assistant Director) at the Lagos State Ministry of Economic Planning and Budget/ Lagos Bureau of Statistics; Dr. Idowu Abiola (Director, Lagos Health Management Information System) and Dr. Kuburat Enitan Layeni-Adeyemo (Director, Occupational Health Services) at Lagos State Ministry of Health; Mr. Ayodipupo Quadri (Environment and Safety Specialist) at Lagos Metropolitan Area Transport Authority; Mr. Lewis Gregory Adeyemi (Chief Scientific Officer) at the Lagos State Ministry of Environment/Lagos State Environmental Protection Agency; Mr. Adedotun Atobasire (Deputy Director, Census) at the National Population Commission; Mr. Charles Ikeah, Director Pollution Control and Environmental Management; and Mr. Emmanuel Ojo (Former Focal Point and Deputy Director, Pollution Control and Environmental Health Department) at the Federal Ministry of Environment. Prof. Oluwatoyin Ogundipe, Vice Chancellor of the University of Lagos. Dr Rose Alani, Lead, Air Quality Monitoring Research Group of the Department of Chemistry, University of Lagos. Professor Wellington Oyibo, Director of Research and Innovation Unit, University of Lagos

The report is a product of the Environment, Natural Resources and Blue Economy Global Practice of the World Bank. This work was conducted under the supervision of Ernesto Sanchez-Triana (PMEH Program Manager), Sanjay Srivastava (Practice Manager, SAWE4), and Christian Albert Peter (Practice Manager, SENGL).

The financial support of the World Bank's Pollution Management and Environmental Health (PMEH) Multi-Donor Trust Fund in the preparation of this report is gratefully acknowledged. PMEH is supported by the governments of Germany, Norway, and the United Kingdom.

LIST OF ABBREVIATIONS

ACBP	Africa Climate Business Plan
ACRIF	African Climate Resilience Infrastructure
AFC	Africa Finance Corporation
AfDB	African Development Bank
AFOLU	Agriculture, Forestry and Other Land Use
ALRI	Acute Lower Respiratory Infections
AQI	Air Quality Index
AQM	Air Quality Management
BEV	Battery Electric Vehicle
Bpd	Barrels per Day
BRT	Bus Rapid Transport
CBA	Cost-Benefit Analysis
CFC	Chlorofluorocarbon
CH_4	Methane
CHA	Cardiovascular Hospital Admission
CI	Confidence Interval
Cl	Chloride Ion
CMB	Chemical Mass Balance
CNG	Compressed Natural Gas
CO	Carbon Monoxide
CO_2	Carbon Dioxide
COPD	Chronic Obstructive Pulmonary Disease
CSO	Civil Society Organization
DPR	Department of Petroleum Resources
ECOWAS	Economic Community of West African States
EGASPIN	Environmental Guidelines and Standards for the Petroleum Industry in Nigeria
EIB	European Investment Bank
EPA	Environmental Protection Agency
ERF	Exposure-Response Function
EU	European Union
FFMM	Fact-Finding Air Quality Monitoring Mission
FMEnv	Federal Ministry of Environment
FMPR	Federal Ministry of Petroleum Resources
GBD	Global Burden of Disease
GCF	Green Climate Fund
GDP	Gross Domestic Product
GEF	Global Environment Facility
GEMM	Global Exposure Mortality Model
GHDx	Global Health Data Exchange

GHE	Global Health Estimates
GHG	Greenhouse Gas
GWP	Global-Warming Potential
HCA	Human Capital Approach
HCFC	Hydrochlorofluorocarbon
HFC	Hydrofluorocarbon
HFO	Heavy Fuel Oil
HIA	Health Impact Assessment
HRAPIE	Health Risk of Air Pollution in Europe
IEA	International Energy Agency
IER	Integrated Exposure-Response
IFC	International Finance Corporation
IHD	Ischemic Heart Disease
IHME	Institute for Health Metrics and Evaluation
I&M	Inspection and Maintenance
IQ	Intelligence Quotient
IPCC	Intergovernmental Panel on Climate Change
ISDB	Islamic Development Bank
IT	Interim Target
kW	Kilowatt(s)
LACVIS	Lagos Computerized Vehicle Inspection Service
LAGFERRY	Lagos State Ferry
LAMATA	Lagos State Metropolitan Transport Agency
LASEPA	Lagos State Environmental Protection Agency
LASG	Lagos State Government
LASWMO	Lagos State Wastewater Management Office
LAWMA	Lagos Waste Management Agency
LBS	Lagos Bureau of Statistics
LGA	Local Government Area
LMoE	Lagos State Ministry of Environment and Water Resources
LMoEMR	Lagos State Ministry of Energy and Mineral Resources
LMEPB	Lagos State Ministry of Economic Planning and Budget
LMoH	Lagos State Ministry of Health
LMICs	Low- and Middle-Income Countries
LMoT	Lagos State Ministry of Transport
LPG	Liquefied Petroleum Gas
LUTP	Lagos Urban Transport Project
MDAs	Ministries, Departments, and Agencies
MDB	Multilateral Development Bank
MSW	Municipal Solid Waste
NAAQS	National Ambient Air Quality Standards
NAP	National Action Plan
NAPEP	National Poverty Eradication Programme
NCD	Noncommunicable Disease
NCF	Nigerian Conservation Foundation

NDC	Nationally Determined Contribution
NEP	National Environmental Policy
NESREA	National Environmental Standards and Regulations Enforcement Agency
NH_3	Ammonia
NILU	Norwegian Institute for Air Research
NIMET	Nigerian Meteorological Agency
NIS	Nigerian Industrial Standards
NNPC	Nigerian National Petroleum Corporation
N_2O	Nitrous Oxide
NO	Nitric Oxides
NO_2	Nitrogen Dioxide
NO_x	Nitrogen Oxides
NOSDRA	National Oil Spill Detection and Regulatory Agency
NSE	Nigerian Stock Exchange
NUPRC	Nigerian Upstream Petroleum Regulatory Commission
O_3	Ozone
OECD	Organisation of Economic Co-operation and Development
PAF	Population Attributable Fraction
PforR	Program-for-Results
PCEH	Pollution Control and Environmental Health
PM	Particulate Matter
PM_1	Particulate Matter with Diameter Less than 1 µm
$PM_{2.5}$	Particulate Matter with Diameter Less than 2.5 µm
PM_{10}	Particulate Matter with Diameter Less than 10 µm
PMEH	Pollution Management and Environmental Health
PMEH-MDTF	Pollution Management and Environmental Health Multi-Donor Trust Fund
PMF	Positive Matrix Factorization
ppb	Parts per Billion
ppm	Parts per Million
PPMC	Pipelines and Product Marketing Company
ppv	Parts per Volume
PWE	Population-Weighted Exposure
REVIHAAP	Review of Evidence on Health Aspects of Air Pollution
RHA	Respiratory Hospital Admission
RR	Relative Risk
SAWE4	Environment, Natural Resources and Blue Economy West and Central Africa
SCC	Social Cost of Carbon
SENGL	Environment, Natural Resources and Blue Economy, Global team
SIP	State Implementation Plan
SO_2	Sulfur Dioxide
SO_x	Sulfur Oxides
SON	Standards Organization of Nigeria
SPO	Second-Party Opinion
TSC	Technical Service Contractor
TSP	Total Suspended Particulate Matter

UK	United Kingdom
UNFCCC	United Nations Framework Convention on Climate Change
UNILAG	University of Lagos
US	United States
US EPA	United States Environmental Protection Agency
VOC	Volatile Organic Compound
VSL	Value of Statistical Life
WBG	The World Bank Group
WHO	The World Health Organization
$\mu g/m^3$	micrograms per cubic meter

EXECUTIVE SUMMARY

INTRODUCTION

Ambient air pollution is a major contributor to illness and premature deaths in much of the developing world, including Lagos. The World Bank is committed to supporting countries severely affected by pollution through its advisory service, technical assistance, and lending. With funding from the Pollution Management and Environmental Health Multi-Donor Trust Fund (PMEH-MDTF), the World Bank, in collaboration with the Lagos State Government (LASG), and specifically the Lagos State Environmental Protection Agency (LASEPA), contracted consultants to establish the scientific basis for air quality management (AQM) and to develop an AQM plan for Lagos State. The effort included the following:

- Establishment of a network of six air-quality-monitoring stations to collect 12 months of air quality data on $PM_{2.5}$, $PM_{10,}$ other criteria pollutants (sulfur dioxide [SO_2], nitrogen dioxide [NO_2], carbon monoxide [CO], ozone [O_3]), greenhouse gases – GHGs (carbon dioxide [CO_2], methane [CH_4], nitrous oxide [N_2O], black carbon [BC], chlorofluorocarbons [CFCs], hydrofluorocarbons [HFCs]), and meteorological data
- Chemical analysis and source apportionment analysis of collected aerosol particulate matter (PM) to determine the composition and likely sources of PM emissions
- Development of an inventory of air pollutant emissions
- Photochemical dispersion modeling to reconcile the inventory with observed pollutant concentrations and to estimate the exposure in each local government area (LGA)
- Assessment of the health impacts of air pollution in Lagos by estimating the effects of air pollution on the incidence of premature mortality and illness in each LGA
- Economic and financial analysis of the costs of premature mortality and illness due to air pollution, and the costs and benefits of measures to control pollutant emissions
- Assessment of existing institutional and governance structures for successful AQM in Lagos and Nigeria
- Recommendation of an integrated AQM plan and establishment of an air quality index (AQI) for the State of Lagos.

AIR QUALITY CONDITIONS IN LAGOS

The World Health Organization (WHO) guideline for annual average $PM_{2.5}$ concentrations is 5 μg/m^3 (micrograms—or one-millionth of a gram—per cubic meter) of air. This project found annual average $PM_{2.5}$ concentrations at the six monitoring sites ranging from 30 to 97 μg/m^3, with a population-weighted average of 47 μg/m^3. The highest average $PM_{2.5}$ was found in the industrial/residential area of Ikorodu, an industrialized LGA in Lagos. Concentrations of lead aerosol in Ikorodu were also dangerously high—more than 10 times the US EPA standard of 0.15 μg/m^3 for lead aerosol. Measurements of gaseous pollutants also showed concentrations of CO and NO_2 in excess both of Nigerian air quality standards and of WHO guidelines.

The PM source apportionment conducted for this project found that open burning of biomass and solid waste accounts for about 30 percent of the annual ambient $PM_{2.5}$; gasoline and diesel engines combined account for about 16 percent; and industrial emissions account for about 18 percent on average (ranging from 48 percent at Ikorodu to less than 9 percent at other sites). Ammonium nitrate and ammonium sulfate—produced by chemical reactions between gaseous sulfur oxides (SO_x), nitrogen oxides (NO_x), and ammonia (NH_3)—make up 10 percent of the $PM_{2.5}$. Dust, including dust from roads, construction sites, and agricultural fields as well as the seasonal *Harmattan,* makes up about 26 percent of ambient $PM_{2.5}$ and 50 percent of PM_{10}.

HEALTH AND ECONOMIC IMPACTS OF AIR POLLUTION

Exposure to $PM_{2.5}$ pollution is a serious, but preventable, public health hazard, especially in children under 5 years. In Lagos, $PM_{2.5}$ exposure is estimated to cause between 16,000 and 30,000 premature deaths per year, with about half of these being infants under 1 year. Air pollution is also estimated to cause 180,000 to 350,000 acute lower respiratory infections (ALRI) per year, primarily cases of pneumonia in children under 5. Another 250 to 500 deaths are estimated to be due to PM_{10} exposure during the *Harmattan* season. Exposure to lead aerosol in Ikorodu is estimated to have cost the LGA's children an average of 6.2 intelligence quotient (IQ) points and to be causing another 300 to 400 deaths from cardiovascular disease per year. Mortality and morbidity due to gaseous pollutants were not estimated but would likely increase these numbers by about 10 percent.

Using the human capital method, which essentially values a life at the time of death equal to the amount that a person could earn over his or her remaining life, the economic costs of $PM_{2.5}$ air pollution in Lagos State are estimated at US$1.2–2.3 billion per year—1.6 to 3.2 percent of Lagos' gross domestic product (GDP). Using the value of a statistical life (VSL) approach, which considers how much society is willing to pay to reduce a small risk of death, the costs are estimated at US$3.1–5.8 billion (4.2 to 8.1 percent of Lagos' GDP). The economic costs of exposure to lead aerosol in Ikorodu are estimated at an additional US$300–600 million per year, or US$400–600 for every resident of that LGA.

POTENTIAL EMISSION CONTROL MEASURES

Given the range of human-made air pollution sources that have been identified in Lagos, a multi-sectoral approach is needed to improve air quality. The following are key air-quality policies recommended for near-term implementation in Lagos, based on measured pollution levels, assessed health impacts, readiness for implementation, and consistency with the National Action Plan (NAP) to Reduce Short-Lived Climate Pollutants.

Solid waste. While the per capita generation of municipal solid waste (MSW) in Lagos is still low by international standards, based on air pollution modeling and source apportionment, a large fraction of MSW appears to be openly burned. For air pollution control, open burning of waste should be banned, along with a public information program to explain the health impacts of open burning. Lagos should also strive to collect as much MSW as possible and ensure that open burning is not taking place at landfills or transfer stations. Recycling and composting can reduce the amount of MSW destined for landfills by as much as two-thirds while also generating revenue from the sale of products such as fertilizer and cardboard to offset the costs.

Power. Small, engine-driven generating sets (gensets) are estimated to account for nearly half of the total electricity produced in Lagos and are responsible for a much larger share of air pollution from power generation. Gensets are one of the least regulated sources of air pollution in Lagos. There is an urgent need to reduce emissions from gensets by substituting electricity from the grid or from distributed power generation (such as from solar photovoltaic) and by setting and enforcing genset emission standards.

Transport. Over the long term, public transport (buses, light rail, ferries) can reduce air pollution from the transport sector in Lagos by lessening road congestion and the number of private passenger vehicles. At the same time, it is essential to control emissions from vehicles through a systematic process of improving vehicle emission standards and the quality of transport fuels. Achieving Euro 3 and Euro 4 vehicle standards could reduce PM emissions from transport in Lagos by an estimated 65–83 percent, compared to Euro 1 vehicles. Economic Commission of West African States (ECOWAS) directive C/Dir.2/09/20 requires imported light-duty vehicles to meet Euro 4 standards from January 2021, and requires vehicles in circulation to meet them from January 2025. Heavy-duty trucks and buses are required to meet Euro 6 standards. Given that Euro 4 vehicles have been manufactured globally since 2006, it is well within the capacity of Lagos State to achieve a high share of such vehicles in its total vehicle population through a program of emissions testing and vehicle retrofits.

Fuel quality. One of the key constraints on reducing emissions from transport vehicles (and stationary engines for industry or power generation) has been the lack of clean gasoline and diesel fuel. To reduce air pollution, many megacities around the world, including in Mexico City, Delhi, Santiago, and Rio de Janeiro, have established stricter fuel quality standards than their respective countries. In the face of numerous incentives to adulterate fuel, it is necessary for fuel quality to be regulated and enforced at retail outlets.

Industry. Industrial emissions account for a sizable share of $PM_{2.5}$ emissions in Lagos, principally in Ikorodu, but also throughout the state. Continuous-emissions-monitoring equipment should be employed to regulate emissions from large industrial sources, with fines imposed for noncompliance. LASEPA staff have legal authority to carry out emissions source tests to enforce emission standards; they should be trained and equipped to do so.

Financing for air quality. An AQM program in Lagos could build on existing public support for the transport and solid waste sectors, and for industrial relocation through environmental financing. Green bonds, supplemental finance from multilateral organizations, and climate finance can be used to support the intersection between air quality and climate change, such as for solid waste management, electric power reform, public transport, and alternative fuels.

LAWS, REGULATIONS, AND INSTITUTIONAL CAPACITY

Under the Lagos Environmental Management Protection Law of 2017, LASEPA has the legal authority to enforce emission standards on industrial, agricultural, and government sources, as well as generating plants in residential and commercial areas; to set and enforce vehicle emission standards; and to set up an air quality monitoring network. However, it mostly lacks the technical capacity and staff to do so effectively. Training and capacity building, together with additional staff and equipment investments, are needed for LASEPA to effectively fulfill its statutory role in AQM. This will require an increase in budget. As a parastatal, the agency has the capacity to be self-funding and already derives a large fraction of its budget from fees, fines, and the Environmental Development Charge.

TABLE 1.1. RECOMMENDED AIR QUALITY STRATEGY FOR LAGOS

S/No	Short-term recommendation – 1 year	Medium-term recommendation – 3 years	Responsible authority
Air quality monitoring			
1	Resume air quality monitoring at the six sites for which a monitoring record already exists, and begin planning an expanded network.	Establish 8–12 additional air quality monitoring sites, including upwind and downwind locations as well as sites influenced by the ports, traffic, and industrial areas, to better monitor population-based exposure and to strengthen the basis for air quality modeling.	LASEPA, Lagos State Ministry of Economic Planning and Budget (LMEPB)
2	Train and equip LASEPA staff to carry out emission measurements on industrial sources and begin such testing with the largest and worst emitters.	Strengthen the scientific basis for AQM by continuing to develop the emissions inventory, strengthening oversight of the emissions auditing process, and strengthening the reporting of health and economic statistics.	LASEPA, Lagos State Ministry of Environment and Water Resources (LMoE), Lagos Bureau of Statistics (LBS)
Health			
3	Provide education, training, and lifelong learning to health personnel on the health effects of air pollution.	Strengthen the scientific basis for health impact assessment, expand the system of health information collection, and initiate epidemiological research on air pollution.	LASEPA, Lagos State Ministry of Health (LMoH)
4		Engage public opinion by adopting an AQI and routinely providing air quality data and forecasts to the media and on LASEPA's website.	LASEPA, LMoH
Regulation and enforcement			
Solid waste management			
5	Redouble efforts to collect and dispose of solid waste by landfill, recycling, composting, and/or incineration with emission controls, and enforce prohibitions on the open burning of waste and biomass.		LAWMA
Industries			
6	Locate and shut down any lead-smelting or battery-recycling operations in Ikorodu, measure lead levels in soil and in the blood of the potentially affected population, and take remedial action as necessary.		LASEPA
Transport			
7	Implement ECOWAS Directive C/Dir.1/09/20, limiting sulfur in gasoline and diesel fuel to 50 ppm by weight; enforce this by collecting and analyzing fuel samples at the port and at retail stations, with fines and/or the loss of retail licenses for noncompliance.		Nigerian Upstream Petroleum Regulatory Commission (NUPRC), Standards Organization of Nigeria (SON)

S/No	Short-term recommendation – 1 year	Medium-term recommendation – 3 years	Responsible authority
8	Begin execution of ECOWAS Directive C/Dir.2/09/20 by notifying vehicle importers and implementing inspections and testing to confirm that newly imported, light-duty vehicles (whether new or used) meet Euro 4 emission standards and that heavy-duty vehicles meet Euro 6 standards.	Strengthen the existing vehicle inspection and maintenance system to enforce the requirement of ECOWAS Directive C/Dir.2/09/20 that vehicles in circulation meet Euro 4 emission standards from January 2025.	National Environmental Standards and Regulations Enforcement Agency (NESREA), Lagos State Metropolitan Transport Agency (LAMATA), Lagos State Ministry of Transport (LMoT)
9		Replace the existing *danfo* (microbus) fleet with larger minibuses, preferably plug-in hybrid electric vehicles with advanced emission controls, and restructure the routes to coordinate with the bus rapid transit (BRT) system. By charging from the power grid when it is available and from their onboard engine when not, plug-in hybrids could provide reliable service in the near term while retaining the ability to switch to all-electric operation in the future.	LAMATA
10		Consider measures to phase out engine-driven taxicabs, *okada* motorcycle taxis, and *keke* NAPEP tricycle taxis in favor of battery electric vehicles (BEVs).	LAMATA
Energy			
11	Set and enforce emission standards for backup generators.	Increase the capacity and reliability of the electric-generating system to reduce the need for backup generators and consider retrofitting the Egbin power plant for combined-cycle operation with low-NOx gas turbines.	LASEPA, Federal Ministry of Power (FMP)
12		Consider grouping small power users into "mini grids" of a few hundred kW incorporating solar photovoltaic panels and diesel-generating sets with advanced emission controls.	Federal Ministry of Power, Lagos State Ministry of Energy and Mineral Resources (LMoEMR), LASEPA
Air quality financing			
13	Consider a percentage of existing or new emission fees and other charges as line charge to sustainably support increased staffing and equipment for LASEPA.		LMEPB, LASEPA
14	Consider multilateral financing and/or an air quality green bond to support needed investments in emission controls, air quality monitoring infrastructure, emissions measurement capabilities, and capacity building for air quality enforcement and management.		LMEPB, LASEPA

CHAPTER 1
INTRODUCTION

Air pollution is a major contributor to illness and premature death in much of the developing world, including Lagos. The World Bank is committed to supporting countries severely affected by pollution through its advisory service, technical assistance, and lending. The World Bank's Environment, Natural Resources and Blue Economy Global Practice has set pollution management and environmental health (PMEH) as one of its five core business lines to increase support in this area. Consequently, the Pollution Management and Environmental Health Multi-Donor Trust Fund (PMEH-MDTF) was established in 2015 to drive actions to address air and land pollution issues in low- and middle-income countries (LMICs).

With funding from the PMEH, the World Bank contracted with Technical Service Contractors (TSCs) to carry out the preliminary work to establish a scientific basis for air quality management (AQM) and to develop an AQM plan for the State of Lagos. This document is the final report of that effort. The effort included the following:

- Establishment of a network of six air quality monitoring stations, which represent six of the land use classes, to monitor and collect 12 months of air quality data on $PM_{2.5}$, $PM_{10,}$ other criteria pollutants (sulfur dioxide [SO_2], nitrogen dioxide [NO_2], carbon monoxide [CO], ozone [O_3]), greenhouse gases – GHGs (carbon dioxide [CO_2], black carbon [BC], methane ([CH_4], nitrous oxide [N_2O], chlorofluorocarbons [CFC] and hydrofluorocarbons [HFC]), as well as meteorological parameters
- Chemical analysis and source apportionment analysis of collected aerosol particulate matter (PM) to determine the composition and likely sources of PM emissions
- Development of an inventory of air pollutant emissions, together with potential measures to reduce those emissions
- Photochemical dispersion modeling to reconcile the emission inventory with observed pollutant concentrations and to estimate the severity of exposure in each local government area (LGA)

- Assessment of the health impacts of air pollution in Lagos by estimating its effects on the incidence of premature mortality and illness in each LGA
- Economic and financial analysis of the costs of premature mortality and illness due to air pollution and of the costs and benefits of measures to control pollutant emissions
- Assessment of the existing institutional and governance structure for successful AQM in Lagos and, more broadly, in Nigeria
- Recommendation of an integrated AQM plan and establishment of an air quality index (AQI) for the State of Lagos.

1.1. LAGOS: POPULATION, ECONOMY, AND ENVIRONMENT

Lagos is the largest city in Sub-Saharan Africa and one of the world's fastest-growing megacities. Although Lagos is the smallest state in the Federal Republic of Nigeria by area, it is among the highest in population. From 7.5 million in 2006 (the most recent census), the population in 2019 was estimated at about 13.5 million by the National Bureau of Statistics, and at 23 million by the Lagos State Bureau of Statistics (LBS). This rapid growth has produced urban sprawl and severely strained the infrastructure and the provision of basic services. More than half the population live in informal settlements.

Lagos State has the highest gross domestic product (GDP) of any Nigerian state, accounting for about 25 percent of national GDP. It is a primary center for the transport and manufacturing industries.

As the economic hub of Nigeria, Lagos experiences significant vehicle traffic, resulting in severe traffic congestion, vehicular emissions, and suspended road dust. Businesses and residences rely on diesel and gasoline generators as a backup to compensate for virtually daily power interruptions. Waste disposal is a critical problem; only about 40 percent of the waste generated is collected and transported to dumpsites. The remaining 60 percent is mostly burned. The dumpsites themselves are in poor condition. Compounding that, Olusosun dumpsite—the largest of three major dumpsites and second largest in Africa—is located within the city. These dumpsites are sources of biomass burning, fugitive dust, and various gaseous emissions such as methane (CH_4).

Lagos bears the additional burden of a coastal city with two busy seaports. Most of Nigeria's maritime trade passes through Lagos' ports of Apapa and Tin Can Island, the largest and busiest in West Africa. The ports are constantly overwhelmed with hundreds of old, diesel-engined tractor-trailers conveying containers from the seaports to other parts of the country and contributing to the traffic congestion and vehicular emissions. Ship traffic is equally congested, with ships often having to wait offshore for weeks to unload. Downwind of the seaports is the Okobaba sawmill, with emissions from the constant burning of sawdust. The Ikorodu industrial zone—one of several in the city—is a major source of the unregulated discharge of industrial emissions.

Physically, most of Lagos is built on a low-lying, wooded coastal plain and adjacent barrier islands surrounding a large lagoon. The climate is warm and humid, with a pronounced wet season from May to September and a dry season the remaining months. During the dry season, occasional strong northeasterly *Harmattan* winds carry dust from the Sahara Desert, resulting in low humidity and extremely high concentrations of airborne PM.

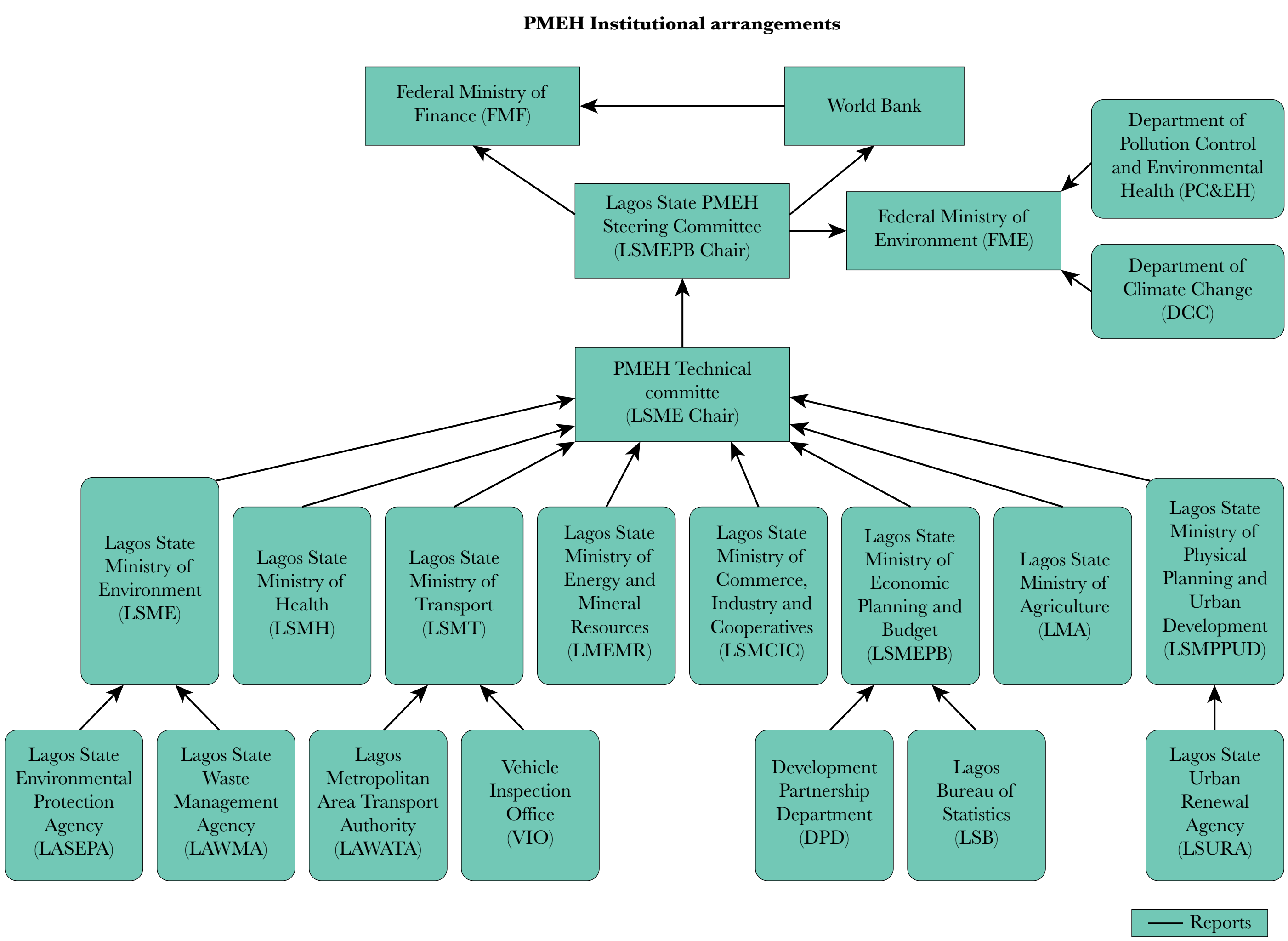
1.2. NEED FOR AN INTEGRATED AIR QUALITY STRATEGY

Lagos currently lacks a standardized AQM system despite the growing evidence of unhealthily high levels of PM and other pollutants and high emissions of GHGs.

A fact-finding air quality monitoring mission (FFMM) was conducted by the World Bank and uMoya-NILU (Norwegian Institute for Air Research)[1] in Lagos between December 11 and 18, 2015 to inform the Lagos AQM plan proposal. Air sampling data collected at eight locations with diverse source characteristics (industrial, commercial, residential, dumpsite, heavy traffic, high population density, conservation, and mixed land use) indicated several cases of extremely high mean PM concentrations.[2] Across locations, the results indicated mean $PM_{2.5}$ levels ranging from 116 $\mu g/m^3$ to 483 $\mu g/m^3$—up to 19 times higher than WHO's 24-hour mean guideline[3] of 25 $\mu g/m^3$—and PM_{10} levels ranging from 55 $\mu g/m^3$ to 442 $\mu g/m^3$, up to nine times higher than the 24-hour mean WHO guideline of 50 $\mu g/m^3$. The results of the FFMM showed remarkably high ambient PM levels at industrial, commercial, traffic, dumpsites, and mixed-residential areas, signifying that substantial PM emissions are being generated from diverse sources such as motor vehicles, domestic power plants, and improper management of wastes.

Both the Nigerian Federal Government and the State of Lagos have developed plans to address emissions that contribute to climate change but, compared to other megacities in the developing world, much less attention has been given to ambient air pollution in the major cities. The major exception was the Federal Government's 2018 plan for managing short-lived GHGs (Government of Nigeria 2018), which explicitly considered the benefits of reducing $PM_{2.5}$ pollution in concert with reductions in black carbon and CH_4 emissions.

FIGURE 1.1. PMEH INSTITUTIONAL ARRANGEMENTS



An integrated approach to pollution management, targeting global warming, air pollution, solid waste, and wastewater management is increasingly important in order to manage the interrelated and complex pollution issues and maximize the benefits of environmental regulation. Some of the impediments to an integrated approach in Lagos are:

- The lack of an air quality monitoring network, resulting in the unavailability of good-quality data that would help identify the sources, extent, and impacts of pollution
- Limited institutional and human resource capacity in pollution monitoring and management
- Poor interinstitutional coordination between state and federal government agencies
- The lack of detail and enforcement provisions in air quality standards and regulations
- Limited capacity to monitor and enforce compliance with standards
- The low level of public awareness of sources and impacts of pollution.

For Lagos State, the major obstacle to an integrated approach to addressing air pollution and GHG emissions in a cost-effective, cohesive manner is the complexity in interinstitutional coordination between different sectors to ensure synergy among the different institutions (indicated in figure 1.1).

REFERENCE

Government of Nigeria. 2018. "Nigeria's National Action Plan to Reduce Short-lived Climate Pollutants." https://climatechange.gov.ng/wp-content/uploads/2020/09/nigeria-s-national-action-plan-nap-to-reduce-short-lived-climate-pollutants-slcps-.pdf.

CHAPTER 2

AIR QUALITY CONDITIONS IN LAGOS

AQM planning must start with knowledge of the existing conditions. Until August 2020, only limited and discontinuous measurements of air quality had been carried out in Lagos. The PMEH therefore funded a TSC to carry out 12 continuous months of air quality monitoring at six monitoring sites. Monitoring began in August 2020 and concluded at the end of July 2021. Details of the monitoring are given in the TSC's report (EnvironQuest 2021a).

The main air quality measurements at each monitoring site were $PM_{2.5}$ and PM_{10}. These were collected on filters for 24-hour periods every three days. The filter collection followed US EPA reference methods, and the samplers used were considered "near-reference" quality. Each monitoring site was also equipped with a weather station, equipment to collect ambient air samples in a vacuum canister over a 24-hour period, and a low-cost, continuous air quality monitoring system. The latter system was included for evaluation. It used an optical sensor to estimate concentrations of PM_{10}, $PM_{2.5}$, and PM_1 and electrochemical sensors to measure gaseous pollutants. As further discussed in section 2.2, the results from this system were of limited value.

From January 1, 2021, the US Consulate in Lagos also began reporting hourly $PM_{2.5}$ concentrations measured by a US EPA reference-grade instrument. Those data are also summarized in this report. Figure 2.1 shows a satellite view of the Lagos metropolitan area, with markers showing the locations of the US Consulate and the six air quality monitoring sites.

FIGURE 2.1. SATELLITE VIEW OF LAGOS SHOWING THE SIX MONITORING SITES, MAIN ROADS, AND THE US CONSULATE

Source: Satellite data—Google Earth.

2.1. PARTICULATE MATTER

Table 2.1 shows the average of the $PM_{2.5}$ and PM_{10} filter measurements taken every third day at each monitoring site as well as the year-to-date measurements by the US Consulate. The Abesan, Jankara, Lagos State Environmental Protection Agency (LASEPA), and University of Lagos (UNILAG) sites are all typical urban locations, with average $PM_{2.5}$ concentrations ranging from 40.3 to 46.5 µg/m^3. This range is probably representative of most of the urban areas. The Nigerian Conservation Foundation (NCF) site is in a protected and undisturbed natural ecosystem near the coast, which is considered to represent regional background concentrations. The Ikorodu site shows extremely high PM concentrations. It is located at a school in a residential area near a concentration of heavy industry. Finally, the US Consulate site is located across the ship channel from Apapa and Tin Can Island ports, so it may be affected by the emissions there.

Figure 2.2 is a chart showing the individual measurements taken at each site over the year of monitoring. These are 24-hour averages collected every three days, except for the US Consulate data, which are hourly. Figure 2.3 is a similar chart of PM_{10} measurements over the year. As these figures show, the WHO guidelines for 24-hour average $PM_{2.5}$ and PM_{10} concentrations are exceeded nearly every day of the year.

As Figure 2.2 and Figure 2.3 show, the PM concentrations at Ikorodu are systematically much higher than at the remaining sites, which tend to bunch closely together. The hourly $PM_{2.5}$ data from the US Consulate also agree well with the PM filter measurements. Both $PM_{2.5}$ and PM_{10} concentrations are noticeably higher during the dry season. Finally, the effects of the *Harmattan* winds in January 21–26 and February 19–24 can be seen in the extremely high concentrations of both $PM_{2.5}$ and PM_{10} across all of the monitoring sites during those periods.

TABLE 2.1. ANNUAL AVERAGE PM CONCENTRATIONS COMPARED TO WHO GUIDELINES

Location	Concentration (μg/m³)	
	$PM_{2.5}$	PM_{10}
Abesan	46.5	119.4
Jankara	41.5	104.9
LASEPA	40.3	103.3
UNILAG	41.7	96.2
Ikorodu	96.8	170.5
NCF	29.5	73.6
US Consulate	49.2[a]	
WHO guidelines (μg/m³)		
Annual average	5	15
24-hour average	15	45

Note: a. January 1 to October 15, 2021

In addition to the PM filter measurements, the low-cost Earthsense Zephyr monitoring systems estimated $PM_{2.5}$ and PM_{10} concentrations using an optical sensor. Unfortunately, these estimates were not very accurate. Figure 2.4 compares the PM concentrations determined by the filter samplers with the average of the optical sensor concentration estimates over the same sampling period. The correlation coefficient is only moderate, with R^2 about 0.62. The slope of the best-fit line for $PM_{2.5}$ is 2.94 and that for PM_{10} is 4.3. Thus, the optical sensor greatly underestimated the actual PM concentrations as measured by the filters.

While far from perfect, the inexpensive optical sensor in the Earthsense Zephyr correlates well enough to give a reasonable indicator of PM levels in real time. Figure 2.5 plots the optical sensor reading for $PM_{2.5}$ for one of the sites—corrected using the best-fit equation shown in Figure 2.4—with the corresponding results from the 24-hour PM filter measurements. Figure 2.6 shows a similar plot for PM_{10}. The two sets of data agree well, except for the month of October. The same is true for the remaining sites, except for Ikorodu. The anomalously high readings from the optical sensor during October occurred in the early- to mid-morning hours and may have been due to fog.

FIGURE 2.2. $PM_{2.5}$ MEASUREMENTS AT EACH MONITORING SITE

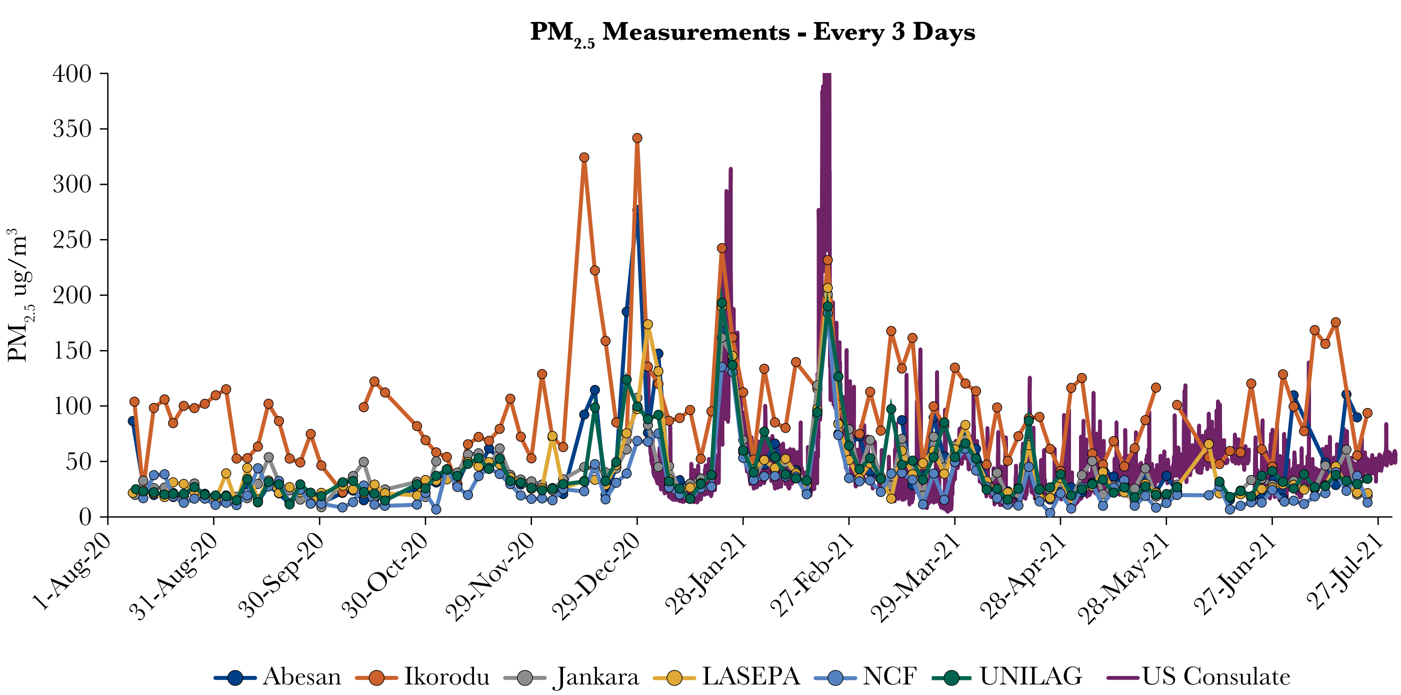
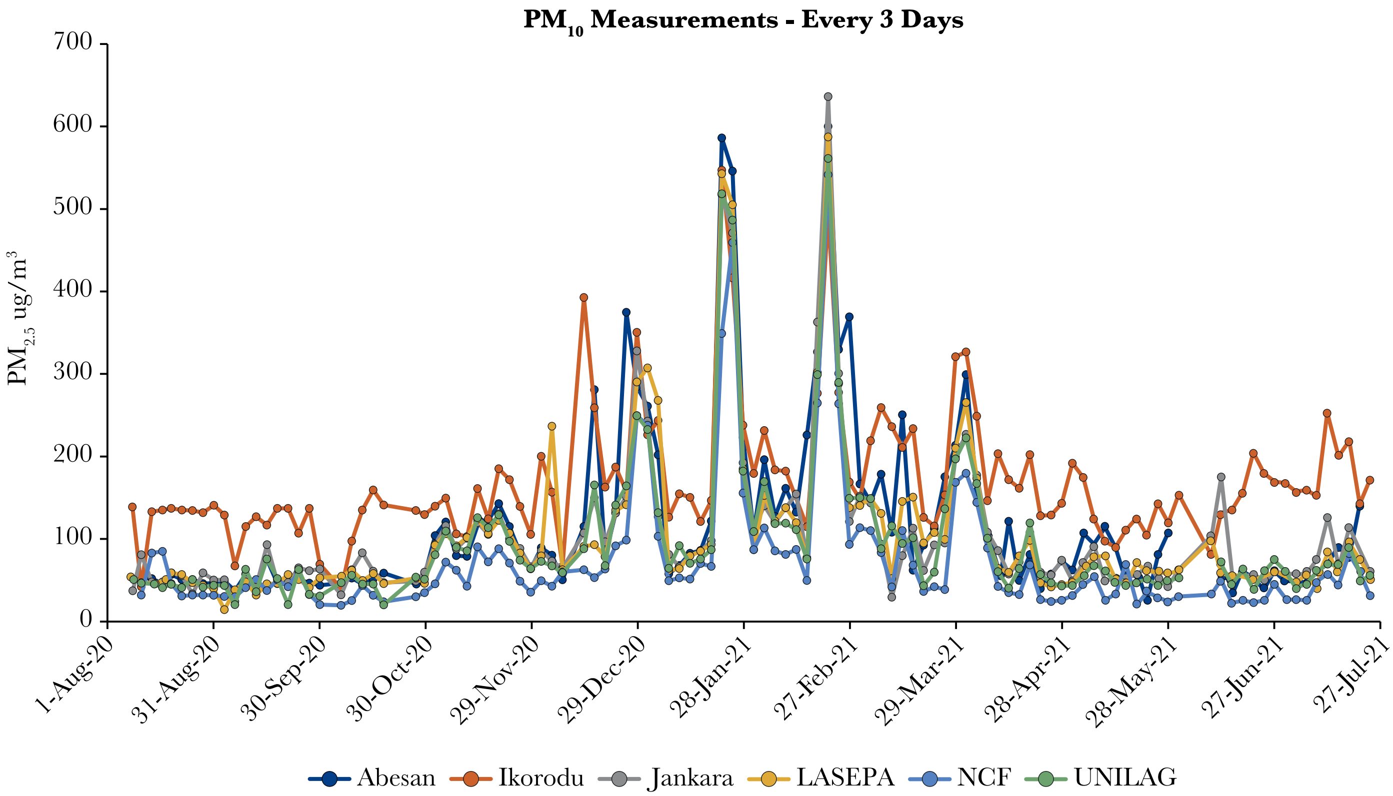


FIGURE 2.3. PM_{10} MEASUREMENTS AT EACH MONITORING SITE



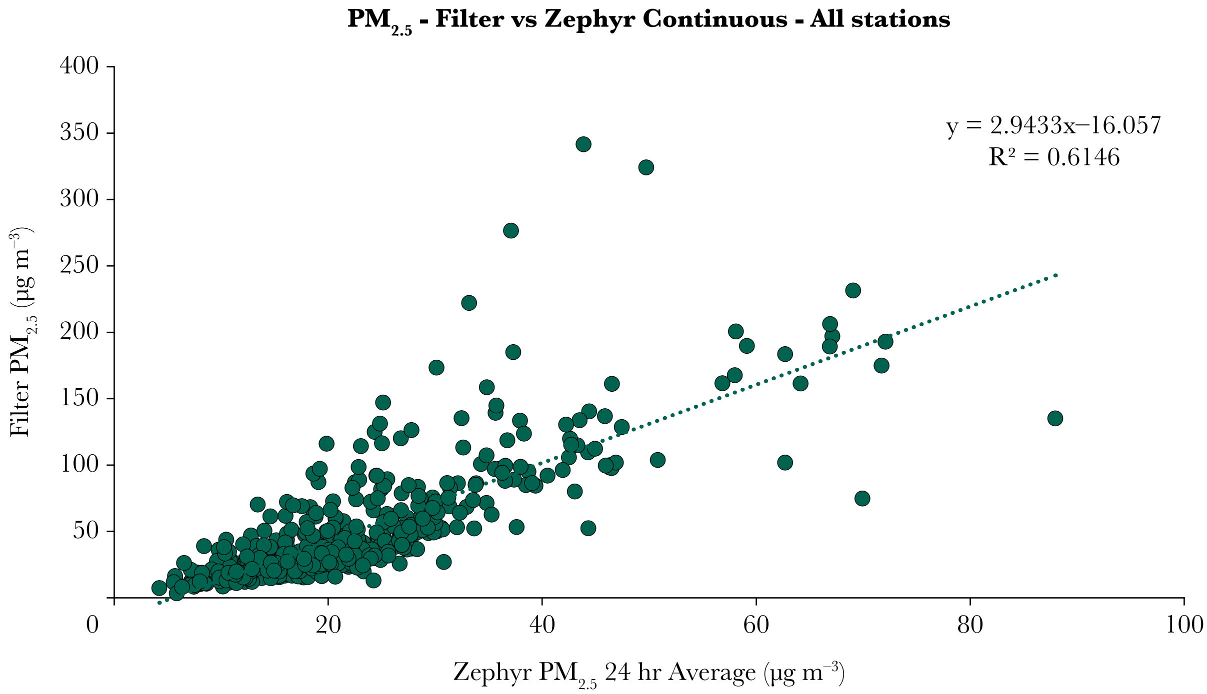
2.1.1. PM COMPOSITION

In addition to measuring the amount of PM mass collected, the TSC carried out chemical analysis of a subset of the PM filters. Generally, the filters analyzed were those from the three monitoring days at each site that showed the highest $PM_{2.5}$ concentrations. For each set of filters, the measurements included concentrations of 41 chemical elements (from sodium to uranium), as well as elemental carbon, organic carbon, and six water-soluble ionic species. The concentrations of 225 organic marker species were also measured. These data were analyzed to apportion the PM present among different source categories. Details of the chemical analysis can be found in the TSC's final report (EnvironQuest 2021a).

The results of the chemical analysis are summarized in Figure 2.7. For the $PM_{2.5}$ samples analyzed, elemental carbon (EC) made up about 10 percent and a mix of organic compounds (OM) made up about 30 percent of the total. Fine soil made up between 25 percent and 36 percent, while ammonium nitrate and ammonium sulfate made up about 10 percent. Other trace elements such as zinc and unidentified material made up about 15 percent, except at Ikorodu, where they accounted for about 33 percent. Much of the unidentified material was likely made up of oxygen combined with the metallic trace elements or water adsorbed by the particulate matter.

Ammonium nitrate, ammonium bisulfate, and other sulfates are typically secondary pollutants, meaning that they are not emitted directly but are formed in the atmosphere through chemical reactions among gaseous pollutants: NH_3, SO_2, and NO_2. Some of the particulate organic matter is also formed by secondary reactions involving gaseous hydrocarbons in the atmosphere. The remaining pollutants and the bulk of the organic matter are primary pollutants, meaning that they are directly emitted into the atmosphere by various sources.

FIGURE 2.4. CORRELATION BETWEEN PM FILTER DATA AND 24-HOUR AVERAGE OPTICAL SENSOR PM ESTIMATES



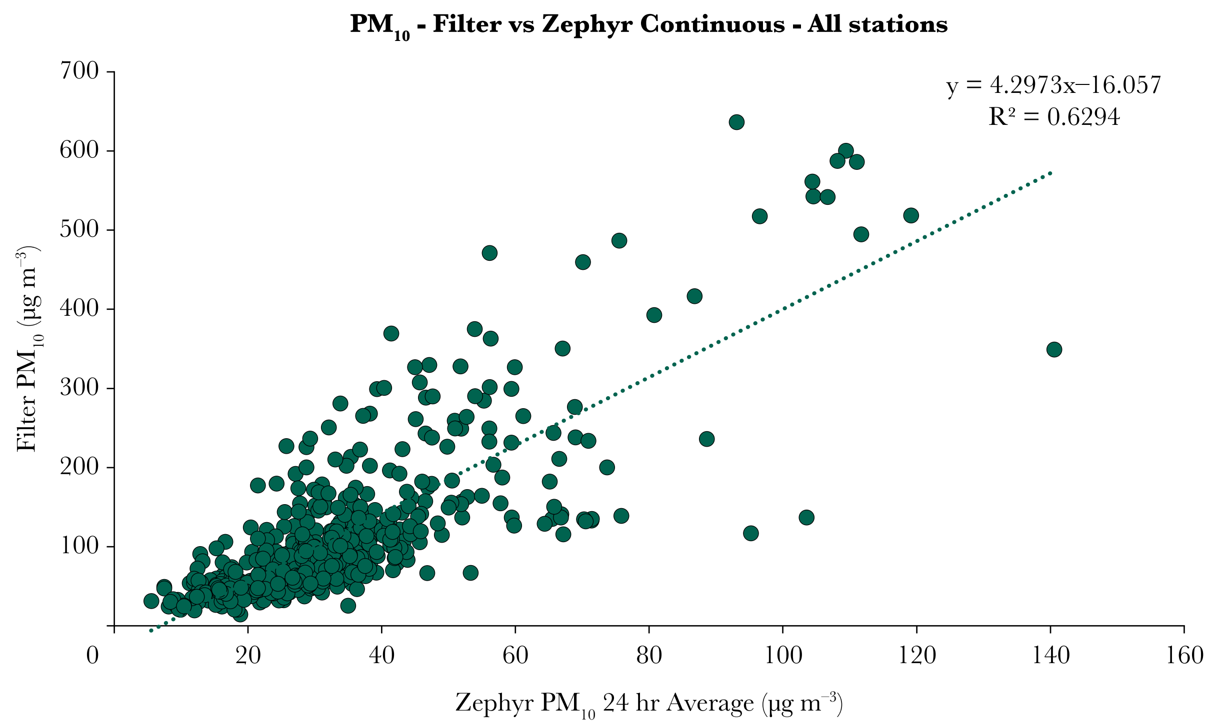


FIGURE 2.5. CORRECTED OPTICAL SENSOR $PM_{2.5}$ READINGS VERSUS 24-HOUR FILTER MEASUREMENTS—JANKARA SITE

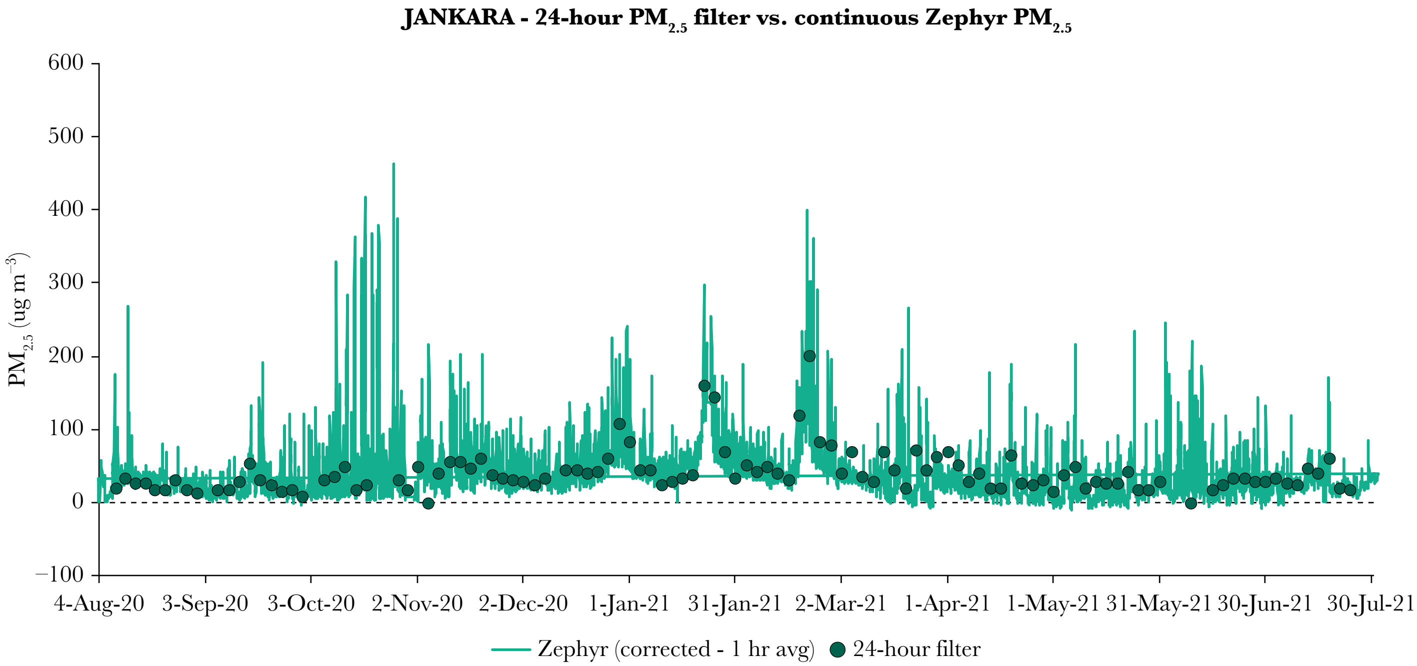


FIGURE 2.6. CORRECTED OPTICAL SENSOR PM_{10} READINGS VERSUS 24-HOUR FILTER MEASUREMENTS – JANKARA SITE

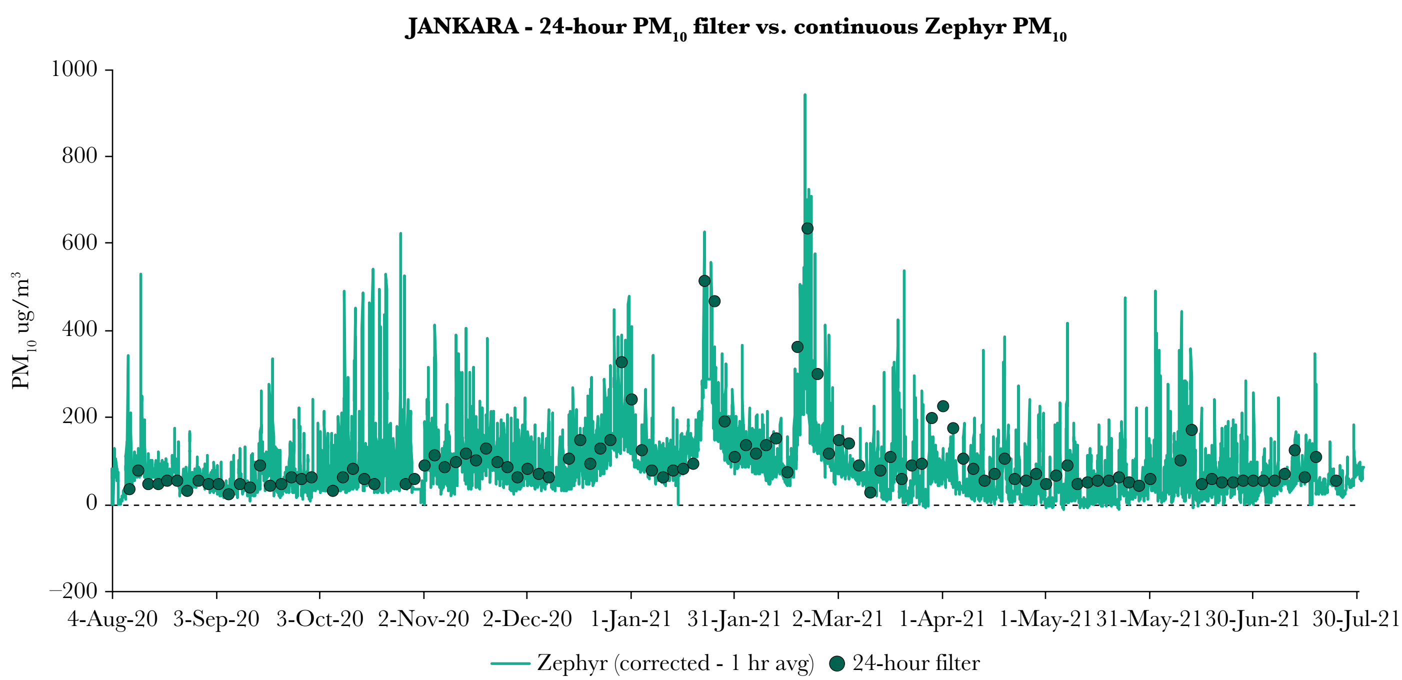
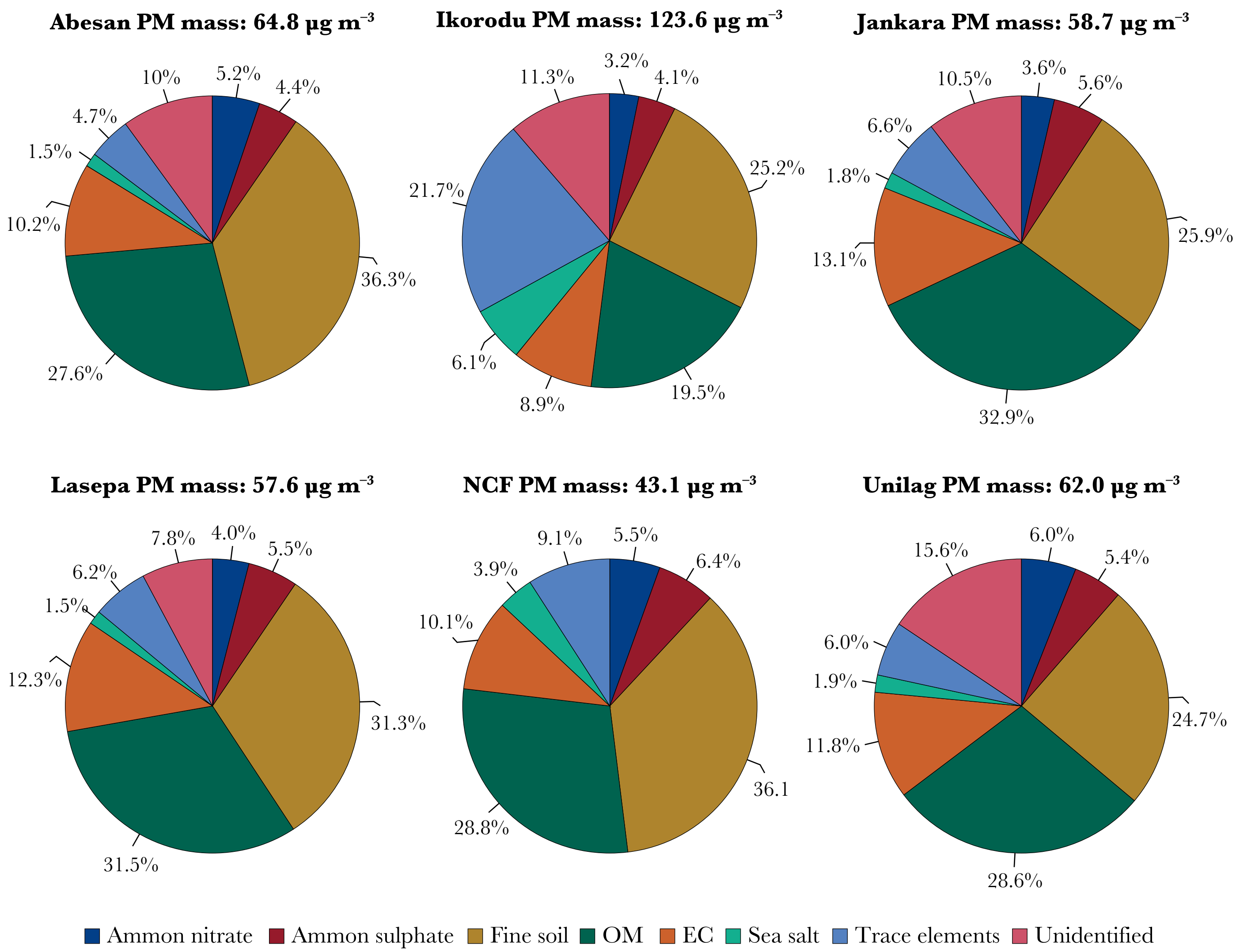


FIGURE 2.7. SUMMARY OF THE CHEMICAL COMPOSITION OF $PM_{2.5}$ COLLECTED AT THE SIX MONITORING SITES



2.1.2. PM SOURCE APPORTIONMENT

To better determine the sources of ambient PM concentrations in Lagos, the TSC carried out a source apportionment analysis using the PM compositions. Two different source apportionment techniques were applied: positive matrix factorization (PMF) and chemical mass balance (CMB). Both analyses used techniques and software developed for this purpose by the US EPA. Further details are given in the TSC's report (EnvironQuest 2021b). The results of the source apportionment of $PM_{2.5}$ by PMF are summarized in Figure 2.8, while the results of the CMB analysis are summarized in Figure 2.9. The two techniques gave similar results for PM source apportionment in Lagos during the monitoring period.

The PMF analysis showed nine source types: dust, biomass burning, solid waste burning, diesel combustion, gasoline engine combustion, industrial emissions, ammonium nitrate, sulfate, and a fraction that was rich

FIGURE 2.8. $PM_{2.5}$ SOURCE APPORTIONMENT BY PMF

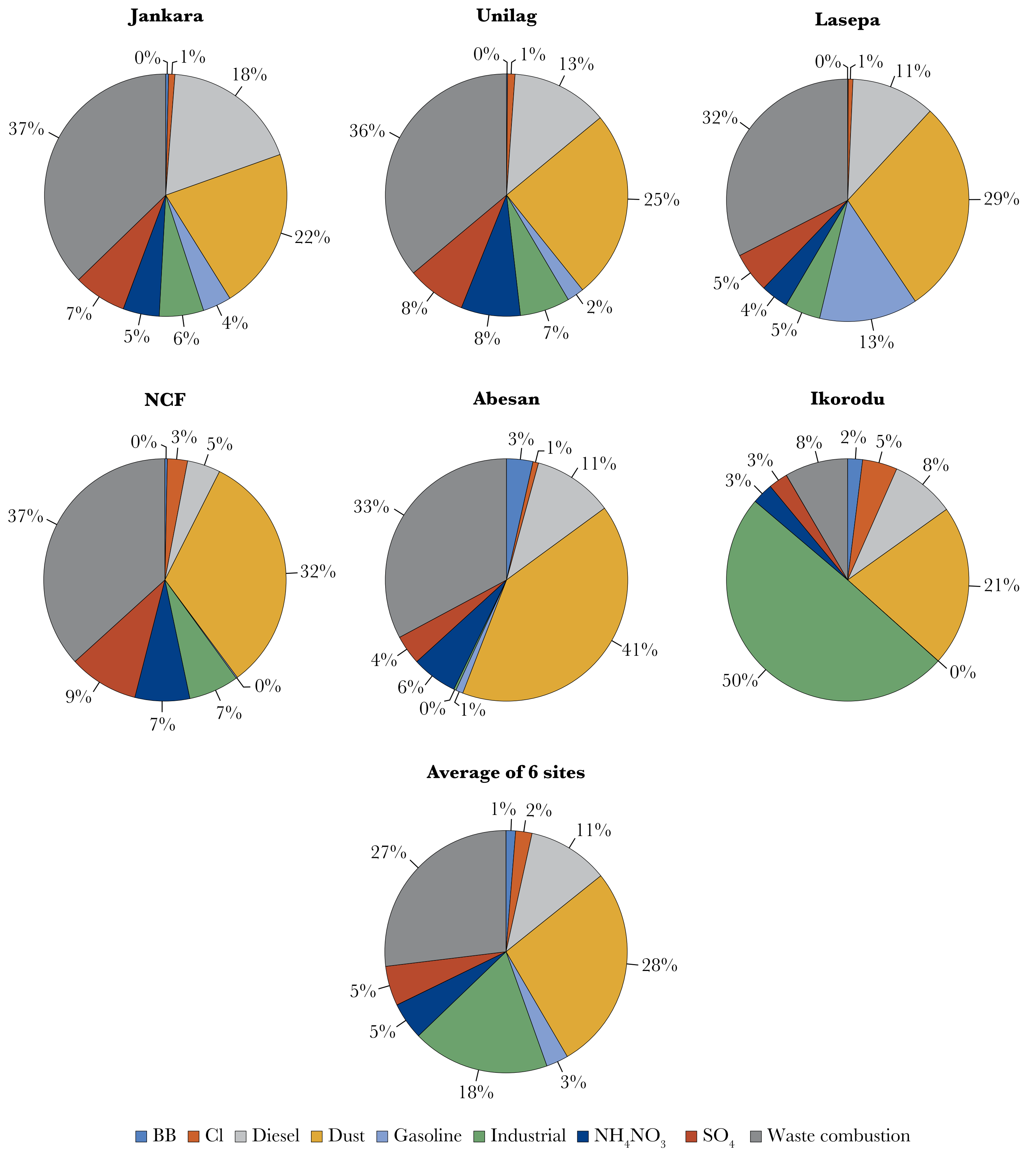
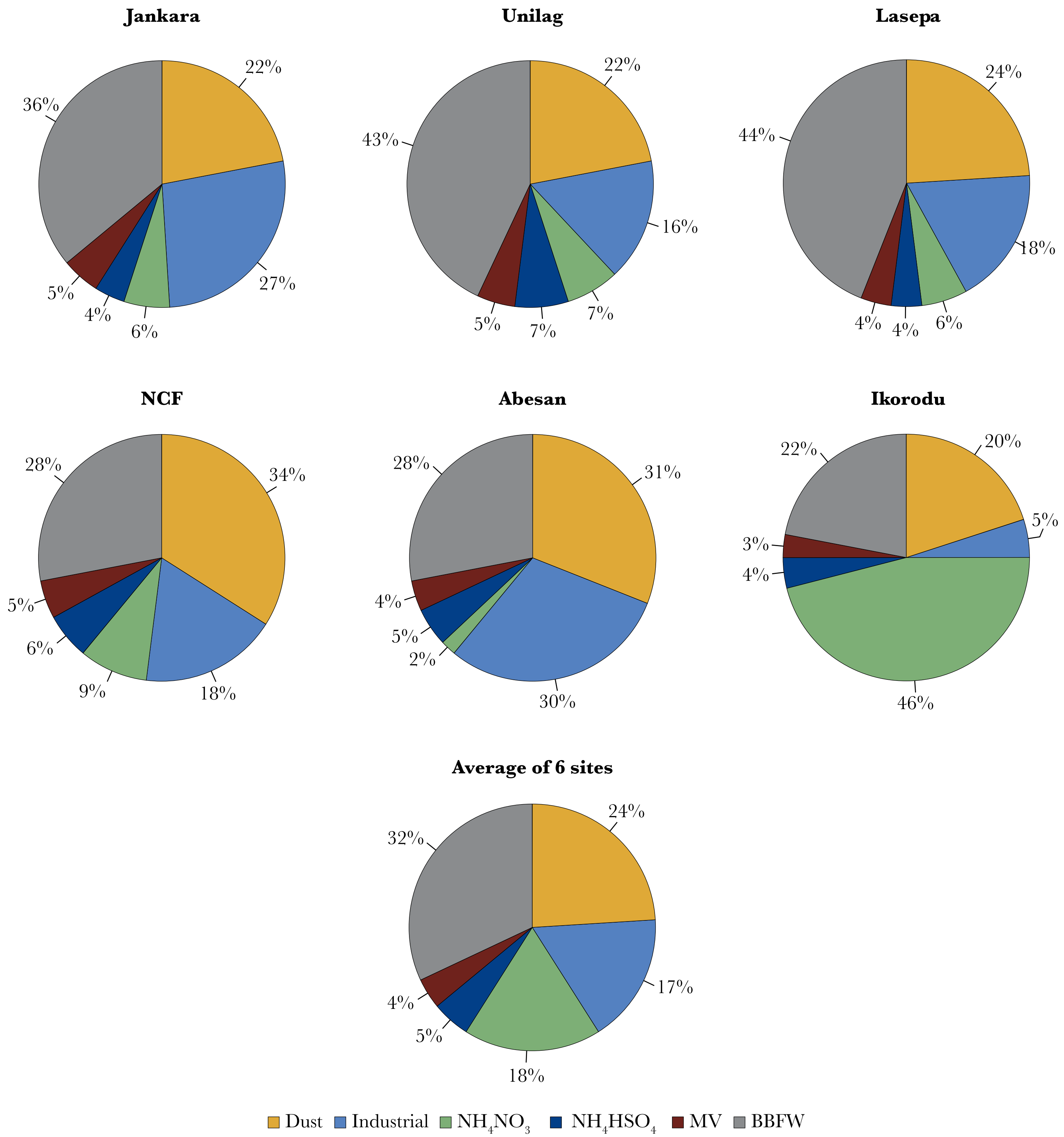


FIGURE 2.9. $PM_{2.5}$ SOURCE APPORTIONMENT BY CMB



in chloride ion (Cl-). The CMB analysis identified only six source types: dust, a combination of biomass with solid waste burning and cooking, motor (gasoline and diesel engines combined), industrial emissions, ammonium nitrate, and ammonium sulfate. Dust makes up 28 percent of the average source composition in PMF and 24 percent in CMB. Open burning of biomass and solid waste makes up 28 percent in PMF; that plus cooking make up 32 percent in CMB. Gasoline and diesel engines combined make up 14 percent in PMF and 17 percent in CMB. Secondary ammonium nitrate and ammonium sulfate make up 10 percent in PMF and 9 percent in CMB. Both techniques show industrial emissions at 18 percent of the average over the six sites. Industrial emissions at Ikorodu are 50 percent in PMF and 46 percent in CMB, less than 1–2 percent at Abesan, and 5–9 percent at the other sites monitored.

The results of PMF source apportionment of the PM_{10} composition data are summarized in Figure 2.10 (no CMB analysis was done for PM_{10}). These results show that the percentage of the PM_{10} due to dust is about twice as high as for $PM_{2.5}$, while the percentage due to the chloride-rich fraction is five times as high. This suggests that the chloride-rich fraction may be due to sea salt particles since these occur primarily in the coarse mode. The contributions of the other sources are reduced more or less proportionally.

2.1.3. SOURCE OF HIGH PM CONCENTRATIONS AT IKORODU

Average PM concentrations at the Ikorodu site were consistently higher than for any of the other monitoring sites. Although the site itself is at a secondary school, it is close to a number of factories that were hypothesized to be the source of the excess PM. To test this hypothesis, the TSC plotted the average $PM_{2.5}$ and PM_{10} concentrations as functions of wind direction and speed, as shown in Figure 2.11. Winds from the directions corresponding to the nearby industrial establishments consistently showed much higher PM concentrations than from any other direction.

2.2. LEAD AEROSOL

Lead aerosol is a highly toxic component of airborne PM. Because of its former widespread use in gasoline and paints, the US EPA has established a separate ambient air standard of 0.15 $\mu g/m^3$ for lead, measured as a quarterly average of total suspended particulate matter (TSP). With the worldwide elimination of leaded gasoline and paints, this limit has largely become irrelevant except in the vicinity of poorly controlled lead-smelting activities such as battery recycling. However, Figure 2.12 shows that the airborne lead concentrations measured at the Ikorodu site are more than 10 times the level of the EPA standard, indicating a grave threat to public health. Four of the other five monitoring sites marginally exceeded the standard during at least one quarter. Only the Abesan site did not. Abesan is also the site furthest from Ikorodu. This could indicate that a major source of lead emissions near the Ikorodu site may be causing exceedance of the lead standard throughout much of the city.

2.3. GASEOUS POLLUTANTS

Common gaseous pollutants for which the Federal Ministry of Environment (FMEnv) has established ambient air quality standards include O_3, NO_2, CO, and SO_2. Table 2.2 shows the air quality standards in effect in Nigeria and the US, along with the recently updated guidelines of the WHO.

Details of the gaseous pollutant measurements and quality assurance are given in the TSC's report (EnvironQuest 2021a). In this monitoring campaign, the gaseous pollutants were measured using low-cost electrochemical sensors. Because of this, the data are not completely reliable. In particular, the measurements of O_3, CO, and SO_2 tend to show spuriously high "spikes" for an hour or two after the monitoring system starts up, while the NO_2 measurements tend to show spuriously low values. During some periods, battery problems with the solar power systems at the LASEPA and Ikorodu sites caused the

FIGURE 2.10. PM_{10} SOURCE APPORTIONMENT OF PM_{10} BY PMF

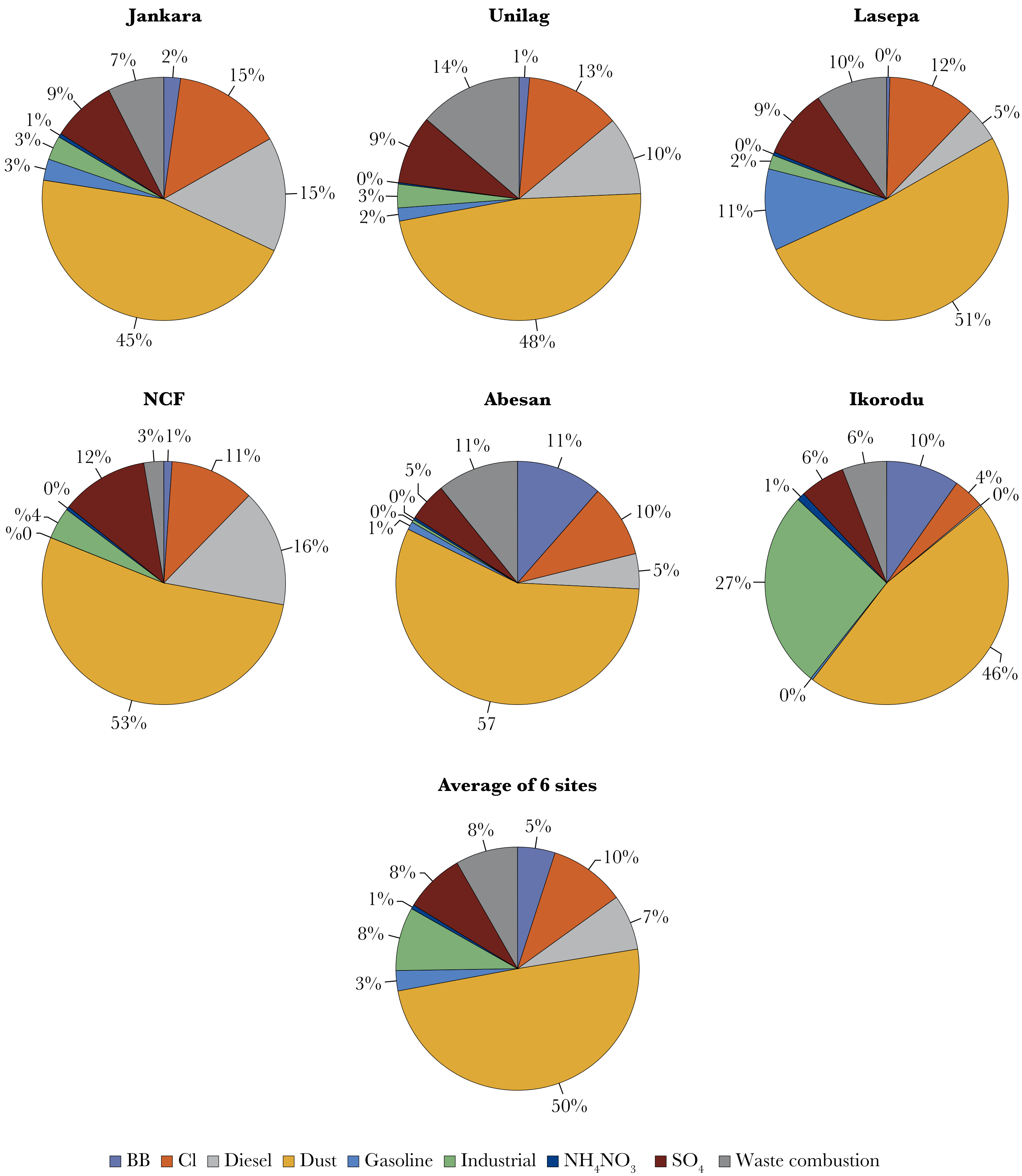


FIGURE 2.11. PM CONCENTRATION VERSUS WIND DIRECTION FOR IKORODU

FIGURE 2.12. QUARTERLY AVERAGE LEAD AEROSOL CONCENTRATIONS MEASURED AT EACH SITE

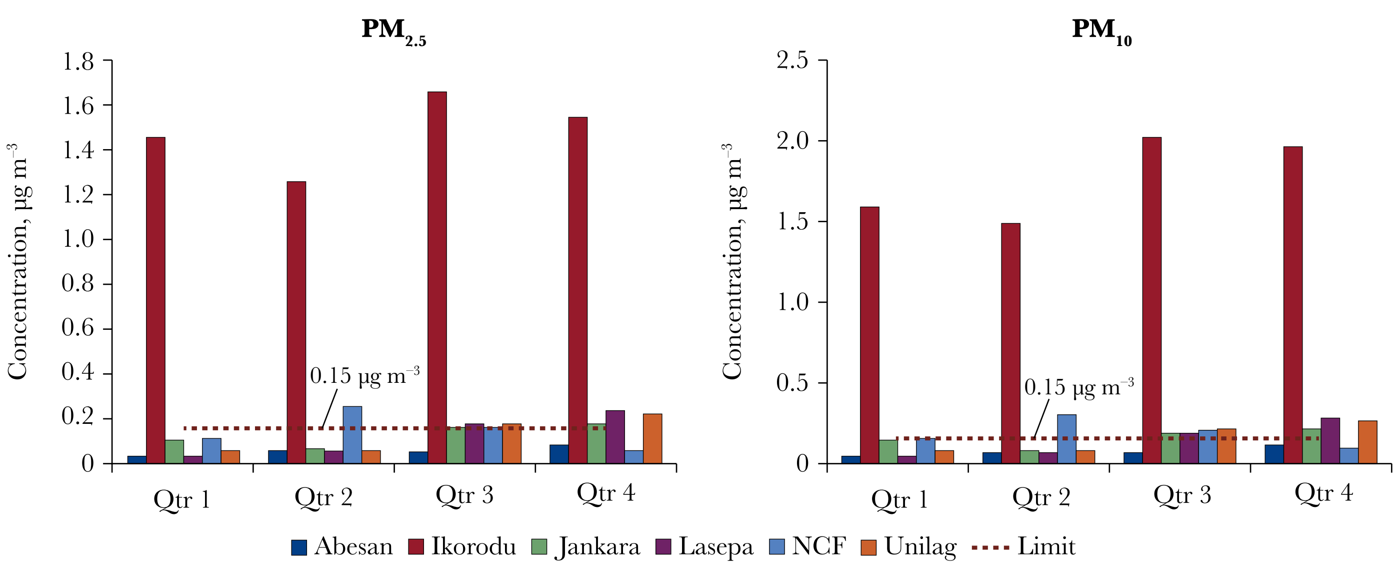


TABLE 2.2. AMBIENT AIR QUALITY STANDARDS AND WHO GUIDELINES FOR GASEOUS POLLUTANTS

Pollutant (units)	Averaging period	US EPA NAAQS	Nigeria AAQS	WHO Air Quality Standard
O_3 (μg/m^3)	6 months[a]	—	—	60
	8 hours	137 (0.07 ppm)	100	100
	1 hour	—	180	—
NO_2 (μg/m^3)	Annual	100 (53 ppb)	—	10
	24 hours	—	120	25
	1 hour	188 (100 ppb)	200	200
SO_2 (μg/m^3)	24 hours	—	120	40
	1 hour	196.5	350	—
CO (mg/m^3)	24 hours	—	—	4
	8 hours	10 (9 ppm)	5	5
	1 hour	40 (35 ppm)	10	10

Note: US EPA National Ambient Air Quality Standards (NAAQS) values in parenthesis are μg/m^3 equivalent at 1 atmosphere and 25°C.

a. Average of daily 8-hour peaks.

monitors to shut down every night and start up the following morning. Data from those periods, as well as other spurious data (to the extent that these could be identified), have been redacted from the database.

After removing the spurious values, the results of the gaseous pollutant monitoring show that concentrations of CO exceeded the Nigerian air quality standards and WHO health guidelines at all six sites. Figure 2.13 shows the 8-hour average CO concentrations measured at each site. All six sites exceeded the Nigerian CO standard of 5 μg/m^3. The Abesan, Jankara, and UNILAG sites show the highest and most frequent exceedances, sometimes exceeding the less stringent US standard of 10 μg/m^3. One-hour average concentrations (not shown) often exceeded the Nigerian standard of 10 μg/m^3 but not the US 40 μg/m^3 standard.

Figure 2.14 shows the 24-hour average NO_2 concentrations measured at each monitoring site. These rarely exceeded the Nigerian air quality standard of 120 μg/m^3 but exceeded the new WHO guideline of 25 μg/m^3 almost all the time. Annual average concentrations ranged from 48 μg/m^3 at NCF to 76 μg/m^3 at Jankara—far exceeding the WHO guideline of 10 μg/m^3.

Figure 2.15 shows the 8-hour average O_3 concentrations measured at each of the six sites. The concentrations at these sites exceeded the Nigerian air quality standard of 100 μg/m^3 twice, while the 1-hour average concentrations exceeded the 180 μg/m^3 Nigerian standard once. The 6-month average peak concentration at Abesan likely exceeded the WHO guideline of 100 μg/m^3 as well. However, all of these sites except NCF were situated close to significant sources

FIGURE 2.13. EIGHT-HOUR AVERAGE CO CONCENTRATIONS AT EACH MONITORING SITE

Green lines, Nigerian/WHO standard, red lines US NAAQS

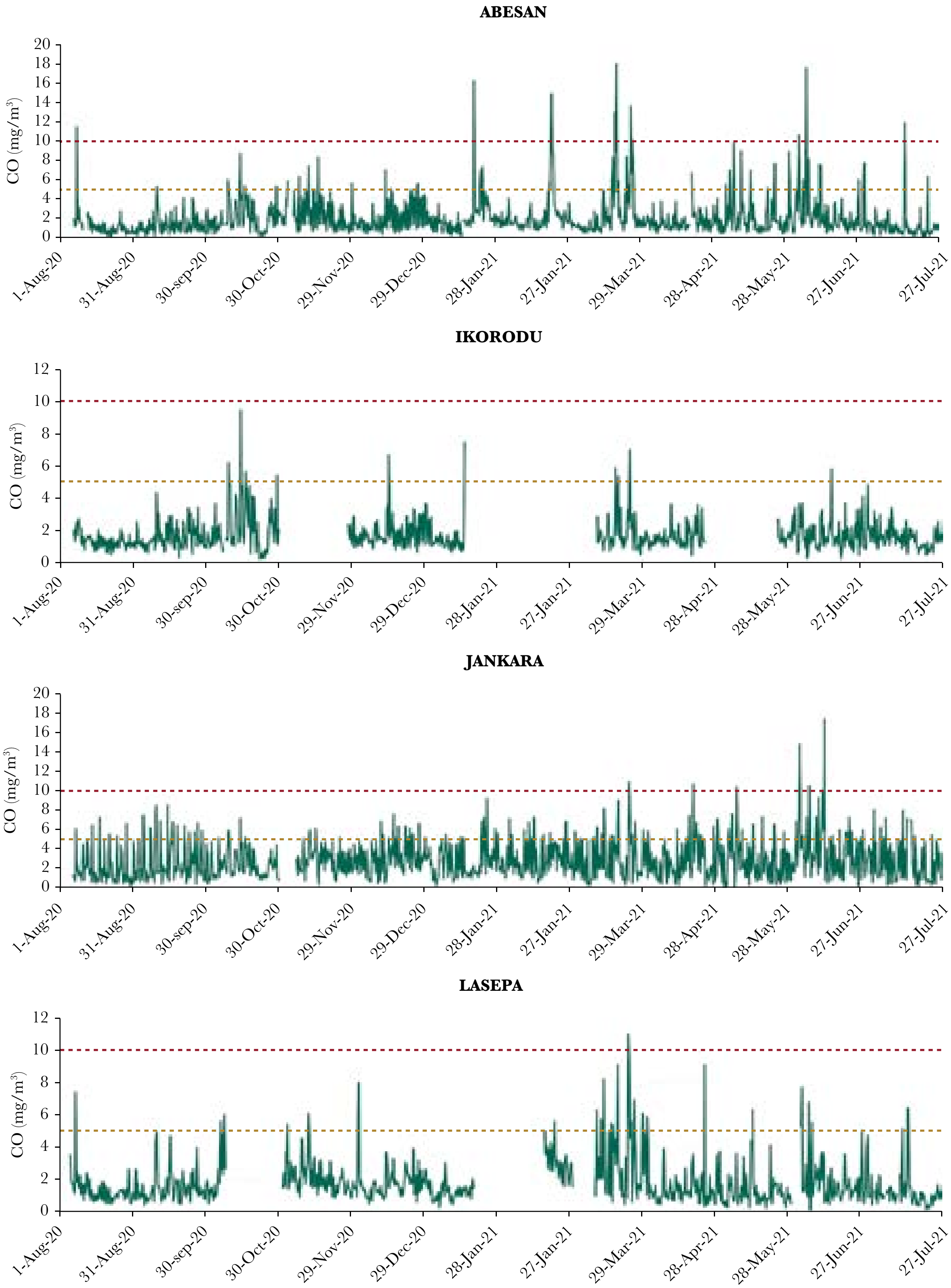
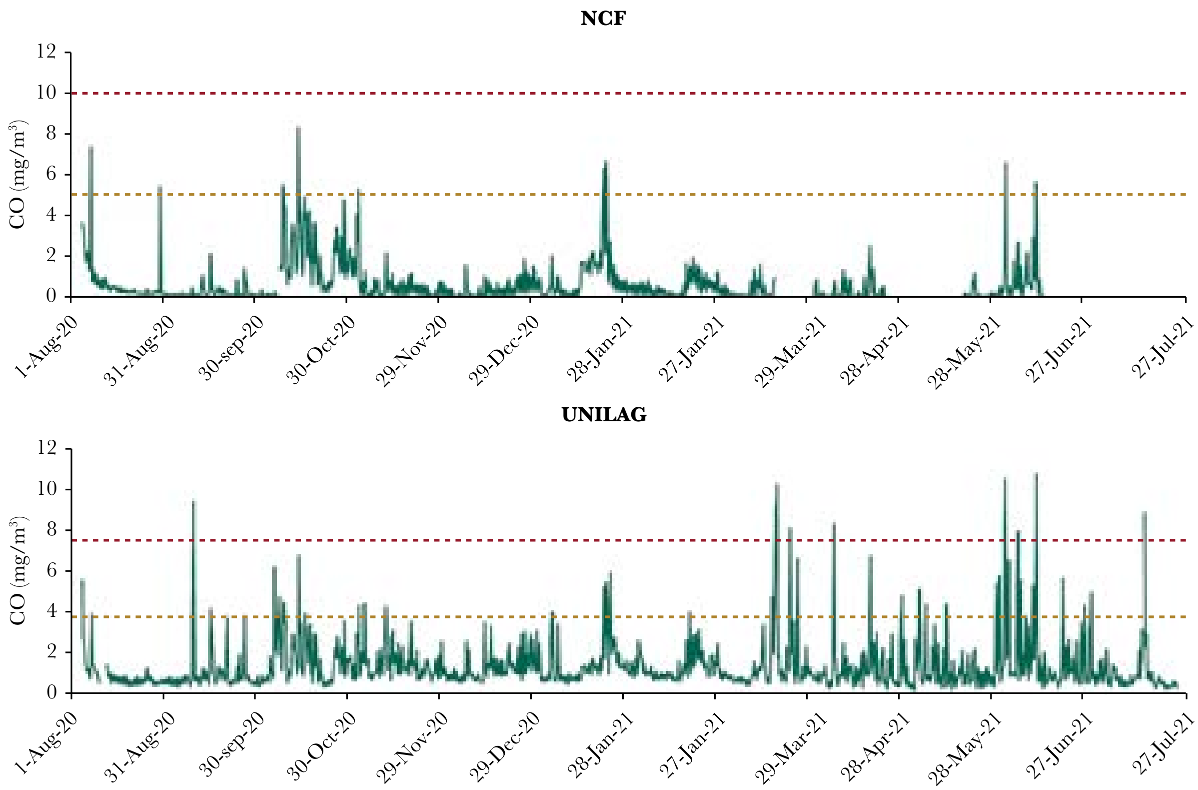


FIGURE 2.13. *(Continued)*



of nitrogen oxides (NOx). The air quality modeling confirmed that much higher O_3 concentrations are to be expected in the region downwind of the city. This is because nitric oxide (NO), the major constituent of NOx, reacts with O_3 to form NO_2 and O_2, thus suppressing O_3 levels close to the emission source. In the presence of sunlight, NO_2 reacts over time with volatile organic compounds (VOCs) in a complex process that produces O_3 and other photochemical oxidants. Thus, as distance from the source of NOx emissions increases, so usually does the O_3 concentration.

The monitoring data for SO_2 show levels generally well below the applicable standards, except for a single event with multiple spikes that was observed by both the UNILAG and LASEPA sites from about 22:00 on October 6 to 06:00 on October 8 (Figure 2.16). At the UNILAG site, this event slightly exceeded the Nigerian 1-hour standard and WHO guideline of 200 μg/m^3. The missing data during the peak may indicate times when the ambient concentration was above the range of the sensor. Several other smaller events are also visible in the UNILAG data.

2.4. ORGANIC COMPOUNDS AND TOXIC AIR CONTAMINANTS

At each of the six sites, the air monitoring TSC collected a total of 22 air samples in evacuated canisters for chemical analysis. Each sample was collected at a uniform rate over 24 hours. The resulting canister samples were

FIGURE 2.14. TWENTY-FOUR-HOUR AVERAGE NO_2 CONCENTRATIONS AT EACH MONITORING SITE

Red lines Nigerian standard, green lines WHO guideline

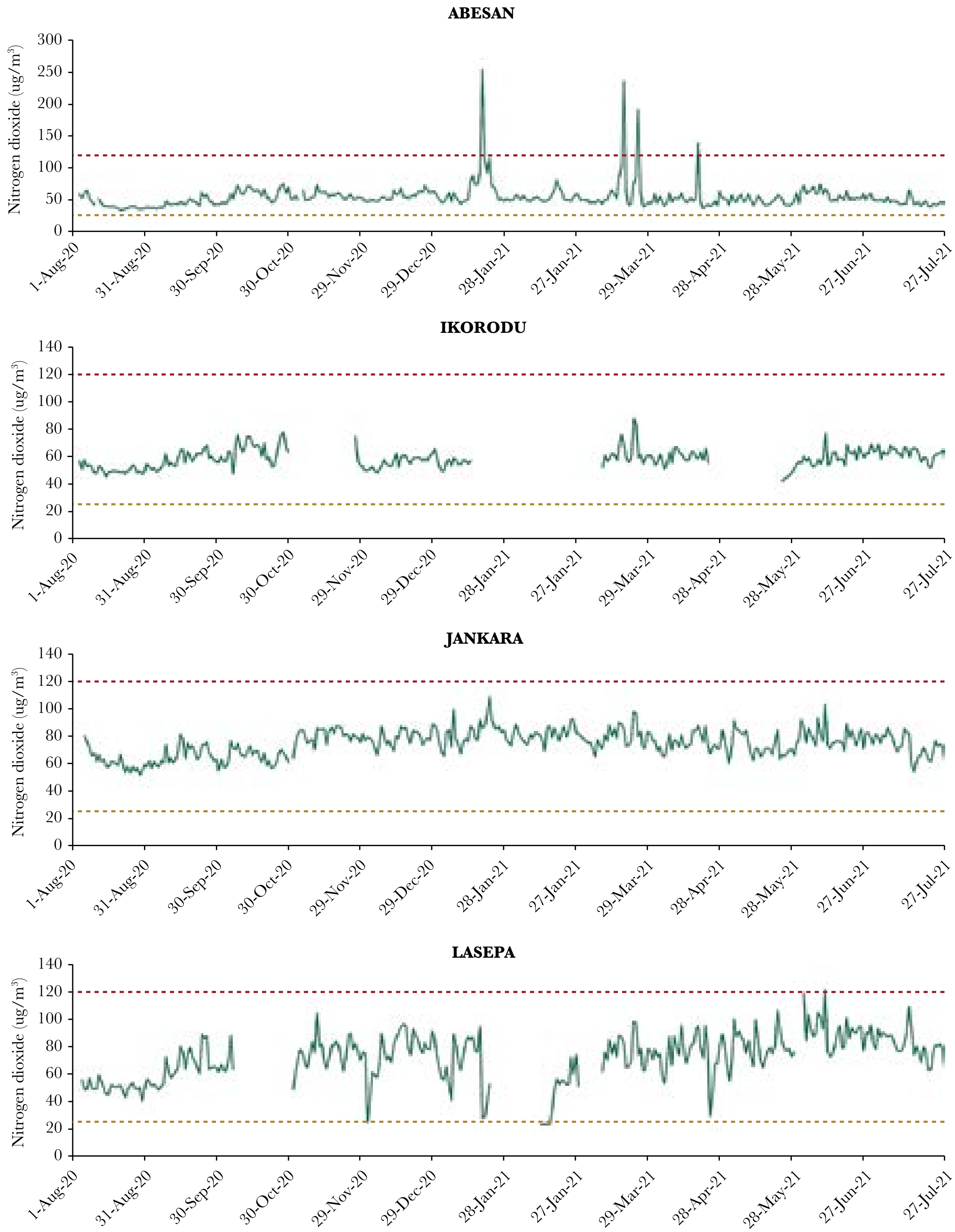
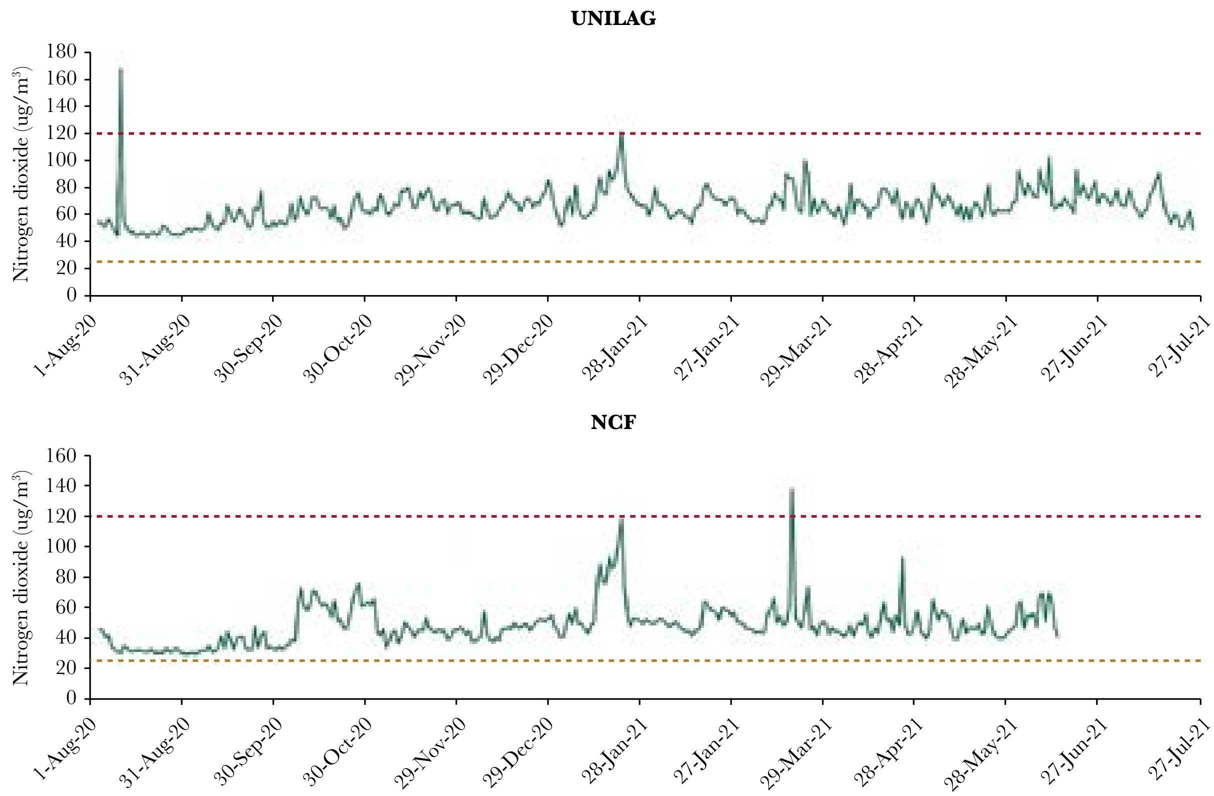


FIGURE 2.14. *(Continued)*



analyzed for their content of 106 organic compounds and other toxic air contaminants, as well as chlorofluorocarbons (CFCs), HFCs, and GHGs.

The results of the organic analysis showed that most compounds are present in less than parts per billion (ppb) concentrations. However, some are at concentrations of ppb or tens of ppb, among them ethane (a minor constituent of natural gas), propane and butanes (from liquefied petroleum gas, or LPG), and products of partial gasoline combustion such as ethylene and propylene. Also present in significant amounts were common solvents such as toluene, naphthalene, acetone, chloromethane, and dichloromethane—all of which are considered hazardous air pollutants. From February, high concentrations of dichloromethane were seen at the Ikorodu and LASEPA sites (67 and 74 parts ppb initially, tapering to about 33 ppb over months). This likely indicates the startup of a large industrial user of dichloromethane solvents with little or no emission control.

2.5. GREENHOUSE GASES

The TSC analyzed the canister air samples for the main GHGs, as well as for common halocarbons (CFCs, hydrochlorofluorocarbons [HCFCs], and HFCs) with high global-warming potential (GWP). The average GHG concentrations at each site are shown in Figure 2.17, while the average concentrations of halocarbons are shown in Figure 2.18.

CO_2 concentrations at all sites were above the global background level, reflecting the substantial CO_2 emissions in the metropolitan area. The same is true of CH_4

and nitrous oxide (N_2O) concentrations. The significance of the variation in average concentrations among the six sites is not clear.

Among the halocarbons measured, concentrations of CFC 11 and CFC 12 were highest at Ikorodu, followed by Jankara. CFC 113 was three times as high at Abesan as at any other site, while CFC 114 was similarly high at UNILAG. This suggests possible emission sources of these CFCs in the surrounding area. HCFCs 141b and 142b at all sites were significantly higher than the global background concentrations, suggesting that emission sources for these chemicals may be widespread throughout the metropolitan area.

FIGURE 2.15. EIGHT-HOUR AVERAGE O_3 CONCENTRATIONS AT EACH MONITORING SITE

Green lines, Nigerian/WHO standard, red lines US NAAQS

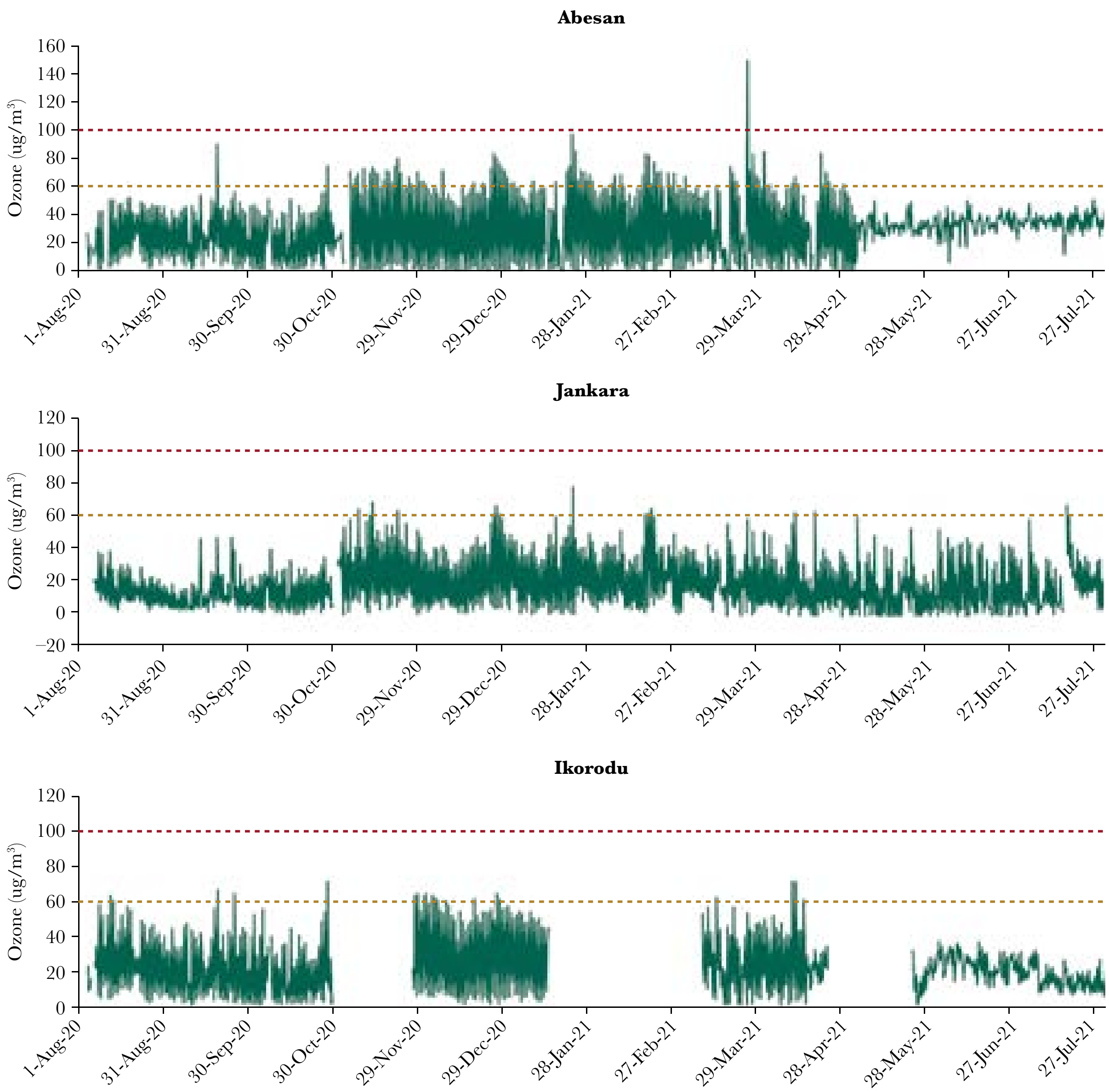
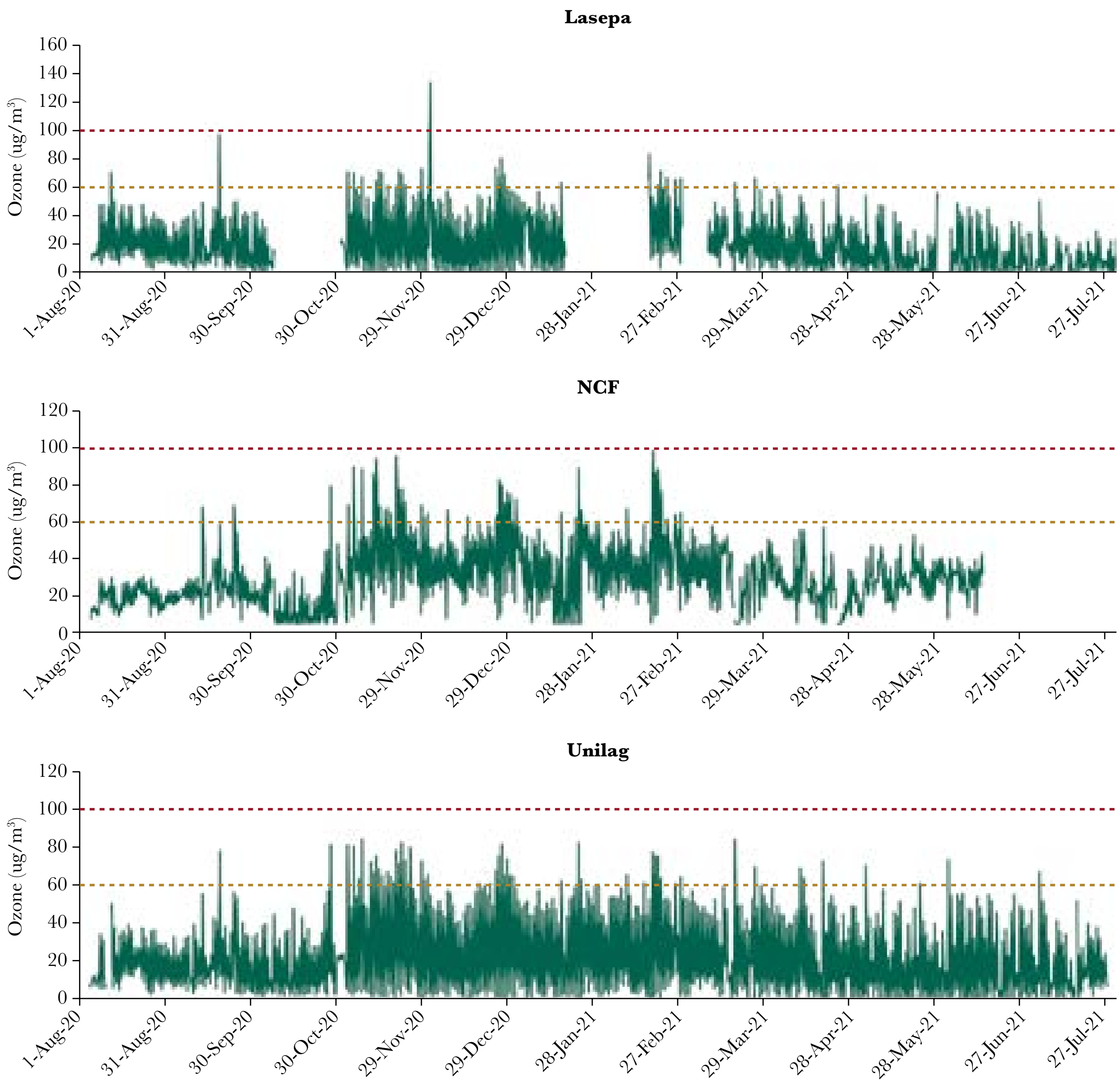


FIGURE 2.15. (*Continued*)



2.6. POLLUTANT EMISSION INVENTORY

An emissions inventory is an estimate of the emissions of each type of pollutant in a given area, broken down by the type of source. Using PMEH funds, the World Bank contracted with a TSC to develop a preliminary emissions inventory for Lagos State (ARIA 2021). The preliminary inventory was then validated against the air quality monitoring data.

2.6.1. CRITERIA POLLUTANTS

Table 2.3 shows the inventory estimates of criteria pollutant[4] emissions and their precursors. For discussion

FIGURE 2.16. SO_2 CONCENTRATIONS AT LASEPA AND UNILAG SITES

Green lines, Nigerian/WHO standard, red lines US NAAQS

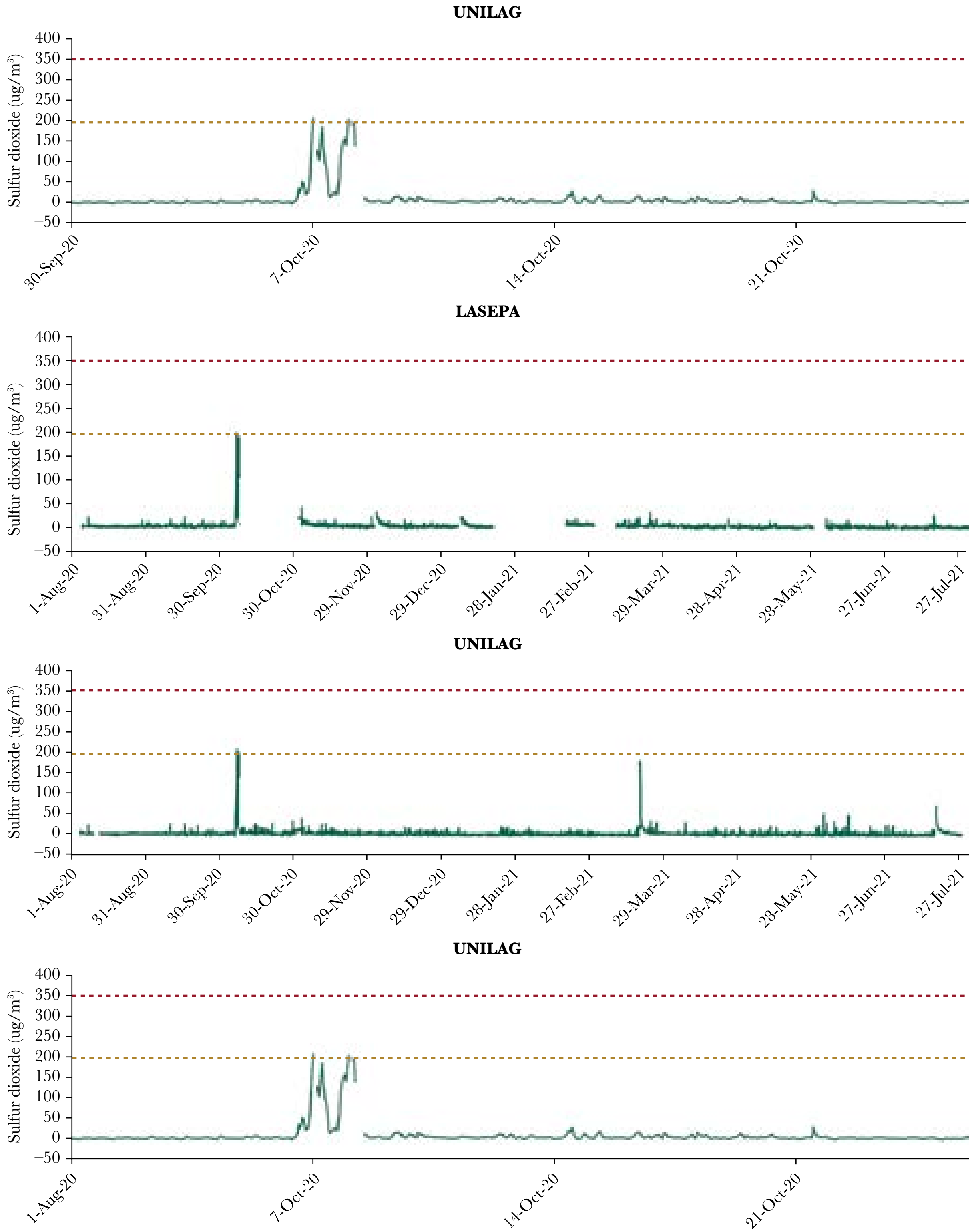


FIGURE 2.17. AVERAGE GHG CONCENTRATIONS MEASURED AT EACH MONITORING SITE

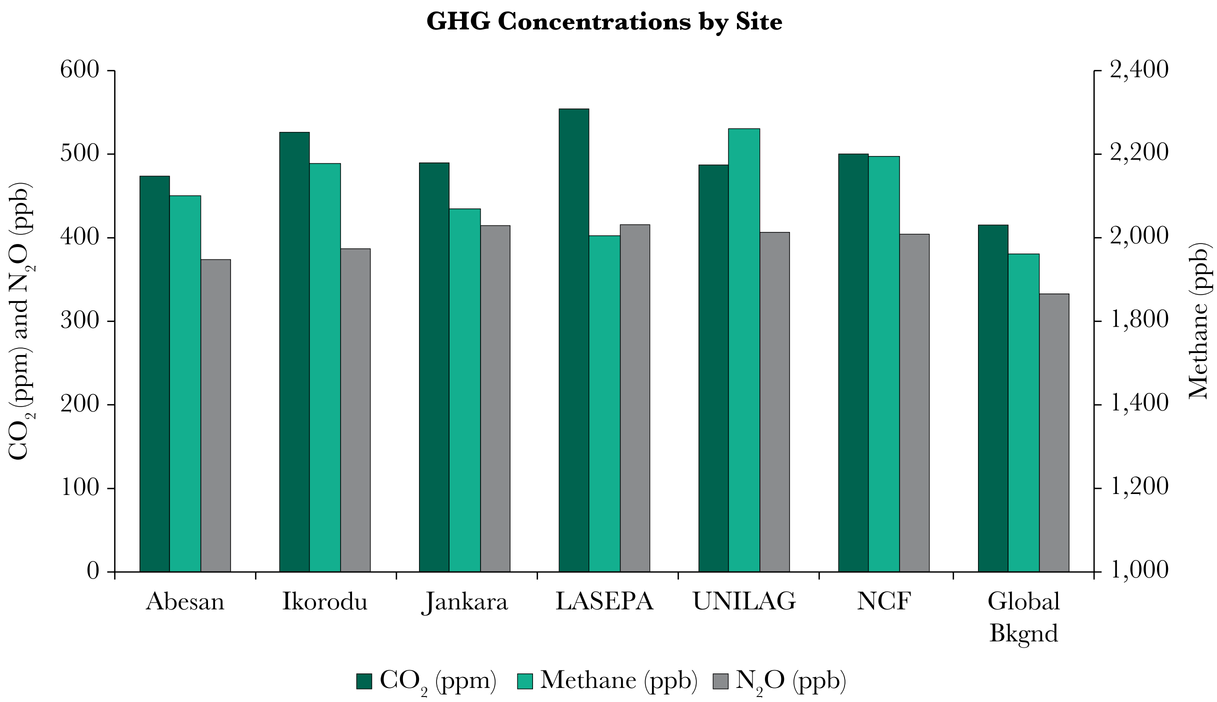


FIGURE 2.18. AVERAGE CONCENTRATIONS OF CFCs, HCFCs, AND HFCs MEASURED AT EACH MONITORING SITE

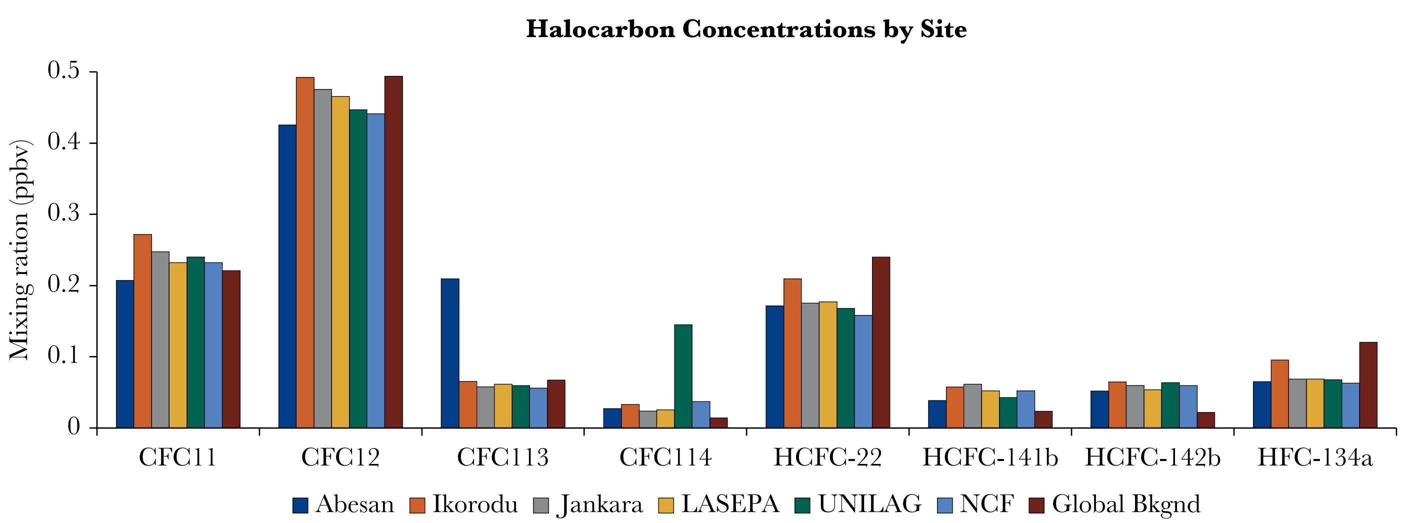


TABLE 2.3. ESTIMATED INVENTORY OF CRITERIA POLLUTANTS AND PRECURSORS FOR LAGOS STATE

	Pollutant emissions (tons/year)						
Source type	**PM_{10}**	**$PM_{2.5}$**	**NOx**	**VOC**	**SOx**	**CO**	**NH_3**
Trash burning	11,345	9,351	3,557	7,162	461	36,272	1,058
Biomass burning	274	159	103	406	10	1,677	21
Generators	1,021	1,021	21,528	27,054	3,542	10,77,489	
Road traffic	1,820	1,470	38,388	38,275	6,529	2,36,771	723
Industry	3,072	2,837	2,915	19,955	1,662	16,612	1,013
Power plants	49	49	5,639	143	15	2,142	0
Seaport	243	243	4,280	197	3,283	607	0
Airport	2	0	726	71	41	587	0
Cooking	185	180	694	168	168	1,536	
Waste disposal[a]	0	0		2,585			58,100
Agriculture	166	7	722	104	0	0	681
TOTAL	18,177	15,317	78,552	96,120	15,711	13,73,693	61,596

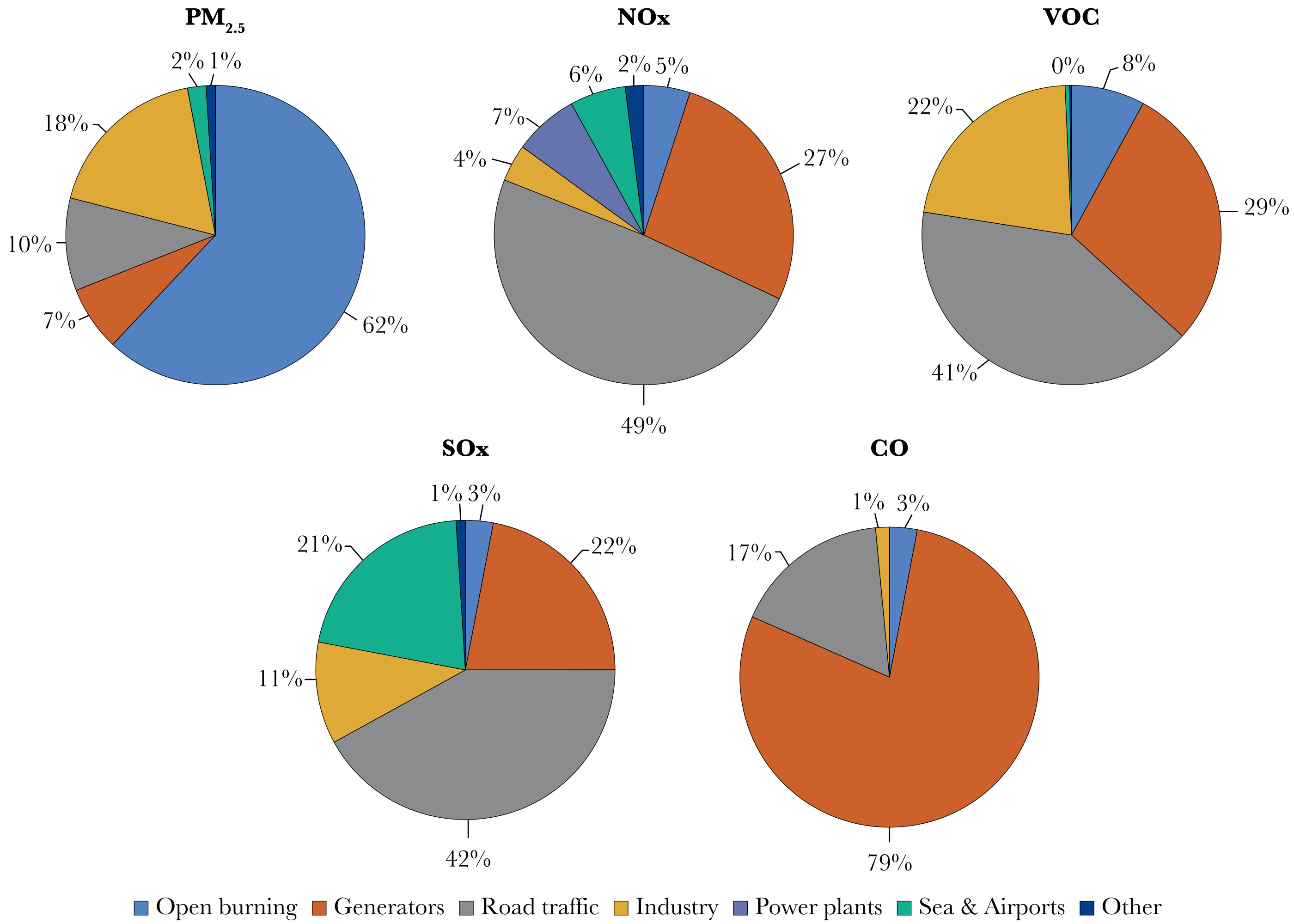
Note: a. Other than open burning. Includes emissions from dumpsites and wastewater.

purposes, the 11 source categories listed can be condensed to 7 by lumping together open burning of trash and biomass, as well as seaports and airports, and combining the minor categories of cooking, waste disposal, and agriculture as "other." Figure 2.19 shows how the emission inventory for each primary pollutant breaks down among these 7 categories.

The PM emission estimates shown in Table 2.3 include only primary emissions of PM and not secondary particles (sulfates, nitrates, and some organic compounds) formed by the chemical reactions of other pollutants in the atmosphere. They also exclude resuspended dust as the emission numbers are not directly comparable to those for the other categories. Dust particles—even in the $PM_{2.5}$ size range—are larger and settle out of the atmosphere much faster than particles from other sources, which are usually less than 1 µm. Based on the source apportionment analysis, dust averages about 25 percent of atmospheric $PM_{2.5}$ and 50 percent of PM_{10}, while secondary material averages about 15 percent of $PM_{2.5}$. Thus, the primary PM sources listed in Table 2.3 are responsible for about 60 percent of the ambient mass of $PM_{2.5}$ but only about 30 percent of ambient PM_{10}.

Of the roughly 60 percent of ambient $PM_{2.5}$ attributable to primary emissions, the majority is estimated to be due to open burning of solid waste and other biomass. Most of the rest is attributed to industry, road traffic (mostly diesel vehicles and two-stroke motorcycles), and backup generators. Diesel and gasoline engines used in road vehicles and generators account for 76 percent of the NOx, 68 percent of the VOC, 96 percent of the CO, and 64 percent of the sulfur oxides (SO_x) emissions (the latter due to average fuel sulfur concentrations of 0.24 percent in diesel fuel and 0.14 percent in gasoline). Nearly 80 percent of the CO emissions are attributed to generators—mostly small, inefficient, portable generators burning gasoline. The ports account for another 6 percent of NOx and 21 percent of SOx emissions—the latter due mostly to ships burning heavy fuel oil (HFO) containing up to 2 percent sulfur.

FIGURE 2.19. BREAKDOWN OF ESTIMATED CRITERIA POLLUTANT EMISSIONS BY TYPE OF SOURCE



Although not itself a criteria pollutant, NH_3 combines with NOx and SOx to form secondary $PM_{2.5}$. Improper disposal of human and animal waste is estimated to account for about 94 percent of NH_3 emissions.

2.6.2. GREENHOUSE EMISSIONS

Estimated GHG emissions are summarized in Table 2.4 and Table 2.5. Estimated CO_2 emissions in Lagos total 16.3 million tons per year, but in the near term their warming effect is outweighed by the effects of short-lived greenhouse pollutants such as CH_4, black carbon, VOCs, and CO. Table 2.4 shows the inventory with CO_2-equivalent values calculated using the estimated 20-year GWP of each pollutant, while Table 2.5 is calculated using the 100-year GWP estimates. In both cases, the N_2O and CH_4 GWPs are those determined by the Intergovernmental Panel on Climate Change (IPCC) AR6 Working Group 1 (IPCC 2021), while those for black carbon, VOC, and CO were selected from among the lower values listed in appendix 8 of the IPCC AR5 Working Group 1 report (Myhre et al. 2013).

It is conventional to calculate GHG inventories and Nationally Determined Contributions (NDCs) using

TABLE 2.4. ESTIMATED INVENTORY OF GLOBAL-WARMING POLLUTANTS FOR LAGOS STATE—CALCULATED WITH 20-YEAR GWPS

	GHG Emissions (tonnes /yr)						
Source Type	**CO_2**	**Black Carbon**	**CH_4**	**N_2O**	**VOC**	**CO**	**Total CO_2 Equivalent**
Global Warming Potential (20 yr)	**1**	**2,900**	**81.2**	**273**	**14**	**7.8**	
Waste burning	13,80,000	607	3,521	0	7,162	36,272	38,09,395
Biomass burning	36,700	10	82	0	406	1,677	91,123
Generators	36,52,686	464	0	0	27,054	10,77,489	1,37,81,456
Road traffic	59,52,524	504	1,971	209	38,275	2,36,771	1,00,13,890
Industry	7,30,000	724	0	0	19,955	16,612	32,38,544
Power plants	29,50,926	1	53	5	143	2,142	29,78,784
Seaport	2,62,349	43	4	12	197	607	3,98,142
Airport	1,57,965	2	11	4	71	587	1,71,323
Waste disposal[a]	0	0	66,593	0	2,585	0	54,43,542
Cooking	11,00,000	18	420	37	168	1,536	12,10,738
Agriculture	0	0	93	2,904	104	0	8,01,800
TOTAL	1,62,23,150	2,373	72,748	3,171	96,120	13,73,693	4,19,38,736
TOTAL CO_2-eq.	1,62,23,150	68,82,280	59,07,138	8,65,683	13,45,680	1,07,14,805	4,19,38,736

Note: a. Other than open burning. Includes emissions from dumpsites and wastewater.

the 100-year rather than the 20-year GWPs, which are higher. We emphasize the 20-year GWPs here because of the urgency of reducing near-term warming to stay within the 1.5°C target and because the air quality measures considered in this report would all take effect in the relatively near term (that is, the next 5 to 10 years).

For Lagos, using either the 20-year or 100-year GWPs, the short-lived pollutants with the greatest global-warming effect are CO, black carbon, and CH_4. Using the 20-year GWPs, these three pollutants are the CO_2 equivalent of about 11, 7, and 6 million tons per year, respectively.

Figure 2.20 shows the breakdown of GHG emissions by source. Generators and road traffic are the sources with the largest GHG impact, largely due to the high CO emissions from gasoline engines.

2.6.3. LIMITATIONS OF THE INVENTORY

An emission inventory can be only as accurate as the data used to calculate it. Emissions from each type of source are calculated by multiplying an estimate of the *activity* attributable to that type of source by an estimate of the corresponding *emission factor*. Activity is typically

TABLE 2.5. ESTIMATED INVENTORY OF GLOBAL-WARMING POLLUTANTS FOR LAGOS STATE—CALCULATED WITH 100-YEAR GWPS

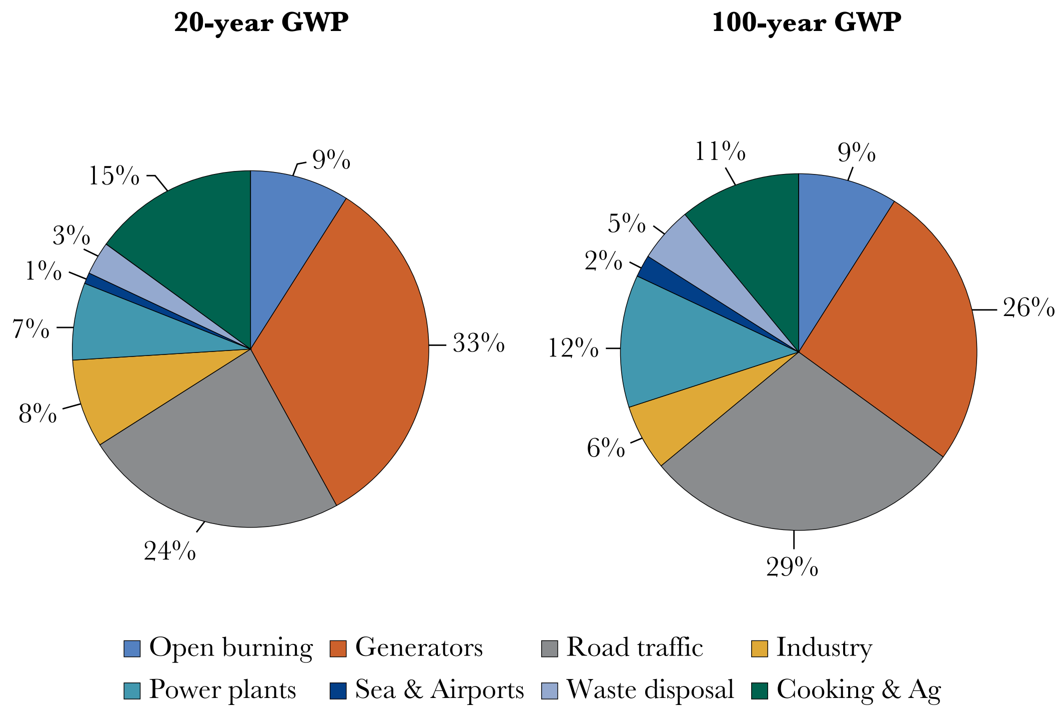
	GHG emissions (tons /year)						
Source type	**CO_2**	**Black carbon**	**CH_4**	**N_2O**	**VOC**	**CO**	**Total CO_2 equivalent**
Global warming potential (100 year)	**1**	**830**	**27.9**	**273**	**5**	**2.2**	
Waste burning	13,80,000	607	3,521	0	7,162	36,272	20,94,073
Biomass burning	36,700	10	82	0	406	1,677	52,804
Generators	36,52,686	464	0	0	27,054	10,77,489	65,30,025
Road traffic	59,52,524	504	1,971	209	38,275	2,36,771	71,76,026
Industry	7,30,000	724	0	0	19,955	16,612	14,57,264
Power plants	29,50,926	1	53	5	143	2,142	29,60,122
Seaport	2,62,349	43	4	12	197	607	3,03,649
Airport	1,57,965	2	11	4	71	587	1,62,635
Waste disposal[a]	0	0	66,593	0	2,585	0	18,69,577
Cooking	11,00,000	18	420	37	168	1,536	11,40,894
Agriculture	0	0	93	2,904	104	0	7,95,855
TOTAL	1,62,23,150	2,373	72,748	3,171	96,120	13,73,693	2,45,42,923
TOTAL CO_2-eq	1,62,23,150	19,69,756	20,29,669	8,65,683	4,32,540	30,22,125	2,45,42,923

Note: a. Other than open burning. Includes emissions from dumpsites and wastewater.

expressed in terms of outputs such as vehicle-kilometers traveled or inputs such as tons of fuel consumed or tons of trash burned. For many of the source types considered in this inventory, reliable data for estimating the output values were not available for Lagos State, so crude estimates or national-level statistics had to be applied. The missing data included information on amounts of trash and biomass burned, industrial production and energy consumption, and the numbers and utilization of small generators for electricity. Details of these estimates are given in the TSC's report (ARIA 2021). Better statistics are needed, especially for critical activities such as trash burning and backup generators.

The applicability of the emission factors used is also subject to question. Few emission measurements have been conducted in Nigeria, so the emission factors had to be based on measurements in other countries, typically in the Organisation for Economic Co-operation and Development (OECD). The degree to which emissions from, for example, small generators measured by the US EPA are representative of small generators used in Lagos is unknown. The same is true of vehicle emission factors, which were estimated by a model based on European emission standards. These factors were adjusted to try to account for the widespread Nigerian practice of removing catalytic converters from imported vehicles, but the

FIGURE 2.20. CO_2 EQUIVALENT EMISSIONS BY SOURCE TYPE



adequacy of this adjustment is unknown. There is also reason to think that the vehicle emission factor model may underestimate $PM_{2.5}$, black carbon, and VOC from diesel vehicles in Lagos because the model assumes European vehicle maintenance practices and lifetimes.

This inventory should thus be considered as a first—and very rough—approximation, and plans for AQM should include research to improve the estimates of both activities and emission factors under Nigerian conditions.

2.7. POLLUTANT DISPERSION MODELING

The TSC responsible for the emissions inventory also conducted air quality modeling using the emissions inventory and the weather conditions recorded during the year of air quality monitoring to simulate pollutant concentrations. One goal of this modeling activity was to validate the emissions inventory by comparing the model results to measured pollutant concentrations. Another goal was to extend the geographic range of the air quality data from the six monitoring sites to all 19 of the LGAs defined in the State of Lagos.

2.7.1. MODELS AND METHODS

The modeling approach is described in the TSC's report (ARIA 2021). Modeling was performed on several different scales. The largest scale encompassed much of Africa and used a global emissions database. This was done using CHIMERE software to establish the boundary conditions for the more detailed modeling. The detailed model covered a rectangle, a little bigger than the State of Lagos, and used FARM software. Both the FARM and CHIMERE models are three-dimensional Eulerian photochemical models capable of modeling the dispersion, chemical transformation, and deposition of pollutants from both anthropogenic and biogenic sources over a given area.

2.7.2. EPISODES MODELED

Modeling was conducted for the five selected episodes indicated by the brown horizontal bars in Figure 2.21. These are September 10–20, December 10–20, March 5–16, April 25–May 5, and June 27–July 7, 2021. These five periods were selected after consultation between the World Bank team and the TSC project team. The first three correspond to observed positive peaks or "spikes" in several air quality variables, notably $PM_{2.5}$ and PM_{10}. The final two periods are considered more representative of "background" conditions, during which the air quality variables O_3, NO_2, $PM_{2.5}$, and PM_{10} varied only subtly above baseline concentrations.

2.7.3. MODEL RESULTS

Initial simulations were conducted on the earliest two episodes in Figure 2.21. Those simulations showed NO_2 concentrations much higher than observed during the air quality modeling, and O_3 concentrations much lower. This suggested that the estimated NO_x inventory was probably too high. A review of the emission inventory found that NOx emissions from generators had been significantly overestimated. Several other errors in the inventory were also found and corrected. Figure 2.22 to Figure 2.26 show the correspondence between the monitoring data at the UNILAG station and the model results using the revised emissions inventory. These show reasonable agreement with the monitoring results.

FIGURE 2.21. EPISODES SELECTED FOR AIR QUALITY MODELING

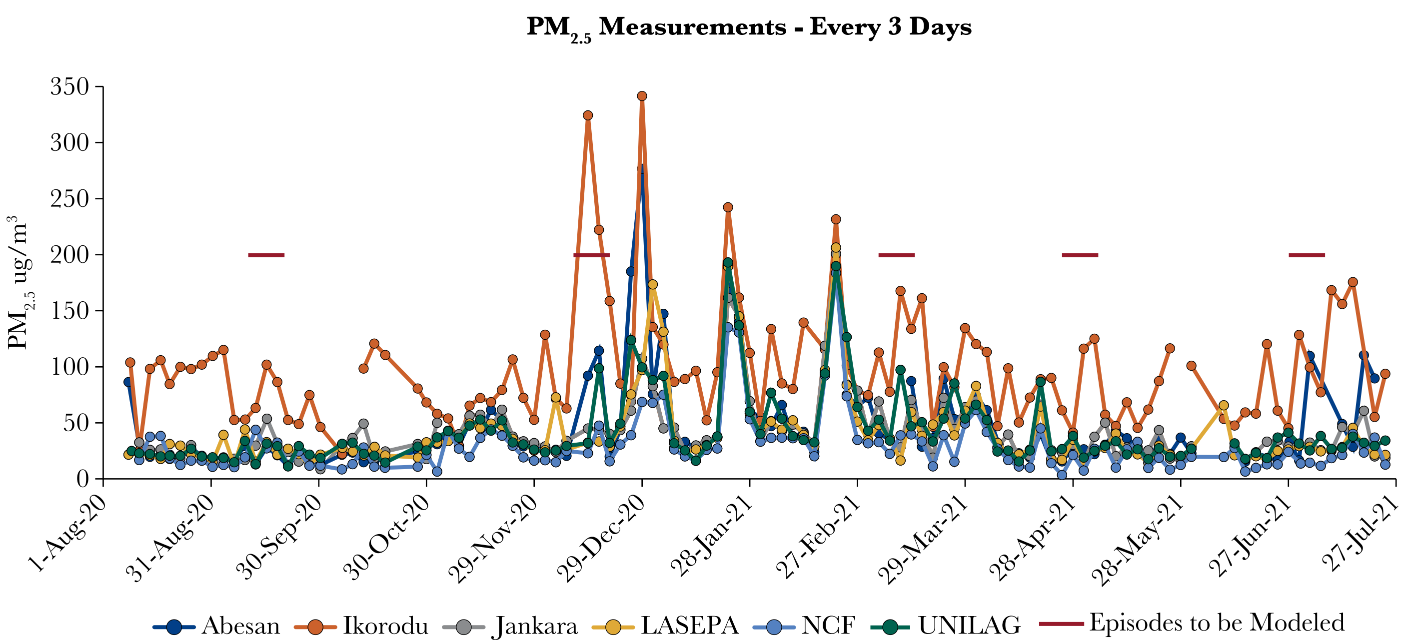


FIGURE 2.22. COMPARISON OF FARM MODEL OUTPUT WITH IN SITU MEASUREMENT FOR O_3, NO_2, $PM_{2.5}$, AND PM_{10} AT UNILAG STATION FOR EPISODE PERIOD OF SEPTEMBER 10–20, 2020

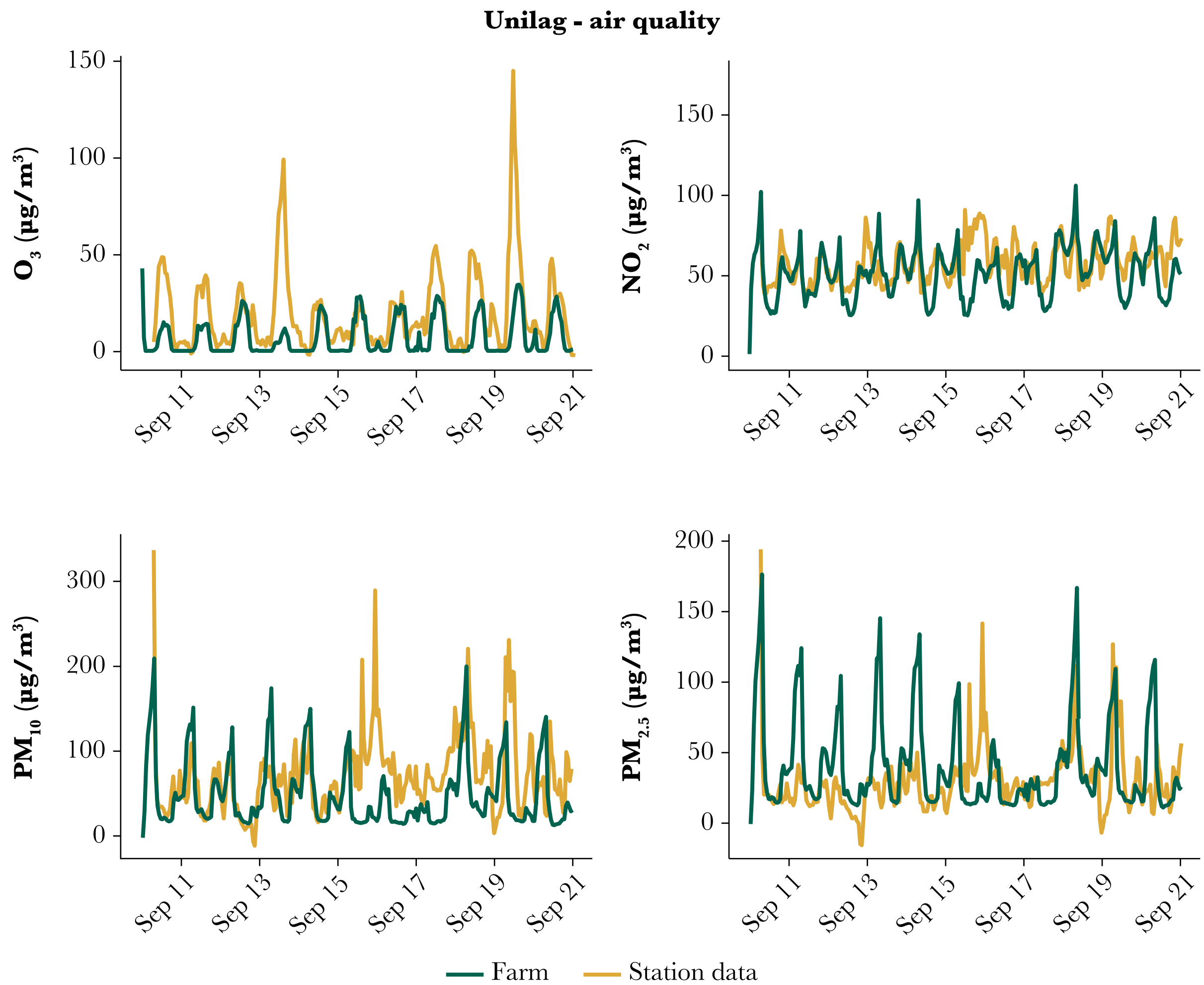


FIGURE 2.23. COMPARISON OF FARM MODEL OUTPUT WITH IN SITU MEASUREMENT FOR O_3, NO_2, $PM_{2.5}$, AND PM_{10} AT UNILAG STATION FOR EPISODE PERIOD OF DECEMBER 10–20, 2020

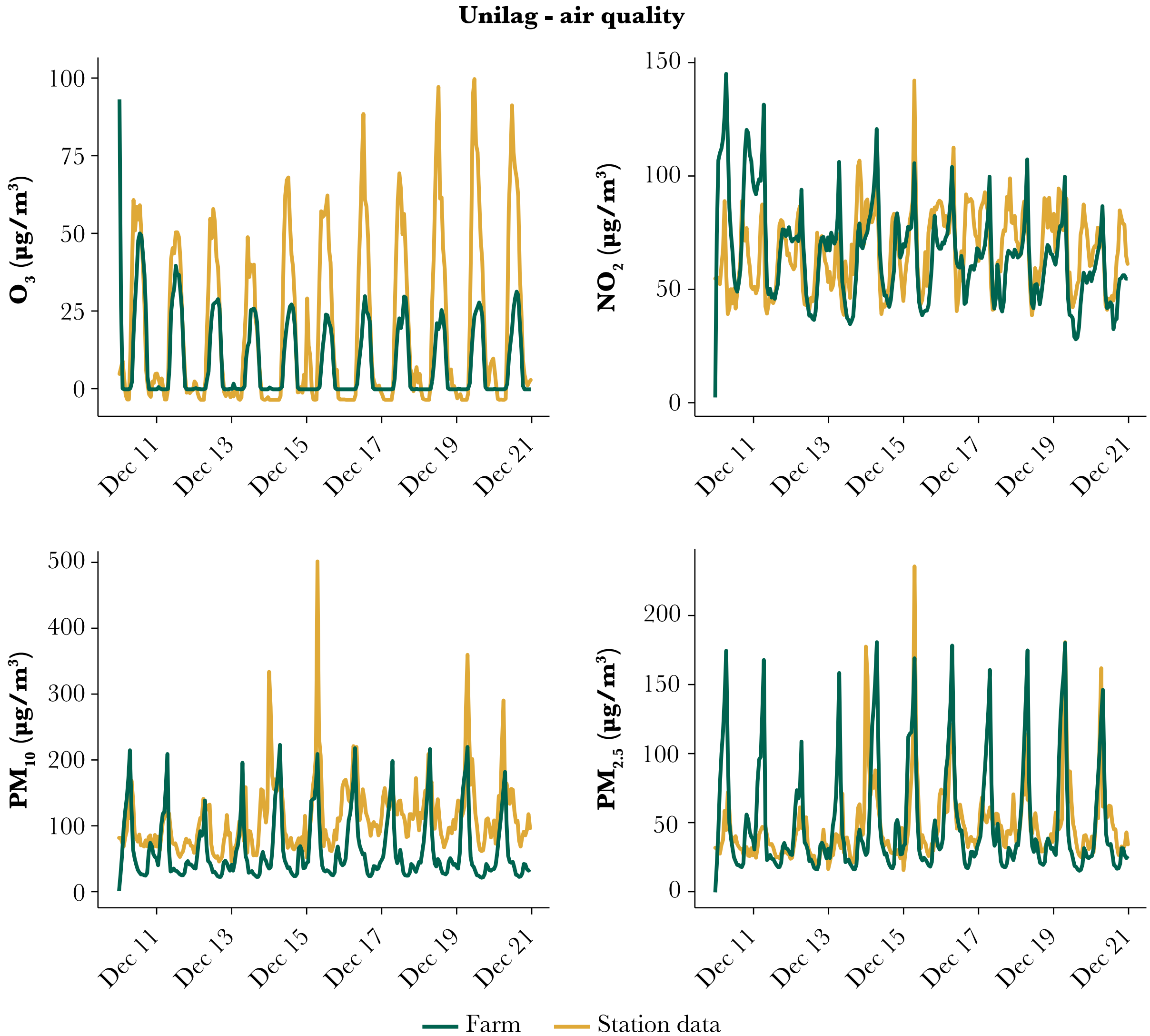


FIGURE 2.24. COMPARISON OF FARM MODEL OUTPUT WITH IN SITU MEASUREMENT FOR O_3, NO_2, $PM_{2.5}$, AND PM_{10} AT UNILAG STATION FOR EPISODE PERIOD OF MARCH 5–16, 2021

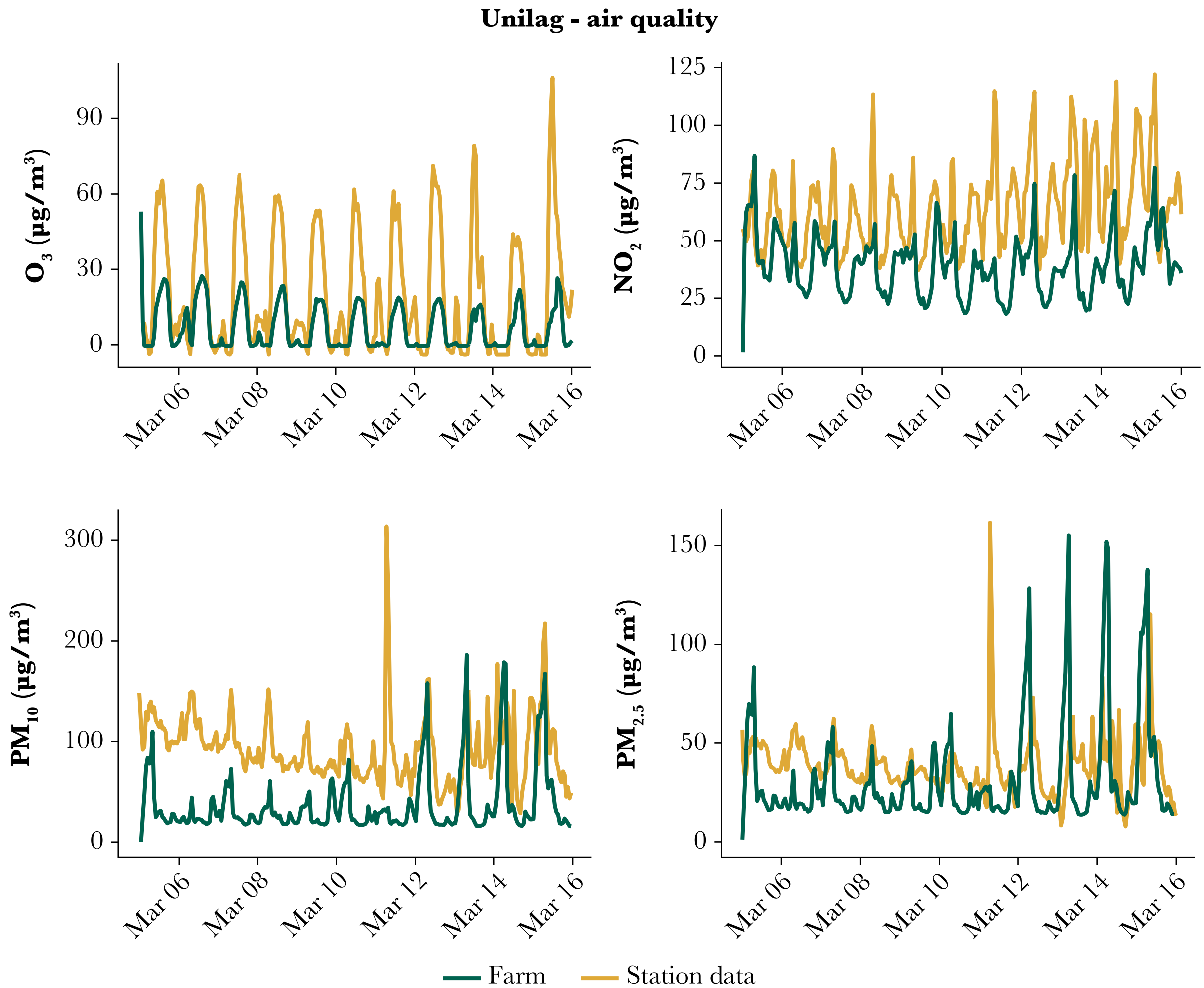


FIGURE 2.25. COMPARISON OF FARM MODEL OUTPUT WITH IN SITU MEASUREMENT FOR O_3, NO_2, $PM_{2.5}$, AND PM_{10} AT UNILAG STATION FOR EPISODE PERIOD OF APRIL 25–MAY 5, 2021

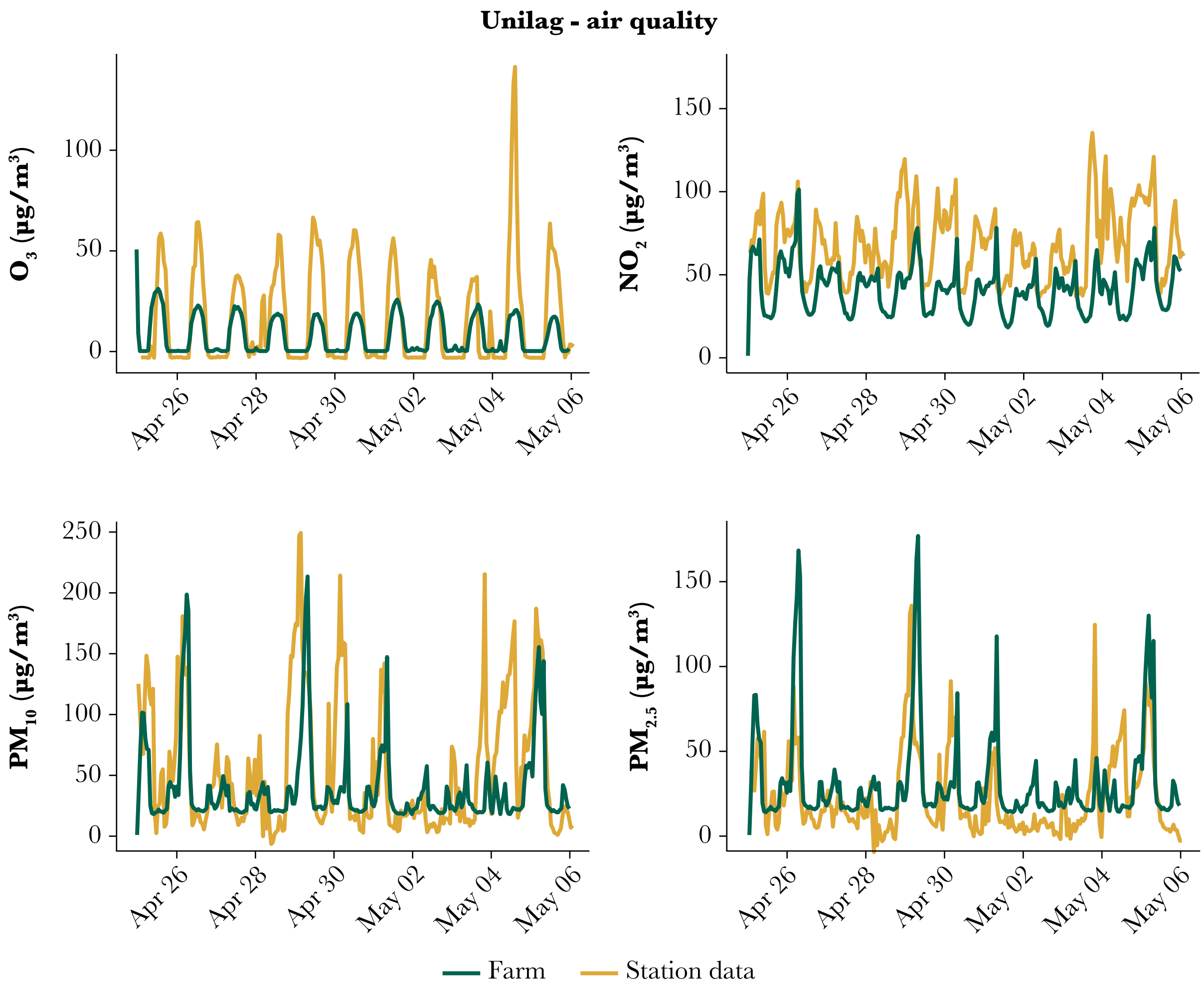
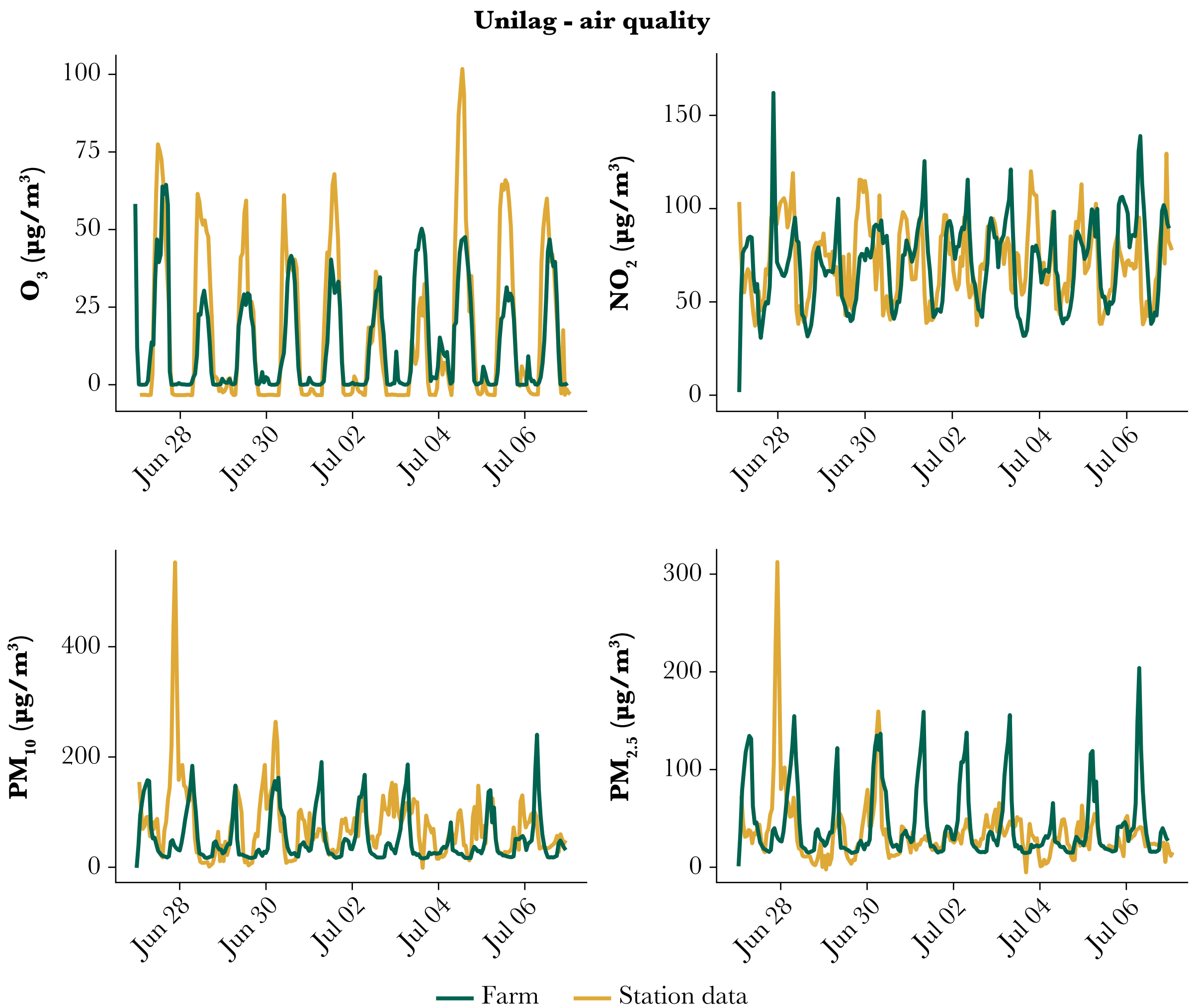


FIGURE 2.26. COMPARISON OF FARM MODEL OUTPUT WITH IN SITU MEASUREMENT FOR O_3, NO_2, $PM_{2.5}$, AND PM_{10} AT UNILAG STATION FOR EPISODE PERIOD OF JUNE 27–JULY 7, 2021



REFERENCES

ARIA. 2021. *Air Pollutant Emission Inventory Development, Modeling and Potential Emission Control Measures for Lagos*. Final report under World Bank Technical Services Contract.7199005.

EnvironQuest Limited. 2021a. *Lagos Air Quality and PM Source Apportionment Study Final 12 Months Summary Report*. Final report under World Bank Technical Services Contract 7195720.

EnvironQuest Limited. 2021b. *Lagos Air Quality and PM Source Apportionment Study Final Source Apportionment Report*. Report under World Bank Technical Services Contract 7195720.

IPCC. 2021. "Summary for Policymakers." In *Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*, edited by V. Masson-Delmotte, P. Zhai, A. Pirani, S. L. Connors, C. Péan, S. Berger, N. Caud, et al. Cambridge University Press.

Myhre, G., D. Shindell, F.-M. Bréon, W. Collins, J. Fuglestvedt, J. Huang, D. Koch, et al. 2013: "Anthropogenic and Natural Radiative Forcing." In *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, edited by T. F. Stocker, D. Qin, G.-K. Plattner, M. Tignor, S. K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex, and P.M. Midgley. Cambridge, United Kingdom: Cambridge University Press and New York: IPCC.

CHAPTER 3

HEALTH AND ECONOMIC IMPACTS OF AIR POLLUTION

PM air pollution ($PM_{2.5}$ and PM_{10}) is the leading environmental risk factor for poor health. Globally, ambient and household air pollution together currently rank 4th for attributable disease and mortality among 20 major risk factors evaluated in the Global Burden of Disease study (GBD), following hypertension, smoking, and dietary factors (GBD 2020). The estimates indicate that around 7 million deaths,[5] mainly from noncommunicable diseases (NCDs), are attributable annually to the joint effects of ambient and household air pollution, with the greatest attributable disease burden seen in low- and middle-income countries (LMICs)—89 percent of the global total, with low- and lower-middle-income countries alone contributing around 40 percent of the total burden. Higher estimates have been published (Burnett et al. 2018). A recent report indicated 10.2 million premature deaths annually from fossil fuel use (Vohra et al. 2021). Regions with large anthropogenic contributions had the highest attributable deaths, suggesting substantial health benefits from replacing traditional fossil fuel-based energy sources (McDuffie et al. 2021).

3.1. METHODOLOGY AND EXPOSURE-RESPONSE FUNCTIONS (ERFS) FOR AIR POLLUTANTS OF CONCERN

Traditionally, $PM_{2.5}$ mass has been used as the index pollutant for quantifying the impact of outdoor air pollution. First, previous studies have demonstrated that mortality from long-term exposure to $PM_{2.5}$ dominates the overall health impact of air pollution.

Second, there is a vast set of published in epidemiological studies from around the world linking $PM_{2.5}$ to mortality (Chen and Hoek 2020). Third, the $PM_{2.5}$ effects observed in epidemiological studies are supported by toxicological and human clinical studies (US EPA 2019). Fourth, $PM_{2.5}$ concentrations can be obtained from monitors and/or satellite data, while chemical transport models can generate modeled data that can be used to assess the impact of emission-reduction strategies on health. Finally, $PM_{2.5}$ is ubiquitous and is generated by many fuel combustion sources in Lagos, including mobile sources (cars, buses, trucks and motorcycles), stationary sources (power plants, port emissions, diesel or gasoline electrical generators, industrial boilers), biomass use, open waste burning, and suspended dust. This set of factors sets $PM_{2.5}$ apart from all other air pollutants.

The health impact assessment (HIA) methodology for air pollution is well documented. A WHO publication (WHO Regional Office for Europe 2016) provides the basic concepts and general principles. Estimations of the burden of diseases linked either to air pollution or to evaluation of policy scenarios and cost-benefit analyses (CBAs) are both possible. Annex 1 details the methods and input data for the HIA applied in Lagos for 2020–2021.

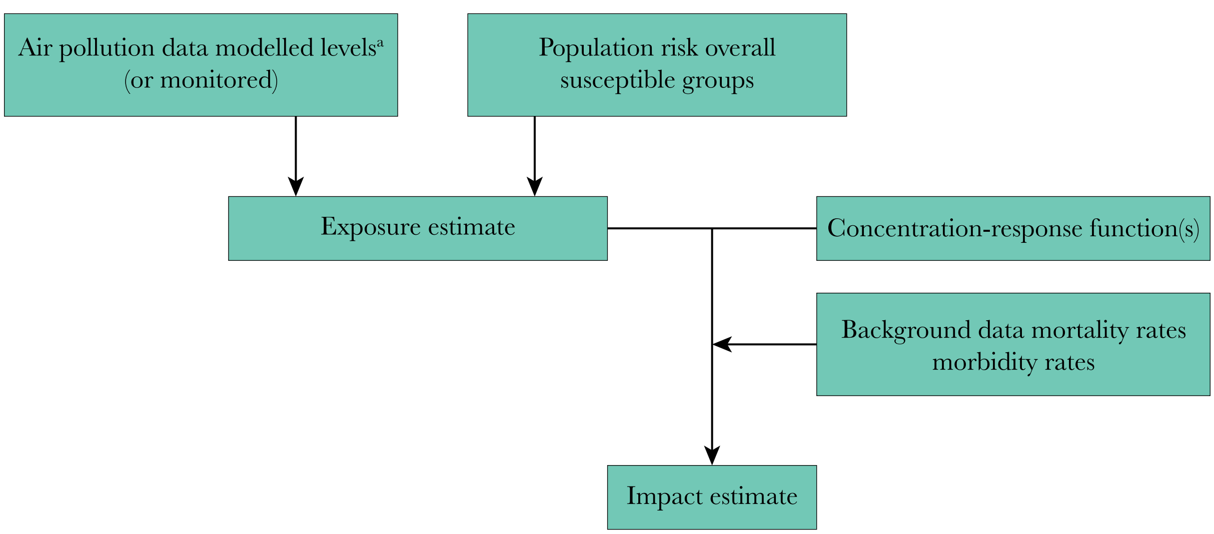
3.1.1. METHODS: INPUT DATA FOR THE HIA IN LAGOS

Figure 3.1 illustrates the key steps in the burden calculation of mortality and morbidity in Lagos due to air pollution.

3.1.1.1. AIR POLLUTION DATA

We have used the $PM_{2.5}$ and PM_{10} concentrations measured during the period of the project. The continuous and filter-based monitored data were limited to six sites in the city of Lagos for the 1-year period from August 2020 to July 2021. The measurements from the six monitors were used to assign an annual exposure for the population of each LGA (local government area) in Lagos State, where the monitors were located. For the LGAs without monitors, we have used the results of the dispersion modeling described in section 2.7 to derive adjustment factors between the LGAs with and without monitors. These models covered five distinct episodes distributed throughout the monitoring period. For this exercise, data from the recent emission inventory were used as inputs to the

FIGURE 3.1. SCHEMATIC PRESENTATION OF THE MAIN STEPS IN THE AIR POLLUTION HIA



[a] If modelled data are used, the approach can be used to assess the impact of emission reduction strategies on different health outcomes.

dispersion analysis. We first estimated a provisional population-weighted exposure (PWE) for each LGA using the results of the dispersion analysis, coupled with a high-resolution map of the population density distribution within each LGA, to calculate the grid-level representation of the LGA-specific PWE. We then derived the PWE for the entire Lagos State by weighting each LGA by its population size. Average annual exposures for Lagos State and each LGA were used in the impact assessment (Figure 3.2).

3.1.1.2. POPULATION DATA

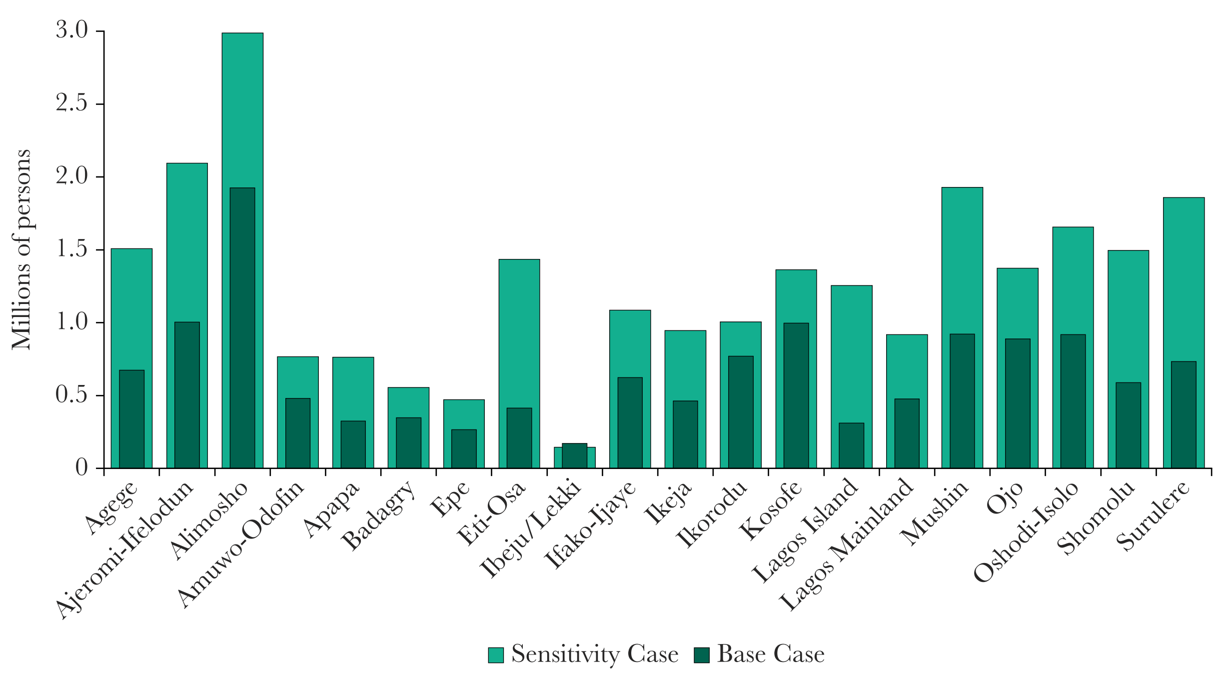
Two alternative population compositions (base and sensitivity case population) by quinquennial age group for Lagos State in 2018 have been used with further details specified by LGA. The base case reflects the population as estimated by the National Bureau of Statistics, and the sensitivity case reflects that estimated by the Lagos Bureau of Statistics (LBS). Estimates at the LGA level are calculated assuming the same age composition in each LGA. Figure 3.2 illustrates the population by LGA according to the base and sensitivity case populations.

3.1.1.3. MORTALITY AND MORBIDITY DATA

For the estimation of the mortality data, two international sources were consulted to derive the required information for the base case and sensitivity case populations: the Global Health Data Exchange (GHDx) database of the GBD (IHME 2021), and the Global Health Estimates (GHE) database (WHO 2021). The number of deaths for each age group is calculated as the product of the national hazard rate (number of deaths of a particular outcome per 100,000 population from either the GHDx or GHE database) and the age-specific population size in Lagos.

For $PM_{2.5}$ (long-term exposure), the following health endpoints were considered:

FIGURE 3.2. SIZE OF THE LAGOS POPULATION BY LGA ACCORDING TO THE BASE AND SENSITIVE CASE POPULATIONS



» Mortality due to NCDs and specific GBD categories, including acute lower respiratory infections (ALRI), ischemic heart disease (IHD), stroke, chronic obstructive pulmonary disease (COPD), lung cancer, and type 2 diabetes
» Infant (<1 year) mortality. According to the GHDx and GHE databases, the infant mortality rate stands at 6.7 percent and 7.5 percent, respectively
» Lower respiratory tract infections in children under age 5 (mainly pneumonia). The number of incidences per 1,000 children is 302 (95 percent confidence interval [CI]: 160–538) and was obtained from the study by McAllister et al. (2019)
» Chronic bronchitis incidences in adults over 27 years (3.9 cases per 1,000 individuals). These data were taken from Health Risk of Air Pollution in Europe [HRAPIE] (WHO 2013)
» Restricted activity days (19 days per year per person of all ages). These data are from HRAPIE (WHO 2013). Hospital admissions were subtracted to calculate net PM-related cases
» Respiratory hospital admissions (RHAs) and emergency room visits, which include pneumonia, bronchitis, and asthma. The baseline statistics for the entire Lagos State were estimated based on public hospital data, assuming that private hospitals had a similar caseload of patients (2017 data)
» Cardiovascular hospital admissions (CHAs) and emergency room visits, which consist of IHD (including heart attacks), heart failure, and stroke. The baseline statistics for the entire Lagos State were estimated based on public hospital data, assuming that the private hospitals had a similar case load of patients (2017 data).

We also estimated the impact of short-term exposure to PM_{10} on daily mortality during the *Harmattan* season. In the specific situation of Lagos, daily population exposure to PM_{10} has importance and, in some instances, it does not correlate well with that of $PM_{2.5}$. This happens on days when the *Harmattan* wind is prevalent (between the end of November and mid-March). It is a dry, dusty wind from the North-East originating from the Sahara Desert, and it involves a large increase of particles in the air, especially the coarse fraction of PM (between 2.5 and 10 μm in diameter).

3.1.1.4. EXPOSURE-RESPONSE FUNCTIONS

The ERFs from the epidemiological literature, which quantitatively relate the health risk to a $PM_{2.5}$ exposure level, have been reviewed in annex 1. The epidemiological studies provide an estimate of the percent change in risk that might be expected per unit change in air pollution. The best approach has been to use the integrated exposure-response (IER) functions developed by GBD (2020) for cause-specific mortality, and the exposure response function (ERF) of the Global Exposure Mortality Model (GEMM) (Burnett et al. 2018) for the noncommunicable plus ALRI diseases. For infant mortality, we used the ERF for Africa derived by Heft-Neal et al. (2018). For the assessment of the short-term burden on mortality due to the *Harmattan* season, we applied the short-term ERF for PM_{10} from Orellano et al. (2020). Graphical representations of the ERFs used in this work are presented in annex 1.

Finally, the concentration of lead in $PM_{2.5}$ and PM_{10} observed at Ikorodu LGA (1.35 $\mu g/m^3$) has been found to be particularly elevated when compared to the US EPA standard (0.15 $\mu g/m^3$). Following the methodology in the US EPA report (1999), the air lead concentration has been converted into blood lead levels, using a conversion factor of 4 for children (0–6 years) and 2 for adults (over 40 years). Based on the estimated blood lead levels, the impact of lead exposure on children's IQ (intelligence quotient) has been estimated (change in IQ equal to 1.15 points per 1 μg/dl (microgram per deciliter) blood lead change; Pew Charitable Trusts, 2017, 104) as well as the impact of lead on adult cardiovascular mortality (Brown et al. 2020). Lead exposure is also implicated in adverse behavioral outcomes (for example, learning disabilities and disorderly conduct), but lack of local data in Lagos prevented a quantitative estimation of these health burdens.

3.1.2. COUNTERFACTUAL CONCENTRATIONS (AND AIR QUALITY TARGETS)

In the HIA, a $PM_{2.5}$ counterfactual concentration (the lowest level of PM below which no health effects are calculated) has been used to estimate the burden of disease. For the IER assessment, the counterfactual is a uniform distribution over the interval 2.4–5.9 μg/m³ $PM_{2.5}$ used in the GBD (2020) study. A single value (2.4 μg/m³ $PM_{2.5}$.) is applied in the case of GEMM and for infant mortality. Multiple annual air quality targets have been examined, such as the new WHO air quality guideline of 5 μg/m³ and the WHO four interim targets (35, 25, 15, 10 μg/m³ $PM_{2.5}$) to quantify the health benefits achieved from exposure reductions.

3.2. QUANTIFICATION OF HEALTH IMPACTS

3.2.1. $PM_{2.5}$ RELATED PREMATURE MORTALITY AND MORBIDITY

Figure 3.3 shows the estimates of $PM_{2.5}$ PWE by LGA. The overall concentration for Lagos State is 47 μg/m³ and 114 μg/m³ for $PM_{2.5}$ and PM_{10}, respectively, for the base case. Only a small difference has been estimated when using the sensitivity case population (46 μg/m³ and 116 μg/m³ for $PM_{2.5}$ and PM_{10}, respectively). The population living in Ikorodu, Shomolu, Mushin, and Oshodi are exposed to particularly high values of $PM_{2.5}$ ambient pollution (97, 85, 71, and 60 μg/m³, respectively).

Figure 3.4 summarizes the results of the calculation of the $PM_{2.5}$ attributable burden of mortality and morbidity in Lagos for both the base and sensitivity case populations. For the base case, the estimated annual mortality attributable to $PM_{2.5}$ is 15,850 deaths, of which 7,790 are infant deaths, or around 50 percent of the total mortality. In total, 182,400 annual cases of lower respiratory infections in children up to 5 years were estimated, together with 14,700 new cases of chronic bronchitis in adults, 46 million restricted activity days, and 1,490 hospital admissions for cardiovascular and respiratory diseases. Alimosho, Ikorodu, and Oshodi are the LGAs with the greatest impact.

The estimates are double when considering the sensitivity case population: Annual mortality is 30,350 deaths (14,890 infant deaths), 349,000 annual cases of lower respiratory infections in children up to 5 years, 28,300 new cases of chronic bronchitis in adults, 88 million restricted days, and 2,840 hospital admissions. In this sensitivity calculation, the LGAs with the greatest impact were Alimosho, Mushin, Shomolo, and Oshodi.

Additional results are reported in annex 1, including attributable cases of premature mortality by cause of death, applying the GBD 2020 IER functions. The age-specific mortality results using baseline mortality data from GHDx and GHE for the base case population and sensitivity case population are also reported.

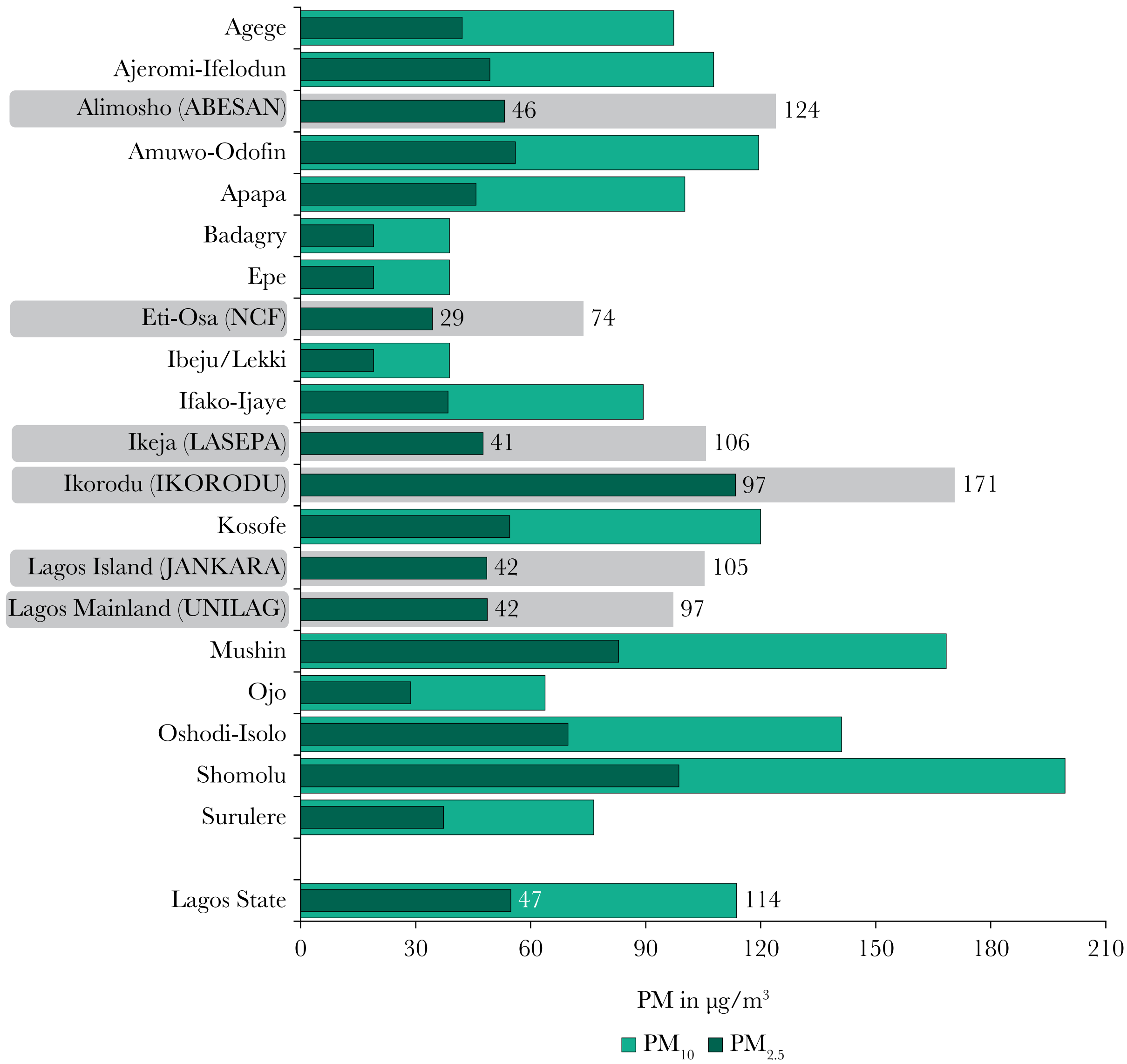
3.2.2. HARMATTAN HEALTH BURDEN

Attributable mortality due to short-term exposure to PM_{10} during January and February has been estimated. We have assumed an excess PM_{10} exposure equal to the difference of the average concentration for the months January and February and the average of the shoulder months December and March. In January and February, the excess PM_{10} concentration was 88 μg/m³ PM_{10} for the base case population and 90 μg/m³ for the sensitivity case population, contributing a total of 250 and 500 premature deaths, respectively. These deaths are in addition to the long-term $PM_{2.5}$-related mortality.

3.2.3. HEALTH BENEFIT ANALYSIS FROM IMPROVEMENTS IN AIR QUALITY

Figure 3.5 indicates the health benefits that could be achieved if $PM_{2.5}$ concentrations across Lagos State

FIGURE 3.3. LAGOS STATE AND LGA AMBIENT AIR QUALITY DATA



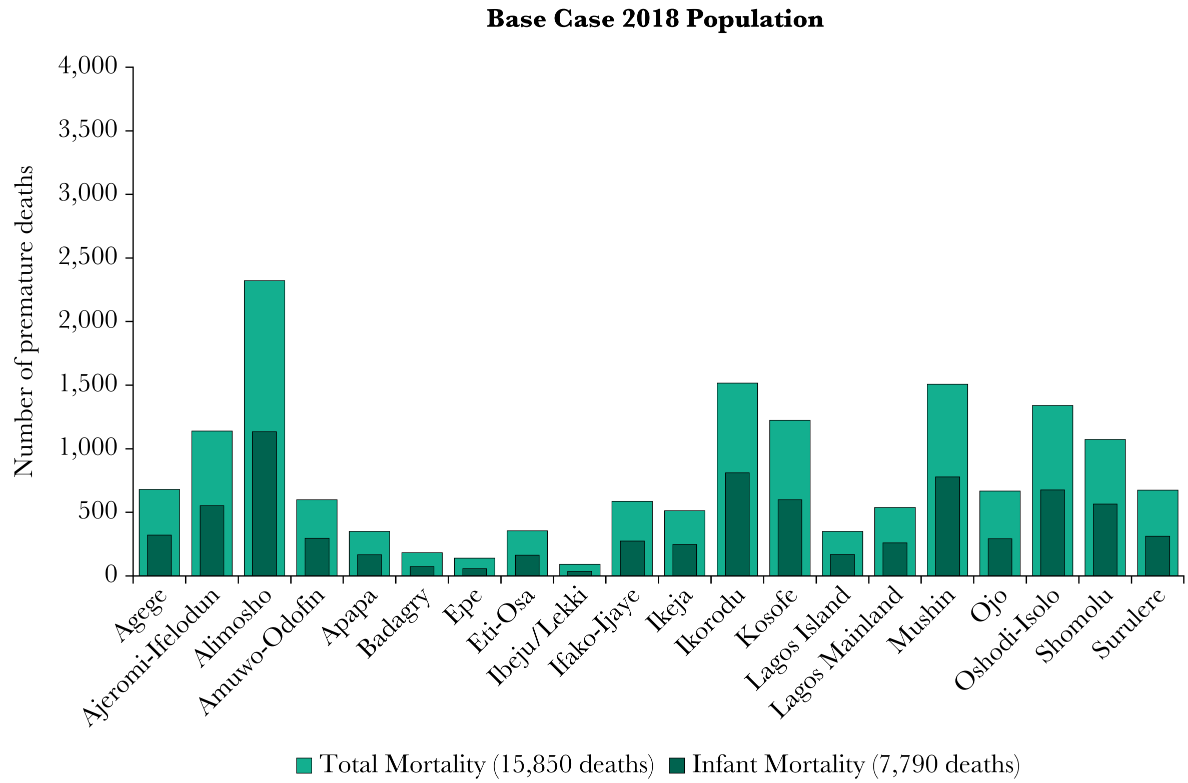
Note: The names of the six LGAs where daily ambient concentrations were monitored during the 1-year campaign between August 2020 and July 2021 are highlighted by the gray boxes along the y-axis on the left.

were reduced compared to present values. Progressively attaining the different 2021 WHO-recommended interim targets for $PM_{2.5}$—IT 1 (35 µg/m^3), IT 2 (25 µg/m^3), IT 3 (15 µg/m^3), IT 4 (10 µg/m^3) and the WHO air quality guideline (5 µg/m^3)—would avert 29 percent, 46 percent, 66 percent, 77 percent, and 90 percent, respectively, of the current attributable premature deaths.

3.2.4. IMPACT OF LEAD EXPOSURE ON CHILDREN'S IQ AND CARDIOVASCULAR MORTALITY

The results of the impact assessment of lead contamination in Ikorodu based on measured air contamination (1.35 µg/m^3 air lead) indicate that every child in Ikorodu (125,500 according to the base case and 163,800 according to the

FIGURE 3.4. $PM_{2.5}$ ATTRIBUTABLE MORBIDITY AND MORTALITY IN LAGOS STATE FOR PWE DATA AND GHE (WHO 2021) BASELINE MORTALITY RATES



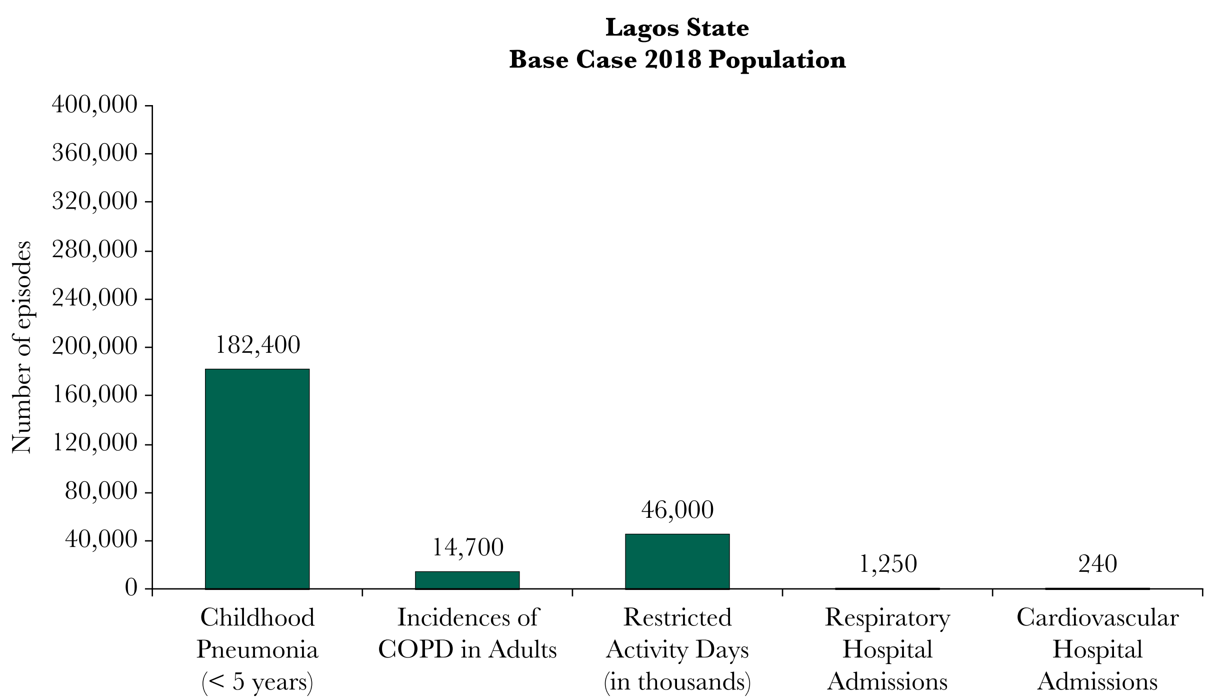
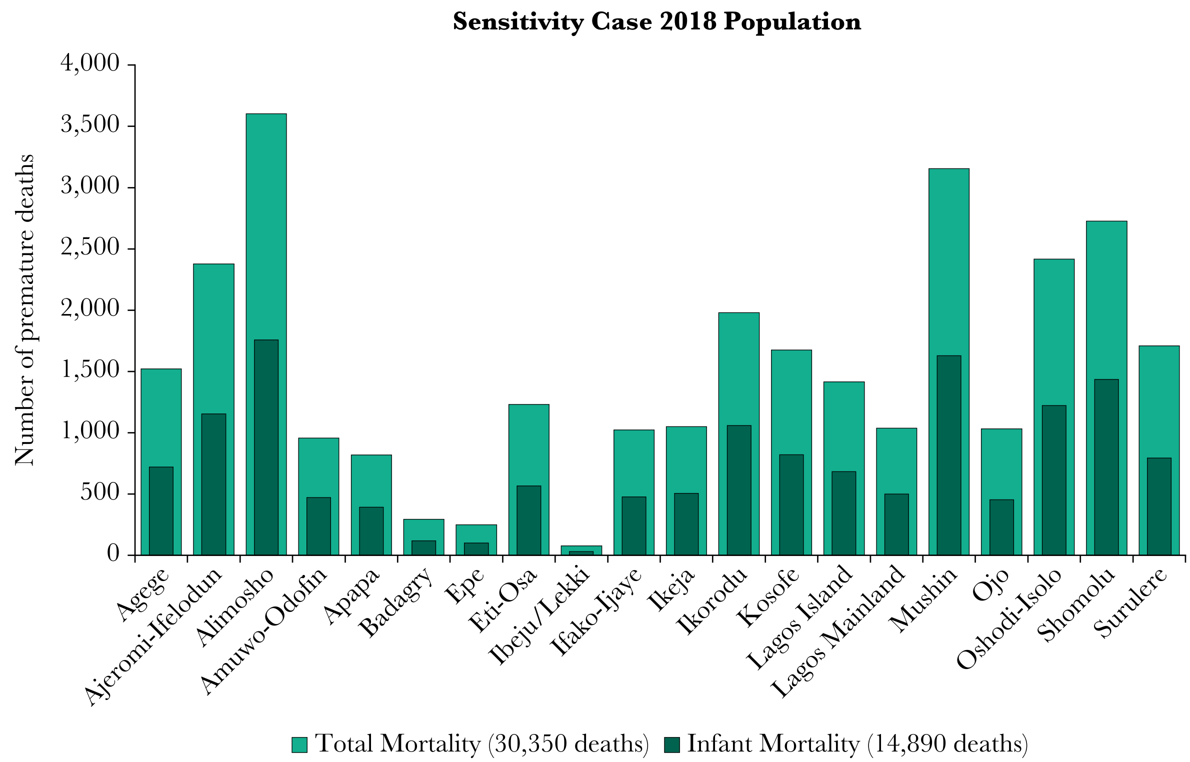


FIGURE 3.4. *(Continued)*



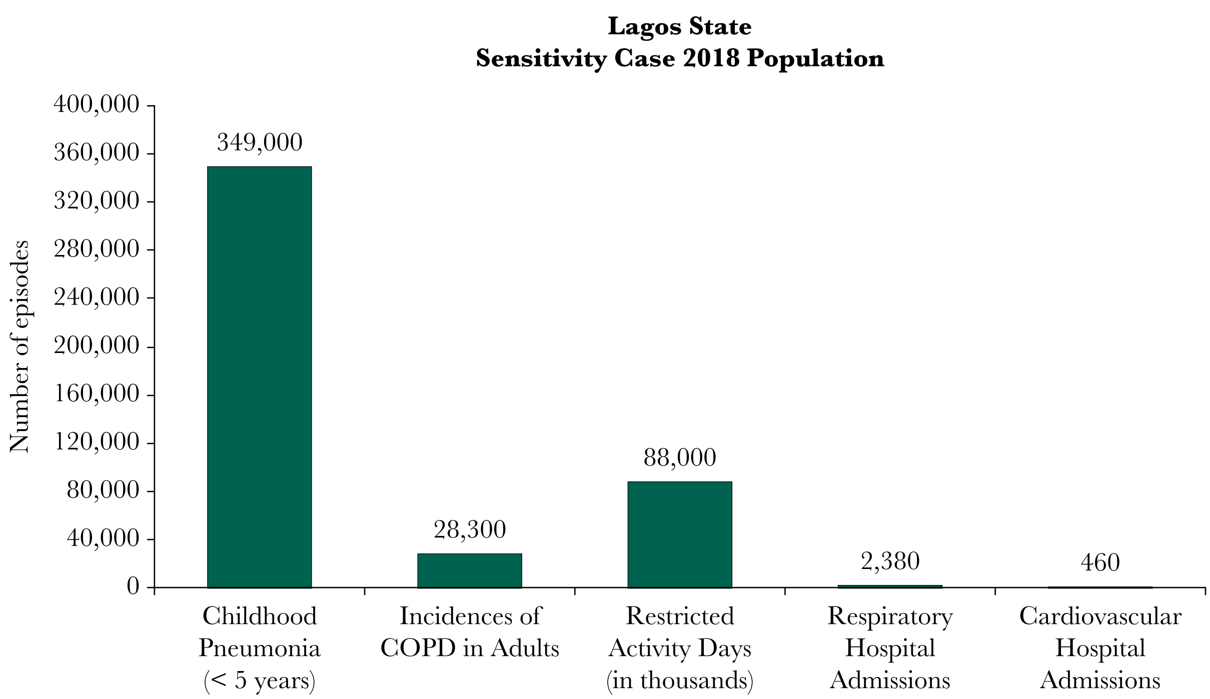
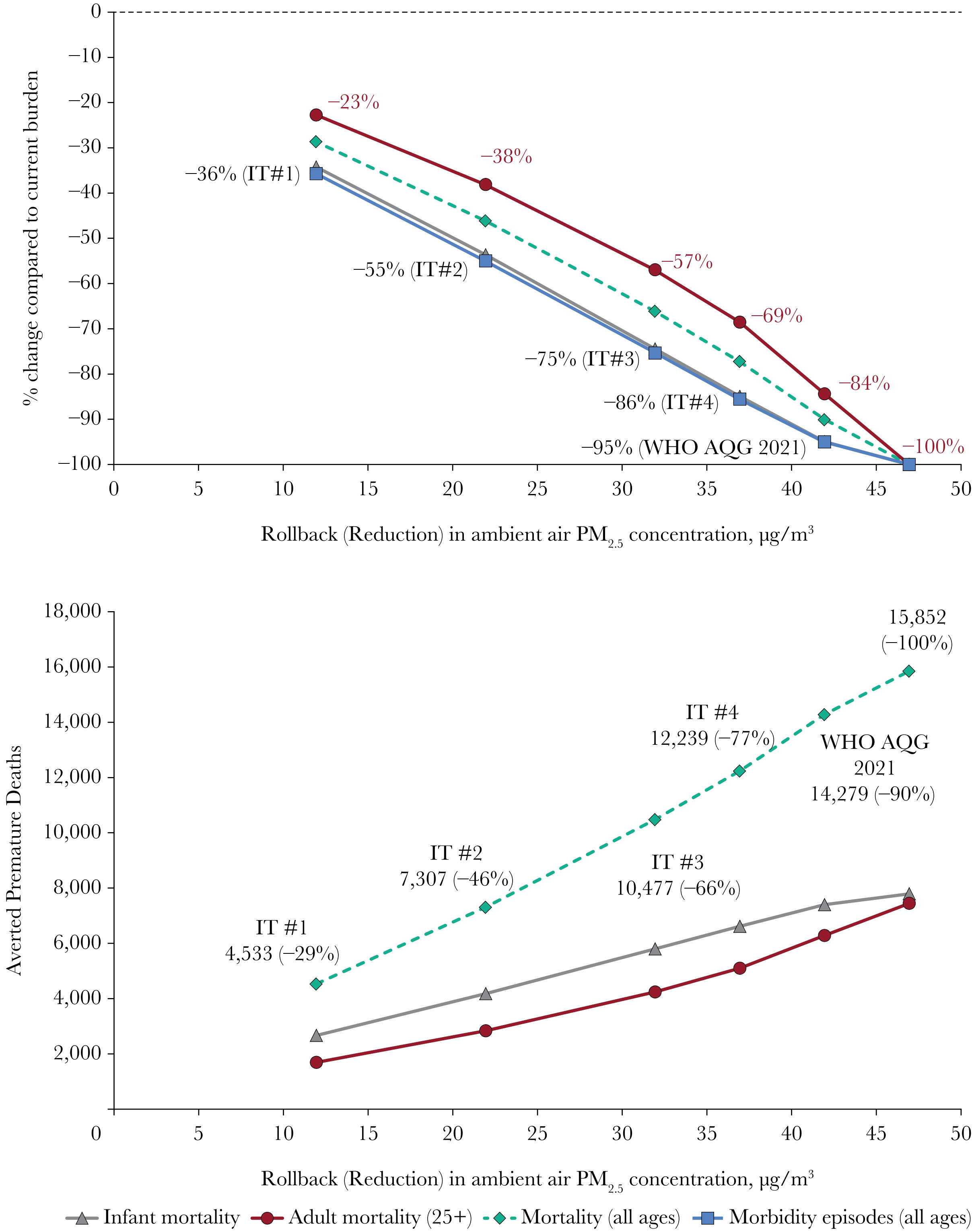


FIGURE 3.5. HEALTH BENEFITS FOR A REDUCTION IN AMBIENT AIR POLLUTION ACROSS LAGOS STATE



Note: The top figure shows the relative mortality and morbidity reduction compared to the current state, while the figure below shows the averted deaths for the base case population and applying the WHO GHE baseline mortality rates.

TABLE 3.1. VALUE OF MORBIDITY (SENSITIVITY CASE POPULATION)

	Childhood pneumonia (Under 5)	Onset chronic bronchitis (adult 27+)	Restricted activity days (all ages)	Hospital admissions (all ages)	Total
Number of incidences	348,900	28,280	87.61 million	2,840	
Value (US$, millions)	87.2	109.0	674.6	0.4	871
Share of GDP (2018) - %	0.121	0.151	0.94	0.001	1.2

Note: ***Childhood pneumonia*** is valued at five times the daily wage assuming the illness lasts for one week, during which time a parent or guardian remains home. ***Onset chronic bronchitis*** assumes EUR 68,000 per case transferred to Lagos using the benefit-transfer method of US$3,855 per incident. ***Restricted activity days*** are valued at an average cost of $7.7 per day. ***Hospital admissions*** are valued at between N30,000 and N100,000, or an average of US$158 per hospital admission.

sensitivity population) is significantly affected by lead exposure. The calculated loss of intelligence by each child is 6.21 IQ points, which represents a huge physical burden on the current generation and potentially a significant loss of future income. The total loss in IQ points is 780,000 and 1,017,000 for the base case and sensitivity case population, respectively. Additionally, the impact of lead on cardiovascular mortality in adults is remarkably high; the attributable premature mortality is 285 and 373 deaths for the base case and sensitivity case populations, respectively.

3.3. VALUATION OF HEALTH IMPACTS

The financial value of the air pollution health impacts has been estimated to be between 1.0 and 6.9 percent of the GDP of Lagos State (Table 3.2). The wide range in value is due to (a) the difference in the total population exposed to air pollution, reflected in the base case and sensitivity case population estimates for Lagos State, and (b) different methodologies for valuing loss of human life.

Health impacts include both morbidity and mortality due to air pollution. The value of morbidity includes things such as hospital costs, medications, and lost wages from patients or caregivers during the illness. As in other studies, the estimated cost of mortality dwarfs the morbidity cost. In this study, mortality values accounted for more than 85 percent of the total health impacts using the VSL (value of a statistical life) method for valuing the loss of human life.

3.3.1. LEAD IMPACTS

Lead exposure in children has been found to be associated with additional medical costs as well as impacts on cognitive development, which in turn can affect earnings later in life. Recent studies in the US have estimated that the value of a reduction in IQ on earnings can amount to US$12,000–17,500 per IQ point lost (Zhou and Grosse 2019). Based on the measurements of lead exposure in Ikorodu, the impacts amount to US$318 million–464 million in the base case (780,000 IQ points lost) and US$416 million–606 million in the sensitivity case (1,017,000 IQ points lost). Additionally, adult deaths associated with lead exposure are valued at US$47 million–61 million using the VSL method.

3.3.2. VALUE OF STATISTICAL LIFE (VSL)

Valuing the loss of human life, not surprisingly, can be a controversial topic. Here, two methods have been used. The first, the VSL method, attempts to provide a value by society of preventing a fatality of an anonymous person.

The VSL is society's willingness to pay to reduce the marginal risk of mortality. This can be observed in the market, for example, through wage-risk studies or contingent valuation studies. For this study, the value of a statistical life has been estimated as US$164,000 (2018) per premature mortality.[6]

3.3.3. HUMAN CAPITAL APPROACH (HCA)

The HCA values life as the productivity or lifetime income that is lost due to premature mortality. Because lost productivity is age-specific, the HCA value will be different depending on the age when the life was lost. The average wage used for the HCA calculations was US$10,000 per year (2018), multiplied by the average years lost, with the total discounted over time at 3 percent.

Using the same VSL and HCA methodologies, it is possible to estimate the benefits of lowering ambient air pollution levels to the WHO interim targets. Table 3.2 shows the reductions in mortality (both total and infant), along with the value, expressed as a share of Lagos' 2018 GDP. The value of reducing air pollution from current levels of average of 45 μg/m^3 to 10 μg/m^3 is estimated to be between US$0.55 billion and US$3.8 billion, or between 0.76 and 5.3 percent of GDP (Table 3.3).

3.4. DISCUSSION AND CONCLUSIONS

These health impact estimates show that air pollution from $PM_{2.5}$ poses a serious public health hazard, especially among children younger than 5. The PWE is high, reaching 47 μg/m^3, a value nearly 10 times higher than the new recommended WHO air quality guideline of 5 μg/m^3 (WHO 2021). Urgent action to reach at least the WHO IT 1 (35 μg/m^3) is therefore recommended. The overall impact of the present $PM_{2.5}$ levels on mortality across all the age groups is responsible for between 15,850 and 30,350 premature deaths per year, with the largest contribution related to infant mortality (between 7,790 and 14,890 infant deaths). For adult mortality, the impact is largest for cardiovascular diseases. The impact on morbidity, especially pneumonia and other acute respiratory

TABLE 3.2. VALUATION OF MORTALITY DUE TO AIR POLLUTION IN LAGOS

Lagos Population Scenarios	Air Pollution Mortality	Value of Statistical Life		Human Capital	
	Total Attributable Mortality (all ages)	Value of Mortality (VSL= USD 164,000) (b USD)	Share of GDP (%)	Human Capital Approach (annual wage = USD10,000) (b USD)	Share of GDP (%)
Base Case Population (13.3 m)	15,850	$2.6 b	3.6%	$0.7 b	1.0%
Sensitivity Case (25.6m)	30,350	$5.0 b	6.9%	$1.4 b	1.9%

TABLE 3.3. VALUE OF LOWERING AIR POLLUTION TO WHO INTERIM TARGETS

	Air Pollution Reduction Scenarios			
Air Quality Target*0	**35 ug/m³**	**25 ug/m³**	**15 ug/m³**	**10 ug/m³**
Reduction in $PM_{2.5}$	–10.0	–20.0	–30.0	–35.0
Reduction in Total Mortality	4,533–8,316	7,307–13,747	10,477–19,969	12,239–23,370
Benefit of Reduced Mortality (VSL) mUS$	$734–$1,364	$1,198–$2,255	$1,718–$3,275	$2,007–$3,833
Share of GDP (2018)	1.03–1.89%	1.66–3.13%	2.39–4.55%	2.79–5.32%
Benefit of Reduced Mortality – Human Capital Approach (HCA) mUS$	$202–$371	$326–$613	$467–$890	$546–$1,042
Share of GDP (2018)	0.28–0.51%	0.45–0.85%	0.65–1.24%	0.76–1.45%

conditions in children 0–5 years (between 182,400 and 349,000 incidences), is particularly worrisome. Other outcomes were also estimated and they contribute to increasing the overall burden.

Two additional critical contributions should be added to the estimated loss of life from long-term exposure to $PM_{2.5}$: (a) the impact of the daily high levels of PM_{10} during the *Harmattan* period and (b) industrial air pollution in Ikorodu with the relevant lead contamination, which accounts for a sizable loss of intellectual capabilities in children (a total of 780,000 to 1 million IQ points lost at the population level), and a high attributable cardiovascular mortality in that particular LGA (285 to 373 premature cardiovascular deaths). The quantified health burdens should be interpreted as conservative estimates because the additional impact from direct exposure to other critical pollutants (for example, gaseous air pollutants such as NO_2 and SO_2) has not been quantified in this work. A preliminary estimate of the potential burden on mortality from direct exposure to NO_2, for example, could add another 10 percent to the $PM_{2.5}$ total mortality. However, the adverse health effects from exposure to secondary inorganic aerosols (a component of PM) created through chemical transformation of NO_2 and SO_2 precursor emissions are already incorporated in the main $PM_{2.5}$ impact assessment.

The exposure assessment is one of the most important aspects of the study; it is based on an extensive monitoring program of ambient air pollution that has been set up in several locations with standardized procedures and quality controls. The results of the monitoring program have been coupled with the results of a dispersion model and with population data to estimate population-weighted exposures (PWEs) at the LGA level. In this way, the concentration values are referred to the population, which is the target of the HIA. We have considered a variety of possible outcomes, encompassing both mortality (natural mortality, which excludes accidental deaths, and cause-specific mortality) and several morbidity outcomes. We have addressed not only $PM_{2.5}$ but also the complementary contributions of daily levels of PM_{10}, mainly attributable to episodes of *Harmattan* desert dust, and the lead contamination in Ikorodu. Children are the segment of the population most affected by air pollution: they suffer from extraordinarily high infant mortality, experience frequent episodes of pneumonia and other respiratory disorders, and have to cope with a large limitation of their intellectual capability. It is irreversible damage to the next generation. Finally, we have considered several methodological aspects in our assessment (exposure estimation, choice of the ERFs, alternative demographic assumptions) to overcome the main limitations described below.

The HIA for Lagos refers to the most recent period of ambient air pollution monitoring—August 2020 to July 2021. This is the period with the most accurate measurement of air pollution. The other data for the HIA refer to a preceding period (that is, 2018 population data and available health statistics for 2017 and 2018). We believe that the error induced by this choice is minimal because the recent mortality rate has trended lower over the past decade, although population growth has been observed at the same time. The net effect is that our estimates are on the conservative side. In addition, it should be noted that the measurement period occurred during the COVID-19 pandemic. The pandemic has affected Africa including Nigeria, with a decrease in economic activity as reflected by the change in the internal gross product, a 3.5 percent drop in 2020 at the national level compared to the previous year when there was no COVID-19. This aspect makes our assessment for 2020–2021 somehow conservative in comparison to the air pollution data probably experienced in past years.

The most relevant uncertainty regarding our work stems from the difficulty of estimating the population at risk. Two different sources have been considered in this work because they provide potential extremes of the population size estimate. Assumptions about age distribution across different LGAs, often driven by operational choices, are another source of uncertainty. The difficulties in such estimations stem from the large size of slum settlements that are a prominent feature of the urban landscape of Sub-Saharan Africa, and from the dynamic nature of this population (Amegah 2021; Thomson et al. 2021). We are confident that our sensitivity choices, though imperfect and leading to a wide spread in the estimates, are the best approach to characterizing the size of the Lagos population.

Another concern about the estimates relates to the absence of reliable baseline health data for the entire population. The value of good-quality mortality data for public health is widely acknowledged. While effective civil registration systems remain the gold-standard source for continuous mortality measurement, in most African countries fewer than 25 percent of deaths are registered, and it appears to be the same in Lagos (Joubert et al. 2012). In addition, only a fraction of the hospital institutions (the public sector) register mortality and morbidity statistics, and a large fraction of health care providers do not release regular information. This difficulty is coupled with the traditional lack of medical certification for persons dying at home. We have used two sources of mortality information related to Nigeria (GBD and WHO) and have scaled down to Lagos, accounting for the differences between national and local age distribution. For hospitalizations, we have used the registrations of the events in the public sector with the strong assumption that the private sector has a proportionally similar load of patients. Finally, it is clear that a source-specific HIA was not performed because a clear partition of $PM_{2.5}$ exposure data was not available.

Presently, there is still limited experience with HIAs of air pollution in Africa. Among the few extant studies, we cite the HIA study in Cairo, Egypt (Wheida et al. 2018); in Addis Ababa, Ethiopia (Kumie et al. 2021); and in Accra (Garcia et al. 2021; Kanhai et al. 2021). In 2020, Croitoru, Chang, and Akpokodje published the first HIA of the burden of fine particulate matter in Lagos State. According to this study, in 2018, there were 11,200 premature deaths attributed to exposure to $PM_{2.5}$ air pollution. The mortality was quantified using the 2017 version of the cause-specific IER functions developed by GBD (2018). In Table 3.4, we compare the mortality rates (annual deaths per 100,000 population) calculated in this work against the estimates published by Croitoru, Chang, and Akpokodje (2020). Our cause-specific mortality results are based on the 2019 IER functions (GBD 2020).

We also provide results based on the relationships of Heft-Neal et al. (2018) for infant mortality and GEMM (Burnett et al. 2018) for deaths in the broader category of NCDs. The baseline mortality was estimated using the WHO GHE hazard rates. As can be seen, our mortality rates are consistent with the results of Croitoru, Chang, and Akpokodje, when assuming the same $PM_{2.5}$ exposure (68 $\mu g/m^3$) and using the same impact risk model (GBD IER), but our mortality estimates increase by a factor of 2.5 when switching from the IER model to the GEMM and Heft-Neal et al. relationships. The higher premature mortality estimate can be explained in part due to the size

TABLE 3.4. COMPARISON OF CURRENT ESTIMATES OF $PM_{2.5}$ MORTALITY RATES IN LAGOS STATE AND PREVIOUS WORK BY CROITORU, CHANG AND KELLY (2020)

Risk model	Croitoru, Chang, and Akpokodje (2020)	This study
IER functions for deaths due to cardiovascular and respiratory plus lung cancer and diabetes		$PM_{2.5}$ concentration: 47 μg/m³ based on 1-year, 2020–21, measuring campaign 2019 IER functions (GBD 2020) **Base case** population: 13.3 million Mortality rate (per 10^5): **38.5** **Sensitivity** population: 25.6 million Mortality rate (per 10^5): **37.0**
IER functions for deaths due to cardiovascular and respiratory plus lung cancer and diabetes	$PM_{2.5}$ concentration: 68 μg/m³ Population size: 24.4 million 2017 IER functions (GBD 2018) Mortality rate (per 10^5): **45.9**	$PM_{2.5}$ concentration: 68 μg/m³, same as Croitoru, Chang, and Akpokodje (2020) 2019 IER functions (GBD 2020) **Base case** population: 13.3 million Mortality rate (per 10^5): **47.0** Sensitivity population: 25.6 million Mortality rate (per 10^5): **45.5**
GEMM for NCD and lower respiratory illnesses plus Heft-Neal et al. (2018) for infant mortality		$PM_{2.5}$ concentration: 47 μg/m³ based on 1-year, 2020–21, measuring campaign **Base case** population: 13.3 million Mortality rate (per 10^5): **119.2** **Sensitivity** population: 25.6 million Mortality rate (per 10^5): **118.6**

of the baseline mortality used by the different models and, more importantly, because of the different shapes of the exposure mortality functions. For instance, the rate of decrease in the health risk at increasingly higher exposures using GEMM is much less than that predicted by the IER model.

In conclusion, the work illustrates a dramatic situation in Lagos that highlights the large burden of PM air pollution on public health. A future analysis would benefit from greater knowledge about exposure assessment, possibly source-specific, and systematic collection of demographic and health data. Further, it would be useful in follow-up analyses to undertake regional and/or local epidemiologic studies in Lagos so that ERFs would better reflect local conditions. Short of that, it would be ideal to develop disease-specific mortality risk estimates for Lagos that could be utilized to enhance the accuracy of the burden assessment from $PM_{2.5}$ exposure.

REFERENCES

Amegah, A. K. 2021. "Slum Decay in Sub-Saharan Africa: Context, Environmental Pollution Challenges, and Impact on Dweller's Health." *Environ Epidemiol* 5(3): e158. doi:10.1097/EE9.0000000000000158.

Brown, L., M. Lynch, A. Belova, R. Klein, and A. Chiger. 2020. "Developing a Health Impact Model for Adult Lead Exposure and Cardiovascular Disease Mortality." *Environ Health Perspect* 128(9): 97005. doi:10.1289/EHP6552.

Burnett R, H. Chen, M. Szyszkowicz, N. Fann, B. Hubbell, C. A. Pope 3rd, J. S. Apte, et al. 2018. "Global Estimates of Mortality Associated with Long-Term Exposure to Outdoor Fine Particulate Matter." *Proc Natl Acad Sci U S A* 115 (38): 9592–97. doi:10.1073/pnas.1803222115.

Burnett, R. T., C. A. Pope, M. Ezzati, C. Olives, S. S. Lim, S. Mehta, H. H. Shin, et al. 2014. "An Integrated Risk Function for Estimating the Global Burden of Disease Attributable to Ambient Fine Particulate Matter Exposure." *Environ Health Perspect* 122(4): 397–403.

Chen, J., and G. Hoek. 2020. "Long-Term Exposure to PM and All-Cause and Cause-Specific Mortality: A Systematic Review and Meta-Analysis." *Environ Int* 143:105974. doi:10.1016/j.envint.2020.105974.

Croitoru, L., J. C. Chang, and J. Akpokodje. 2020. "The Health Cost of Ambient Air Pollution in Lagos." *Journal of Environmental Protection* 11:753–765. https://doi.org/10.4236/jep.2020.119046.

Garcia, L., R. Johnson, A. Johnson, A. Abbas, R. Goel, L. Tatah, J. Damsere-Derry, et al. 2021. "Health Impacts of Changes in Travel Patterns in Greater Accra Metropolitan Area, Ghana." *Environ Int* 155:106680. doi:10.1016/j.envint.2021.106680.

GBD 2019 Risk Factors Collaborators. 2020. "Global Burden of 87 Risk Factors in 204 Countries and Territories, 1990–2019: A Systematic Analysis for the Global Burden of Disease Study 2019." *Lancet* 396(10258): 1223–49. doi:10.1016/s0140-6736(20)30752-2.

GBD 2017 Risk Factor Collaborators. 2018. "Global, Regional, and National Comparative Risk Assessment of 84 Behavioural, Environmental and Occupational, and Metabolic Risks or Clusters of Risks for 195 Countries and Territories, 1990-2017: A Systematic Analysis for the Global Burden of Disease Study." *Lancet* 392: 1923–1994.

IHME. 2021. Global Health Data Exchange (GHDx, IHME). http://ghdx.healthdata.org/gbd-results-tool.

Heft-Neal, S., J. Burney, E. Bendavid, and M. Burke. 2018. "Robust Relationship between Air Quality and Infant Mortality in Africa." *Nature* 559 (7713): 254–258. doi:10.1038/s41586-018-0263-3.

Joubert, J., C. Rao, D. Bradshaw, R. E. Dorrington, T. Vos, and A. D. Lopez. 2012. "Characteristics, Availability and Uses of Vital Registration and Other Mortality Data Sources in Post-Democracy South Africa." *Glob Health Action* 5: 1–19. doi:10.3402/gha.v5i0.19263.

Kanhai, G., J. N. Fobil, B. A. Nartey, J. V. Spadaro, and P. Mudu. 2021. "Urban Municipal Solid Waste Management: Modeling Air Pollution Scenarios and Health Impacts in the Case of Accra, Ghana." *Waste Manag* 123: 15–22. doi:10.1016/j.wasman.2021.01.005.

Kumie, A., A. Worku, Z. Tazu, W. Tefera, A. Asfaw, G. Boja, M. Mekashu, et al. 2021. "Fine Particulate Pollution Concentration in Addis Ababa Exceeds the WHO Guideline Value: Results of 3 Years of Continuous Monitoring and Health Impact Assessment." *Environ Epidemiol* 5 (3): e155. doi:10.1097/EE9.0000000000000155.

McAllister, D. A., L. Liu, T. Shi, Y. Chu, C. Reed, J. Burrows, D. Adeloye, and Rudan, I. 2019. "Global, Regional, and National Estimates of Pneumonia Morbidity and Mortality in Children Younger than 5 Years between 2000 and 2015: A Systematic Analysis." *Lancet Global Health* 7:e47–57. http://dx.doi.org/10.1016/S2214-109X(18)30408-X.

McDuffie, E. E., R. V. Martin, J. V. Spadaro, R. Burnett, S. J. Smith, P. O'Rourke, M. S. Hammer, et al. 2021. "Source Sector and Fuel Contributions to Ambient PM(2.5) and Attributable Mortality Across Multiple Spatial Scales." *Nat Commun* 12(1): 3594. doi:10.1038/s41467-021-23853-y.

Orellano P, Reynoso J, Quaranta N, Bardach A, Ciapponi A. 2020. "Short-term exposure to particulate matter (PM_{10} and $PM_{2.5}$), nitrogen dioxide (NO_2), and ozone (O_3) and all-cause and cause-specific mortality: Systematic review and meta-analysis." *Environ Int*. 142: 105876. doi: 10.1016/j.envint.2020.105876.

Thomson, D. R., A. E. Gaughan, F. R. Stevens, G. Yetman, P. Elias, and R. Chen. 2021. "Evaluating the Accuracy of Gridded Population Estimates in Slums: A Case Study in Nigeria and Kenya." *Urban Sci.* 5:48. https://doi.org/10.3390/urbansci5020048.

US EPA. 1999. "Implementer's Guide to Phasing Out Lead in Gasoline."

US EPA. 2019. "Integrated Science Assessment for Particulate Matter." EPA/600/R-19/188. U.S. Environment Protection Agency, Research Triangle Park 2019.

Vohra, K., A. Vodonos, J. Schwartz, E. A. Marais, M. P. Sulprizio, and L. J. Mickley. 2021. "Global Mortality from Outdoor Fine Particle Pollution Generated by Fossil Fuel Combustion: Results from GEOS-Chem." *Environ Res* 195: 110754. doi:10.1016/j.envres.2021.110754.

Wheida, A., A. Nasser, M. El Nazer, A. Borbon, G. A. Abo El Ata, M. Abdel Wahab, and S. C. Alfaro. 2018. "Tackling the Mortality from Long-Term Exposure to Outdoor Air Pollution in Megacities: Lessons from the Greater Cairo Case Study." *Environ Res* 160: 223–231. doi:10.1016/j.envres.2017.09.028.

WHO. 2013. *Health Risks of Air Pollution in Europe — HRAPIE Project. Recommendations for Concentration–Response Functions for Cost–Benefit Analysis of Particulate Matter, Ozone and Nitrogen Dioxide*. Copenhagen, Denmark: WHO.

WHO. 2021. *WHO Global Air Quality Guidelines. Particulate matter ($PM_{2.5}$ and PM_{10}), Ozone, Nitrogen Dioxide, Sulfur Dioxide and Carbon Monoxide*." https://apps.who.int/iris/handle/10665/345329.

WHO. 2021. Global Health Estimates (GHE, WHO). https://www.who.int/data/gho/data/themes/mortality-and-global-health-estimates/ghe-leading-causes-of-death.

WHO Regional Office for Europe. 2016. *Health Risk Assessment of Air Pollution – General Principles*. Copenhagen: WHO Regional Office for Europe.

World Bank and Institute for Health Metrics and Evaluation (2016). The Cost of Air Pollution. World Bank, Washington DC.

Zhou, Y., and S. D. Grosse. 2019. "Valuing the Benefits of Reducing Childhood Lead Exposure – Human Capital, Parental Preferences, or Both? Centers for Disease Control and Prevention (CDC)." Prepared for workshop at Harvard Center for Risk Analysis, September 26–27, 2019. https://cdn1.sph.harvard.edu/wp-content/uploads/sites/1273/2019/09/Zhou-Grosse-2019.pdf.

CHAPTER 4
POTENTIAL EMISSION CONTROL MEASURES

In considering potential air pollution control measures, policy makers should consider both the cost to the Government and the overall economic costs and benefits, as well as the implications for other social goals. At COP26, Nigeria committed to achieving net-zero GHG emissions by 2060, and the Climate Action Plan of the Lagos State Government (LASG) calls for net zero by 2050. Thus, any pollution control measures adopted should be consistent with a transition away from fossil fuels. Other social goals to consider include reducing road transport and traffic congestion, with its wastage of time and resources, and reducing pollution of land and water as well as the air.

4.1. POLLUTION CONTROL STRATEGIES BY SECTOR

As explained in chapter 2, the PMEH source apportionment study showed that about 28 to 32 percent of ambient $PM_{2.5}$ is due to open burning, mostly burning of solid waste. Industrial emissions account for about 18 percent on average, though this varies greatly from one location to another. Diesel and gasoline engines used in transport and backup generators account for another 14 to 17 percent. Together, these readily controllable sources of primary PM emissions account for 60 to 67 percent of the $PM_{2.5}$ in the air. Another 28 to 32 percent of $PM_{2.5}$ and 48 to 50 percent of PM_{10} is suspended dust, some of which has natural causes such as the *Harmattan* but much of which is human-generated and therefore controllable. The remaining 15 percent or so comprises sulfates, nitrates, and organic aerosol formed from SOx, NOx, and VOC, respectively, through chemical reactions in the atmosphere. This secondary $PM_{2.5}$ can be controlled by reducing emissions of the reactant species.

4.1.1. SOLID WASTE

Open burning of municipal solid waste (MSW) is estimated to account for as much as 30 percent of the $PM_{2.5}$ present in the air. Present solid waste production in Lagos is estimated at 4.2 million tons per year, of which only about 1.8 million is collected and disposed at one of four active dumpsites. Waste pickers scavenge for usable items, mainly metal and plastics, and the remainder of the waste, much of it organic, is left to decompose. There is a well-developed market for recycled materials (Salau et al. 2017). Most of the waste that is not collected is believed to be burned, and some burning also goes on at dumpsites.

To eliminate the open burning of solid waste would require a substantial improvement in collection efficiency, together with improved enforcement of regulations on waste disposal and open burning. The LASG is already taking steps in this direction, with the planned acquisition of another 100 collection trucks in 2021 and the planned establishment of 20 transfer-loading stations and several material recovery facilities by 2030.

Plans are also being developed to replace the existing dumpsites with modern landfills. Modern landfills are built to capture CH_4 produced from decomposing organic matter. CH_4 captured can be used to generate electricity or supplied to other energy users as fuel. Because CH_4 is a powerful GHG,[7] landfills can earn carbon credits by mitigating the release of CH_4.

Government policies can help minimize the amount of waste to be landfilled by encouraging the separation of solid waste to facilitate recycling and composting. Organic waste, for instance, needs to be separated so that it does not contaminate recyclables such as paper and cardboard. Neighborhood collection sites that allow plastics, metals, and glass to be separated could enhance the feasibility of recycling by reducing the cost of collection and ensuring a higher-quality recycled product. Collection fees for solid waste, if built into the fee structure of essential urban services such as water, could help cover the costs of collecting and disposing of solid waste.

Another potential destination for solid waste is incineration and the production of energy. While generally the costliest method of disposing solid waste, incinerators can reduce the overall volume of solid waste and produce electricity, which can be sold or used by waste management facilities. A project currently under discussion in Lagos is the establishment of a waste-to-energy plant that would convert MSW to electricity (Omorogbe 2021).[8] Aside from investment costs, the main drawback of incineration is that most of the combustible solid waste in Lagos is potentially recyclable—such as paper and plastics—or is organic matter that is not returned to the soil.

Organic matter, which is estimated to be about half of the total MSW in Lagos (LAWMA 2014), has the potential to be composted and turned into fertilizer or a soil additive. Because the separation of organic wastes can be costly, some municipalities have begun their composting programs by targeting large sources of organic wastes, such as produce markets, grocery stores, and restaurants. Compost can also be an important product for urban gardens and municipal landscaping. Cities around the world are increasingly providing collection services for organic waste, such as bins for households, buildings, or neighborhoods, as well as trucks and infrastructure for transport and processing in large-scale compost facilities. Because organic waste is the raw material for CH_4 production in a landfill, reducing the amount of organic matter through composting can limit the amount of CH_4 released into the atmosphere. Composting programs can thus earn carbon credits by diverting organic matter that would otherwise have resulted in the production of CH_4. The EarthCare program in Lagos had an estimated CO_2 reduction of 253,000 tons per year over a 10-year period, for which it could earn carbon credits (World Bank 2010).

4.1.2. FUEL QUALITY

Fuel "quality" is best understood as compliance with the specifications for that type of fuel. From the standpoint of air quality, the most important specification for both diesel and gasoline is the allowable sulfur content.

Most of the sulfur present in motor fuel burns to form SO_2 in the exhaust; this is the main source of SO_2 emission in Lagos. A few percent of the sulfur is emitted in the form of sulfate particles, and these can increase diesel PM emissions significantly. Some of the SO_2 emitted to the atmosphere reacts to form sulfate particles as well.

SO_2 in the exhaust also binds to the catalyst materials used in catalytic converters and diesel particulate filters, reducing their efficiency. Diesel oxidation catalysts can also oxidize SO_2 to SO_3, which combines with water vapor in the exhaust to form sulfuric acid. Operating an engine on high-sulfur fuel can clog diesel particulate filters; for this reason, fuel sulfur limits are needed for adequate emissions control for diesel engines. The US, European Union (EU), and many other countries have set ultra-low fuel sulfur limits of 10 to 15 ppm (by weight) for distillate fuels.

Diesel fuel samples collected at Lagos retail stations in 2020 averaged 2,389 ppm sulfur: for gasoline, 1,424 ppm. New fuel standards allowing 150 ppm sulfur for gasoline and 50 ppm for diesel were set to be introduced in Nigeria in 2017 but have not yet been implemented. Nigeria is also signatory to the agreement of the Economic Commission of West African States (ECOWAS) to limit sulfur to 50 ppm in both diesel and gasoline. By implementing and enforcing these standards, the Nigerian and/or Lagos State Government would make it feasible for used vehicles imported from developed countries to retain the particle filters with which they come equipped, as well as allow the operation of new vehicles meeting Euro 4 or better emission standards (Table 4.1).[9] This would also permit the use of particle filters and other advanced emission controls on backup generators.

Nigeria presently has no operational petroleum refineries, except for some small illegal operations in the Niger delta. The Nigerian National Petroleum Corporation (NNPC) is the only legal importer of refined products, but smuggling is thought to be widespread. The new Dangote refinery[10] now under construction will have more than enough capacity to supply Nigeria's needs and has been designed to produce ultra-low sulfur diesel and gasoline (Euro 5–6 specifications). Until that refinery comes online, all legal refined petroleum products used in Lagos will continue to be purchased on the world market and imported by ship. Gasoline and diesel fuel meeting low or ultra-low sulfur specifications are available on the world market. Thus, to begin enforcing the 2017 or ECOWAS fuel sulfur limits would be relatively simple—NNPC would need to change its purchase specifications and contract to buy fuel meeting the sulfur standards.

The new fuel standards would need to be enforced through collection and analysis of fuel samples both at dockside and in the retail stations. Sulfur removal adds to the fuel cost, so shippers would be tempted to substitute

TABLE 4.1. EUROPEAN DIESEL AND GASOLINE STANDARDS AND EMISSIONS

European diesel (AGO) and gasoline (PMS) standards and emissions					
Standard	**Implementation date (Europe)**	**Sulfur limit AGO (ppm)**	**Emissions (g/km)**	**Sulfur limit PMS (ppm)**	**Emissions (g/km)**
Euro 1	1994	2,000	0.14	2,000	0.09
Euro 2	1996	500	0.08	500	0.01
Euro 3	2000	350	0.05	150	0.01
Euro 4	2005	50	0.025	50	0.01
Euro 5	2009	10	0.005	10	0.005

Source: Transportpolicy.net.

https://www.sciencedirect.com/science/article/pii/S259019822030083X high-sulfur for low-sulfur products if there were no danger of being detected. Similarly, the higher cost of low-sulfur fuel would increase the incentives for smuggling and adulteration at the retail level.

Improved fuel quality would help lower $PM_{2.5}$ emissions, primarily through the introduction of more sophisticated emissions control systems on vehicles, especially advanced catalytic converters and diesel particulate filters. The current fuel quality in Nigeria does not allow the effective operation of vehicle catalysts beyond Euro 1, standards that were implemented in Europe in the early 1990s. Properly functioning Euro 5 vehicles can lower emissions of $PM_{2.5}$ by 28 times compared to Euro 1. To guard against fuel adulteration and protect the emissions control equipment on vehicles, it is necessary to ensure that fuel quality at fueling stations is maintained (box 4.1).

To the extent that the same quality of petroleum products is available to all consumers in Lagos, requiring that they all meet higher fuel specifications will reduce emissions. Conversely, if fuel standards are tightened for transport fuels but not for industrial fuels, there could be leakage or cases of misfueling where vehicle owners end up putting cheaper and dirtier fuels in their vehicles. Requiring that all petroleum products in Lagos meet higher quality standards will reduce misfueling and thus contribute to lowering emissions from the transport sector, industry, and backup electricity generators used throughout Lagos State and Nigeria.

4.1.3. ROAD TRANSPORT

The road transport sector accounts for about 10 percent of primary $PM_{2.5}$ emissions in Lagos and is also a main source of NOx and SO_2, which react to form secondary $PM_{2.5}$. It is also the second-largest source of GHG emissions. Given its importance to the economy—moving people and goods—and the fact that it will certainly grow, effective air pollution control measures for this sector will be essential to sustainable growth. Equally, appropriate technology choices will be needed for the government to meet its target of net-zero GHG emissions by 2050.

BOX 4.1. MEASURES TO ENSURE FUEL QUALITY

Tamper-proof locks. Products are supplied to retail outlets in modified tank lorries fitted with tamper-proof locks.

Comprehensive sealing. Dispensing units are sealed in a comprehensive manner, which makes meter tampering impossible.

Periodic and surprise checks by staff. Stringent, periodic, surprise checks are carried out to ascertain correct delivery and the sealing of the pumps.

Testing of product samples. Regular comprehensive testing of samples is done without prior warning.

Certification of retail outlets. Periodic audits and recertification of retail outlets are carried out by a reputable certification agency.

Source: Rogers 2002 as quoted in Gwilliam, Kojima, and Johnson 2004.
Note: Based on practices of Bharat Petroleum, India.

4.1.3.1. GLOBAL WARMING

The Nigerian Government has committed to achieving net-zero GHG emissions by 2060. Achieving net-zero emissions in the road transport sector will require a massive shift away from fossil fuels and toward more sustainable technologies. Planning to accommodate this shift is needed now, as infrastructure commissioned today is quite likely to be in use in 2060. Thus, shifting to another fossil fuel, even a “clean” fuel such as natural gas, would be contraindicated.

Througout most of the world, battery electric vehicles (BEVs) are now the clear favorites to replace internal combustion engines that burn fossil fuels. BEVs make up a significant and increasing fraction of the new vehicle fleet in Europe, China, and North America. BEVs are most effective where vehicle range requirements are fairly short, such as private automobiles, city buses, drayage and delivery trucks, and taxicabs. Where long range is important, as in long-haul trucking and air travel, liquid fuels such as biodiesel and renewable (synthetic) diesel and jet fuel may continue to have a role.

To be practical in Nigeria, BEVs will require a reliable, low-cost source of electricity for charging, which currently excludes Nigeria’s electric grid. Substantial investment will be required in electric generation and charging infrastructure. This is discussed in the section on electricity generation, below. In the meantime, hybrid vehicles—especially plug-in hybrids—have much to recommend them. This is especially true in stop-and-go traffic, where the use of regenerative braking both saves energy and reduces brake wear. By charging from the power grid when it is available and from their onboard engine when not, plug-in hybrids could provide reliable service in the near term while retaining the ability to switch to all-electric operation in the future.

Of course, for BEVs to reach net-zero GHG emissions, the charging electricity will need to come from renewable sources such as solar photovoltaics and wind. Until those renewable electricity sources are available, however, a plug-in hybrid or BEV charged by (for example) a combined cycle natural gas power plant would still have substantial benefits for the sake of both air quality and climate change priorities.

4.1.3.2. VEHICLE EMISSION STANDARDS

The most effective and least costly way to reduce vehicle emissions is to require new vehicles to comply with emissions standards. Incorporating emission controls into the vehicle design from the beginning is much less costly than to retrofit them. The main drawback is that the vehicle fleet turns over slowly, so the full benefit of new emission standards is not seen for more than a decade. In specific cases such as drayage trucks and public transport vehicles, it may be cost-effective to accelerate fleet turnover by mandating specific emission standards.

Most vehicles in Nigeria were originally sold in Europe or North America and are imported into Nigeria as used upon reaching the end of their economic life in their country of origin. This has the advantage that the vehicles are likely equipped with advanced emission control systems, but the disadvantage that those systems may be in poor condition. At present, the importers typically remove the catalytic converters and/or particulate filters before reselling the vehicles.

Nigeria has joined in the decision of the ECOWAS[11] to require all newly registered vehicles, both new and used, to meet Euro 4 emission standards and for the sulfur content of vehicle fuels to be limited to 50 ppm (UNEP 2020). Imported vehicles are also subject to age limits of 5 years for light-duty vehicles and 10 years for heavy-duty vehicles. Meeting the Euro 4 standards requires that diesel engines be equipped with a particulate filter, and gasoline engines with a three-way catalytic converter and electronic engine controls. These standards would not be feasible without the fuel sulfur limit because sulfur poisons the catalysts used, reducing their effectiveness. So far, the 50 ppm sulfur limit has not been implemented in Nigeria, and it does not appear that the Euro 4 requirement is being enforced.

The requirement that a vehicle meets Euro 4 or equivalent North American emission standards should be implemented as soon as possible. For new vehicles, the manufacturer's certificate of compliance can generally be relied on, though occasional spot-checks are recommended to keep the manufacturers honest. For used vehicles, the vehicle should at least be inspected to ensure that it retains all its emission control equipment and should preferably be subjected to emission measurements under load to verify that the system remains functional. This would require test facilities equipped with chassis dynamometers and appropriate emission analyzers. This testing could potentially be carried out by the Lagos Computerized Vehicle Inspection Service (LACVIS) or another independent testing service but should not be left to the importers themselves.

4.1.3.3. VEHICLE INSPECTION AND MAINTENANCE (I&M)

Even in the absence of emission control systems, a poorly adjusted or worn-out engine will produce much higher emissions than if it were well maintained. Where vehicles are equipped with emission controls, this difference is much greater, and it has been commonly observed that most of the emissions from the vehicle fleet are concentrated in a small percentage of "gross emitters" (Krzyzanowski et al. 2014).[12] These gross emitters include vehicles where the emission control system is malfunctioning and those where it has been removed or tampered with. Inspection and maintenance (I&M) programs are designed to identify those gross emitters and require their repair. They can also perform related tasks such as checking that all required emission control systems are present, functional and interrogating engine electronic control systems for malfunction codes. An effective I&M program is a prerequisite for implementing almost any vehicle improvement program.

Experience has shown that the most effective I&M programs are based in a relatively small number of high-volume stations that do not perform repairs, so that the inspectors have no vested interest in passing or failing a vehicle. LACVIS appears to be of this form, and its establishment in 2016 was an important development in being able to monitor and enforce vehicle emission regulations. Currently, the program requires private vehicles to be inspected for emissions and roadworthiness once a year, and commercial vehicles every 6 months. Vehicles are required to display their roadworthiness certificates on the vehicle or face a fine.

As vehicle emission controls are phased in, LACVIS will need to be strengthened to maintain its effectiveness. This should include upgraded testing equipment to measure particulate emissions and to allow vehicles to be tested under load using a chassis dynamometer. This is especially important for diesel vehicles. ECOWAS directive C/Dir.2/09/20 requires that all vehicles *in circulation* meet Euro 4 emission standards by January 1, 2025. Confirming compliance with the Euro 4 standard would require testing under load in a transient driving cycle.

4.1.3.4. UPGRADING VEHICLE FLEETS

The most effective and least costly way to control vehicle emissions is to replace the existing fleet as they retire with new vehicles that have emission controls designed in from the beginning (Faiz, Walsh, and Weaver 1996). In some cases, it may be cost-effective to retrofit existing vehicles or to accelerate the replacement of the existing fleet with emission-controlled replacements. Public transport and delivery fleets are especially suitable due to their high mileage in urban areas.

Focusing on fleet vehicles such as taxis, buses, or delivery trucks has been a proven approach to introducing alternative fuel vehicles since this requires the establishment and maintenance of fewer refueling facilities, and conversion and maintenance can be handled by dedicated service personnel (Faiz Walsh, and Weaver 1996). It also allows the refueling facilities to maintain their own fuel quality, such as ultra-low sulfur diesel that is required for advanced catalysts and particulate filters. Given the global trend and falling costs of hybrid and electric vehicles, an evaluation of the costs of such vehicles should be undertaken, particularly for fleet vehicles such as buses, taxis, and delivery trucks (Mufson and Kaplan 2021).[13]

4.1.3.4.1 Minibuses/danfos

According to Lagos State Metropolitan Transport Agency (LAMATA), as recently as 2015, the small passenger vans known as *danfos* accounted for about 45 percent of all motorized passenger trips in Lagos. Given the high mileage of *danfos*—reportedly as much as 80,000 km per year—and the relatively old average age of the fleet (two-thirds may be over 17 years old), they would be logical targets for replacement. The government's 2018 plan for reducing short-lived GHGs (Government of Nigeria 2018) calls for phasing out the *danfos* in favor of 5,000 new full-size buses. However, this is likely to face resistance from the *danfo* owners and operators.

The *danfos* are mostly equipped with gasoline engines, which emit little $PM_{2.5}$ unless the engines are worn out and leaking oil into the exhaust. However, these engines are inefficient in urban traffic and emit large quantities of CO and VOC as well as NOx and CO_2. The *danfos'* small passenger capacity of 14 to 18 (crowded) people requires a large number of vehicles to meet passenger demand, so that they are major contributors to traffic congestion. Replacing the *danfos* with a smaller number of 35-passenger minibuses, as in Mexico City, would help reduce congestion, improve passenger comfort and safety, and reduce emissions and fuel consumption. The replacements should preferably be plug-in hybrids to allow for the possibility of electrification later, but even conventional engines meeting Euro 4 emission standards would greatly reduce pollutant and GHG emissions. Such a replacement might logically be combined with improved safety standards and a reorientation of the *danfo* routes to better coordinate with the bus rapid transit (BRT) system.

4.1.3.4.2. Buses

Diesel buses can be significant sources of $PM_{2.5}$ emissions. They tend to operate in crowded areas where many people are exposed to those emissions, are usually centrally fueled (meaning that the buses are all fueled by one particular fleet operator), and are usually either operated or supervised by public agencies. This makes them especially suitable targets for emission control efforts. Many cities around the world have switched their bus fleets to CNG, and an increasing number of BEV buses are also being produced. Many cities have also purchased "clean" diesel buses that are equipped with particulate filters and burn ultra-low sulfur fuel. Some, such as Mexico City, have successfully retrofitted older-model buses with diesel oxidation catalysts and particulate filters (Schipper et al. 2006) (See Box 4.2).

Nigeria has abundant natural gas, so a transition to CNG fuel would be a feasible strategy for buses in Lagos. The government's plan (Government of Nigeria 2018) for reducing short-lived GHGs includes a shift to CNG in buses nationally. This may not be the best course, however, as it would require substantial investment in new fueling infrastructure, which would have limited useful life as Nigeria transitions away from fossil fuels. CH_4 emissions from CNG vehicles and infrastructure are also a concern. Biogas from digesters and sewage treatment plants could be upgraded to "renewable natural gas" for vehicular use but at considerable cost.

Clean diesel technology using particulate filters and ultra-low sulfur diesel can achieve emission levels similar to CNG and would pose less risk of stranded investment. Hybrid buses using clean diesel technology offer the potential for even lower emissions as well as fuel savings and savings on brake maintenance. Pure BEV buses would be the most practical either on short feeder routes or in BRT service, where wireless charging systems could be installed in the stations.

4.1.3.4.3. Motorcycle and tricycle taxis (okada and keke NAPEP)

In Nigeria, motorcycle taxis, both two- and three-wheelers, play an important role in urban transport by providing short-distance mobility and a link for the "first and last mile" of daily commutes. In Lagos, the two-wheel *okada* and three-wheel *keke* NAPEP taxis[14] are also an important source of employment. The 2,000 small buses approved for "first and last mile" trips in

BOX 4.2. FROM COMBIS TO MINIBUSES IN MEXICO CITY

In the early 1990s, public transit in Mexico City was dominated by large number of "combis"—11-seat Volkswagen microbuses with air-cooled gasoline engines that were extremely polluting. These vehicles were privately owned and operated and organized themselves into cooperatives to provide service on defined routes. Their large numbers and lack of regulation led to traffic congestion, competition for passengers, haphazard stops outside of bus zones and in the middle of traffic, and other safety hazards.

As part of its air pollution control program, the Mexico City Government, in 1993, established a maximum age limit of 8 years for combis and required that the replacement vehicles be minibuses. The minibuses are specialized vehicles built on extended van chassis, with seats for 23 passengers and a maximum capacity of about 32. They were equipped with catalytic converters and used unleaded gasoline or in some cases LPG or compressed natural gas (CNG) fuel. Similar minibuses are still in widespread use today.

Combi owners were provided with financing assistance to purchase the new minibuses through credit lines funded in part by the World Bank Transport Air Quality Project. Many combi owners also chose to lease their vehicles through specialized financing companies.

2021 demonstrate the importance of this segment of the commute for getting passengers from their homes to their jobs.

Lagos restricted the import of two-stroke motorcycles in 2014, but it is not clear if that has limited their circulation. Two-stroke motorcycles have been a major contributor to transport-related air pollution in cities all over the world where motorcycles are numerous, such as in South and Southeast Asia. Measures to phase out two-stroke engines in favor of four-stroke have been one of the air quality successes in cities such as Bangkok, Dhaka, and Jakarta (Shah 2003).[15] Like other public transport vehicles, motorcycle taxis should be required to meet emission standards as a condition for their operation.

Given their typically short trip distances, *okada* and *keke* NAPEP taxis in Lagos that presently use gasoline engines could potentially be replaced with BEVs. Battery-electric motorcycles and three-wheelers are already commercially available in some Asian countries. This would eliminate the engine noise and odor as well as pollutant emissions. Reliable charging arrangements would need to be supplied but could be provided by solar photovoltaic panels.

4.1.3.5. PUBLIC TRANSPORT

The expansion of public transport is considered an important way of improving the efficiency of transport in Lagos and of reducing both air pollution and GHG emissions. With support from international donors, Lagos has invested in both the infrastructure and the institutions to improve public transport, including BRT, light rail, and ferries.

The upgrading and expansion of public transport in Lagos could have a large positive impact on air quality. Public transport investments are large and multi-year and must be justified largely on their transportation benefits rather than on their contribution to improving air quality. Although the air quality benefits of public transport can be large, public transport investments need to be evaluated on their long-term contribution to air quality rather than on their capacity to make an immediate positive impact on air quality.

4.1.3.5.1. Bus rapid transit (BRT)

In 2008, Lagos opened the first BRT corridor in Africa. Before the BRT line, passengers in Lagos mostly used "small commuter buses, known as *danfos* (85 percent), large commercial buses (8 percent), and cars (4 percent), and the remaining 3 percent taxis, motorcycle taxis (okada) and shared taxis (kabu kabu)" (World Bank 2013). Among its benefits, the BRT system in Lagos has been successful in reducing travel times, public transport expenditures by low-income households, and road accidents. The BRT system has also proven to be profitable, with the operator of the first BRT corridor recouping the entire capital investment of the bus fleet within 18 months and without attempting to bar competitor services (Gorham et al. 2017).

By using larger buses traveling in dedicated bus lanes, the efficiency of transportation can improve and $PM_{2.5}$ emissions can be reduced. BRT systems can lower air pollution through several means: (a) BRT buses can displace smaller buses (such as *danfos*) and automobiles, which in turn would result in less pollution per passenger-kilometer; (b) dedicated BRT lanes allow buses to run unhindered at higher speeds than traffic on congested roadways—vehicles produce the least amount of air pollution when they are cruising at an even speed rather than stopping and starting; and (c) BRT buses can employ newer bus technologies—clean diesel, CNG, electric—that are able to reduce air pollution emissions better than current vehicle technologies.

The BRT program that has been under development in Lagos since 2008 has resulted in faster commutes, lower fares, and reduced fuel consumption per passenger-kilometer. Under the first phase of the Lagos Urban Transport Project (LUTP), a 22 km BRT corridor was constructed, ultimately transporting around 200,000 passengers per day or 37 percent of all public transport trips in the corridor, while accounting for only 4 percent of vehicles in 2008 (Mobereola, 2009). Several additional BRT corridors have been constructed over the past decade (see Table 4.2). Lower fuel consumption results in reductions in $PM_{2.5}$ as well as CO_2. Based on assessments from phase 1, the original BRT line resulted in 13 percent lower overall fuel consumption as well as lower CO_2 emissions in the corridor.

TABLE 4.2. BRT CORRIDORS IN LAGOS

	Distance (km)	Cost/ km (US$, millions)	Total cost (US$, millions)
Phase 1: Pilot Corridor (2008)	22.0	1.7	37.4
Phase 2: Ikorodu Extension	13.5	7.4	99.9
Phase 3: Oshodi to Abule-Egba	27.0	4.4	118.8

4.1.3.5.2. Light rail

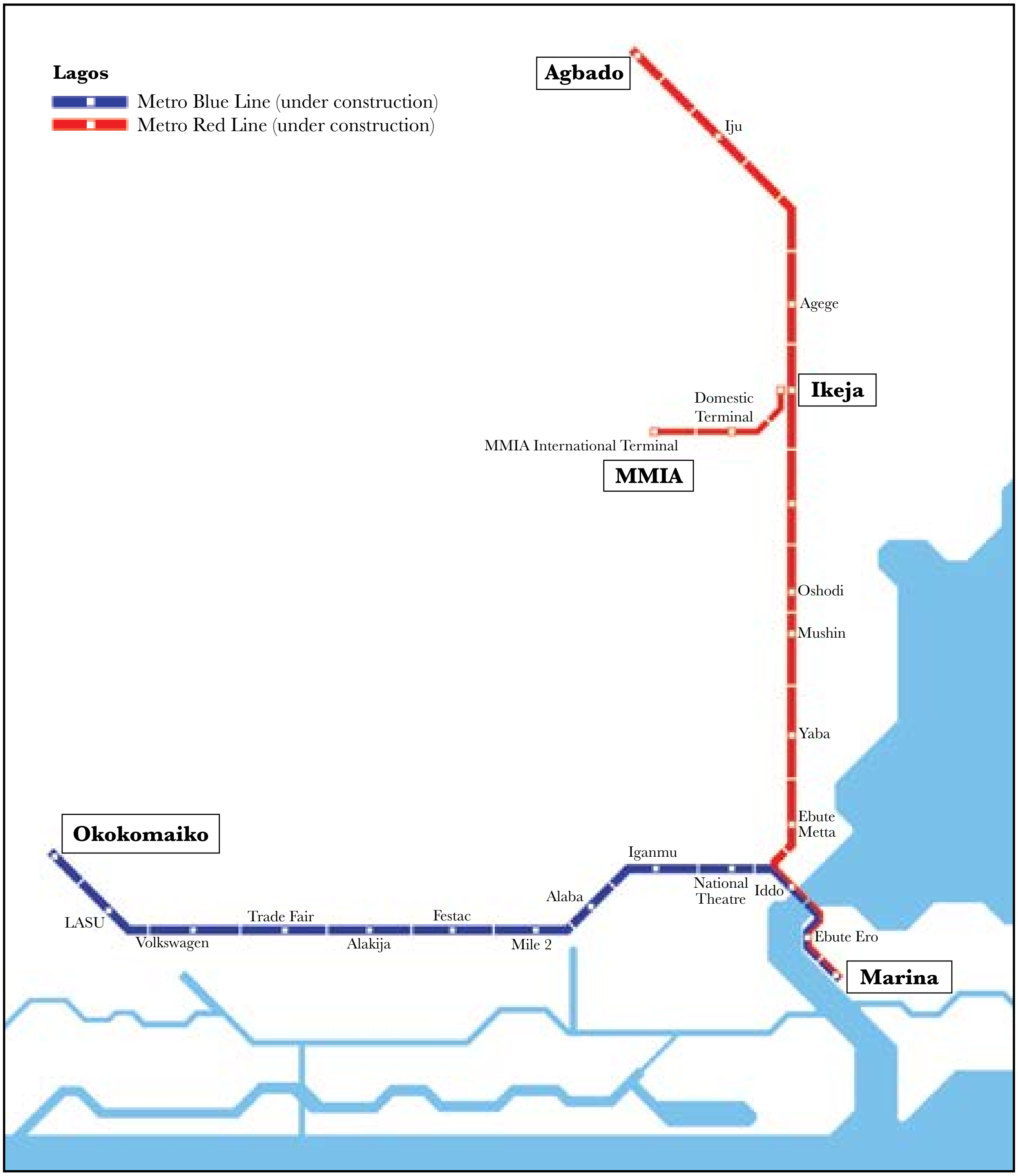
The construction of light rail in Lagos is meant to augment the public transit system, resulting in less private vehicle traffic and lower emissions per passenger-kilometer. The fact that Lagos has a relatively low amount of rail-based public transit compared to other global megacities implies that there is significant potential for expanding light rail in Lagos. For instance, Lagos has about 2 km of light rail per million residents compared to Beijing which has 29 km and London which has 49 km (Croitoru, Chang, and Kelly 2020). Two light-rail corridors (Figure 4.1) are to be the first lines in a passenger rail system in Lagos planned to ultimately include seven lines: blue, red, green, yellow, purple, brown, and orange.[16]

4.1.3.5.3. Public ferries

Given the proximity of Lagos to large inland waterways, ferries could provide an additional source of transport for commuters. Ferry service currently operates on Lagos Lagoon, connecting multiple locations with the commercial center on Lagos Island. Like the investments made for BRT and light rail, it is assumed that ferry service in Lagos could be expanded to help relieve road traffic.

It has recently been reported by Lagos State Ferry (LAGFERRY) that it has a mandate to move 30 percent of commuters. Currently, LAGFERRY operates 12-seater, 30-seater, and 50-seater boats. In its first year (beginning February 2020), LAGFERRY carried 524,000 passengers (or 1,435 trips per day) (The Guardian 2021).

FIGURE 4.1. LAGOS LIGHT RAIL: BLUE AND RED LINES[17]



Source: https://www.railway-technology.com/projects/lagosrailmasstransit/.

Private ferries carry considerably more passengers, with 67 private ferries carrying 6.5 million passengers in 2012, and 165 private ferry operators with a combined public and private tally of 18.8 million passengers (51,507 passengers per day) in 2016 (Lagos State Waterways Authority 2017).

4.1.3.6. FREIGHT TRANSPORT

Much of the container freight traffic for all of Nigeria flows through Apapa and Tin Can Island ports. The resulting diesel truck traffic is probably a major source of $PM_{2.5}$ and other emissions. The new Lagos-Ibadan railway began service in June 2021 and reportedly offers intermodal service from dockside in Apapa to the Inland Container Depot in Ibadan. The line will eventually extend to Kano in northern Nigeria. By diverting large numbers of heavy trucks from Lagos, this intermodal service could save greatly on fuel consumption and travel time while reducing GHG emissions and air pollution.

Further developments could be made by improving the management of local truck traffic to the ports. As Lagos is the economic and manufacturing hub of the country, a significant part of the container flow must be to and from locations in Lagos itself. This will continue to go by truck. In most ports, short-haul container delivery is the last resort for truck-tractors that are too old and unreliable for long-haul service. These trucks are often in poor condition, with high emissions. However, in California, the ports of Los Angeles and Long Beach have had success in limiting access to trucks that meet emission standards. Owner-operators of trucks that do not meet the standards have been provided with financial assistance to replace their old tractors. Apapa and Tin Can Island ports may wish to consider similar actions. Among other advantages, limiting access to only those trucks and drivers that meet standards could well improve safety and efficiency and reduce the need for congestion-causing checkpoints.

Measures to reduce emissions from other freight trucks must also be part of the solution to air pollution in Lagos. In parallel with measures to upgrade light-duty vehicles and buses, there needs to be an expanded program combining vehicle inspections, emissions certificates, fines and removal from service for noncompliance, and a guaranteed supply of clean diesel for heavy-duty trucks. This will require investments in newer trucks and in some cases the retrofitting of existing trucks with pollution controls such as catalysts and diesel particulate filters. California has had considerable success in mandating the retrofitting or replacement of older vehicles in diesel truck fleets. While costly for truck owners, the gains are also likely to be large given the high share of $PM_{2.5}$ emissions from diesel combustion. Although diesel fuel accounted for about 30 percent of petroleum product consumption in Lagos (IEA 2021) in 2020, compared to 65 percent for gasoline, $PM_{2.5}$ emissions from diesel fuel have been found to be 3–4 times higher than from gasoline (see Figure 2.8).

4.1.4. ELECTRICITY GENERATION

The electric power sector in Nigeria is expected to grow rapidly over the next 15 years to meet power demand, which has far outgrown the country's existing capacity. Current electricity consumption per capita in the country is extremely low by international standards. Currently, per capita electricity consumption in Nigeria is only 147 kWh, compared to the average for LMICs of 736 kWh and a global average of 3,298 (World Bank 2020). Nigeria's power sector is characterized by high technical and financial losses, and the current system cannot provide adequate electricity to the economy. As such, Nigeria has among the highest share of electricity provided by backup generators ("gensets") in the world. These generators are expensive to operate, noisy, and highly polluting. Long-term investment in power grid expansion and reliability will eventually reduce genset usage. Improvements to Nigeria's power sector are critical for the sustainability of the system and the economy.

By increasing the supply of electricity, economic losses would be reduced, while tariff revenues would increase, generating considerable income to pay for the reforms.

With the growth of the power sector, baseline emissions of both CO_2 and NO_x might be expected to rise (World Bank 2014). (Since the power plants almost exclusively use natural gas fuel, their $PM_{2.5}$ emission are negligible). However, meeting the commitment to achieving "net zero" emissions by 2050 (Lagos) and by 2060 (Nigeria) will require that most of the new power generation capacity be renewable—for example, wind and solar. Fortunately, the costs of wind and solar power generation have decreased considerably, to the point that they can be cost-competitive with thermal power plants in many locations. In the 2014 low-carbon study for Nigeria, the power sector was estimated to have the largest potential (48 percent of total reduction) among four large sectors (agriculture, forestry and other land use [AFOLU], Oil and Gas, and Transport) for the reduction of GHG emissions over the next 15 years (Cervigni et al. 2013).[18]

One step that could both reduce emissions and increase power output would be to retrofit the Egbin power plant for combined cycle operation. Presently, the plant uses natural gas-fired boilers to generate steam. Adding a gas turbine topping cycle could increase the overall plant efficiency, producing more power from nearly the same fuel input. By fitting these gas turbines with low NO_x burners, the NO_x output from the plant could also be reduced by 75 percent or more.

4.1.4.1. CONTROLLING EMISSIONS FROM BACKUP GENERATORS

Backup generators (gensets) may account for as much as 40 percent or 1,940 GWh of electricity generation in Lagos and a much greater share of pollutant emissions from power generation.[19] While total PM emissions from gensets are difficult to calculate, gensets represent one of least regulated sources of air pollution in Lagos. As noted earlier, improving the quality of diesel and gasoline suppled to Lagos would help reduce emissions from gensets. Currently there are no emissions standards for electricity gensets in Nigeria. As in other countries, the emissions from such generators should be regulated, requiring (a) improvements in fuel and (b) the installation of pollution-control equipment.

While improving the generating capacity and reliability of the electric grid would reduce the need for backup generators, this is at best a long-term goal. One approach in the short run could be to encourage the formation of "mini grids" based on standardized generating sets of a few hundred kW, each equipped with advanced emission controls (for example, US Tier 4 final or EU Stage V). Thus, instead of each family or business having its own 2 kW generator, a 100 such might be connected to a single 200 kW generator. This mini-grid would connect to the main grid through a single transfer switch. A single medium-size generator would be far more efficient than many small ones and would have much lower emissions. Such mini-grids could then be augmented by renewable sources such as solar photovoltaics, with the genset retained as backup.

4.1.5. INDUSTRY

Industry is one of the major contributors to air pollution in Lagos. While a large share of industry is located near Ikorodu, surveys of industry activity confirm that industries are located throughout the metropolitan area, including in the industrial zones of Apapa, Idumota, Ikeja, and Odogunyan. At the Odogunyan site, iron smelting is responsible for extremely high $PM_{2.5}$ concentrations as well as lead emissions (Kemper and Chaudhuri 2020). Industries located in densely populated parts of Lagos need to either control their emissions or relocate. Several such industries have moved in recent years, and the government has assisted in the relocation. The government's main role, however, is the monitoring and enforcement of air pollution standards, which may require automatic pollution-monitoring equipment at major industrial plants. Augmenting LASEPA's ability to perform such monitoring of industrial emissions is critical for their effective control. In general, if an industry is exceeding the emissions standard, it is up to LASEPA to enforce the standard and for the industry to remedy the situation through investments in cleaner fuel and/or pollution control equipment.

Improving fuel quality is one of the most effective ways of reducing air pollution from industrial facilities. Especially for small industries, for which baghouses or other expensive emissions control equipment is not feasible, upgrading fuel quality is the most cost-effective way to reduce air pollution. To the extent that firms can convert from polluting fuels such as fuel oil, diesel, and biomass to cleaner fuels such as electricity and natural gas, it may be possible for industries to remain in urban areas and not contribute significantly to air pollution. The conversion to cleaner fuels can greatly reduce industrial air pollution emissions and often allow industries to meet minimum pollution standards. Industry-wide investments in cleaner energy sources, such as solar photovoltaic on factory rooftops, could be an option for some types of industries that have modest energy requirements and are currently relying on dirty fuels.

The monitoring and enforcement of industrial emission standards, particularly for large and polluting industries such as metallurgy, chemicals, and cement, is important for ensuring that industries control their air pollution. At the same time, helping industries convert to cleaner technologies or fuels, through training and technical assistance, can be an important way for them to remain competitive and improve their productivity and profitability. Cleaner production is critical for the survival of many industries such as food processing or the information technology sector, which is why so many countries have established cleaner production programs for industry.

4.1.6. OTHER SOURCES

While the above analysis has focused on the four main sectors identified as responsible for air pollution ($PM_{2.5}$), there are other pollution sources in Lagos that can be reduced. Some sources can be reduced through a systematic program of cleaner fuels, which for petroleum products such as diesel and fuel oil could correspondingly lower genset and industrial emissions, and pollution from ships.

4.1.6.1. CROP RESIDUE BURNING

Recent studies using satellite imagery indicate severe air pollution ($PM_{2.5}$) associated with the burning of agricultural crop residues in Sub-Saharan Africa, including Nigeria (Hickman et al. 2021).[20] Given the high population density in Nigeria and Lagos State, air pollution from agricultural fires is a risk for human health. Field burning is most severe in Nigeria during the dry season (November–February), and preliminary air-quality monitoring data confirm significantly higher $PM_{2.5}$ levels during this period in Lagos. This is an area where pollution sources outside of Lagos State could be having a significant impact on air pollution, and thus measures to reduce field burning in surrounding areas, especially during the dry season, could be an important air quality measure.

4.1.6.2. COOKING FUELS

Another source of biomass burning in Lagos State is the combustion of charcoal and fuelwood for cooking (residential and commercial). Among low- to medium-income residential areas in Lagos, the use of LPG for cooking is not widespread, unlike kerosene and charcoal (Ozoh 2018).[21] LPG is preferred by most consumers in Lagos but is more costly than other fuels, including for the upfront purchase of the gas cylinder and the fuel (Emagbetere, Odia, and Oreko 2016). A consistent supply of LPG, along with subsidies for low-income consumers, could be effective in reducing PM emissions from solid fuels used for residential and commercial cooking.

4.1.6.3. PORT EMISSIONS

Lagos is home to some of the busiest ports in Africa, Apapa and Tin Can Island being the two largest.

Anecdotal evidence suggests that pollution from ships in Lagos is severe. Measures to reduce the fuel consumption and air pollution emissions associated with ships at port, such as through shore-based electrification, fuel standards, or alternative fuels, may be an effective way to reduce air pollution in Lagos (Sofiev et al. 2018; Winkel et al. 2016). The port authorities should also consider the feasibility of enforcing the limit of 0.5 percent sulfur in marine bunker fuel. Since Nigeria has no refineries, sales of marine HFO are probably limited but the port could take and analyze samples of the fuel on board.

A second source of emissions at the ports relates to the diesel trucks that pick up or drop off loads. Reportedly, as many as 5,000 high-polluting diesel trucks seek access to the ports every day, resulting in congestion and air pollution (Kemper and Chaudhuri 2020). Measures to deal with emissions from the thousands of diesel trucks could include investments in traffic management or systems for better loading and unloading.

4.1.6.4. ABATTOIRS

There are a reported 16 abattoirs (slaughterhouses) in Lagos that generate air and other pollutants associated with the processing of meat and hides and the disposal of animal wastes. Improving the management of abattoirs, as has been done at several state-run facilities, can reduce air pollution emissions. Investment in biogas production from animal wastes is one method that has been used to both reduce air pollution and generate energy for sale or self-use.

4.1.6.5. DUST

One of the major sources of air pollution identified through air quality monitoring—as much as 28 percent of total $PM_{2.5}$—is "dust." The sources of dust include resuspended particulates from unpaved roads, industrial pollution, and windblown soil and sand. Much of this dust may be due to traffic traveling on unpaved roads. While such dust could be assigned to the transport sector, the remedy involves paving roads, watering roads, or simply reducing the amount of traffic or enforcing speed limits on unpaved roads. Sustainable agricultural practices such as those that reduce deforestation or do not leave fields barren between crop seasons can help reduce the amount of windblown soil from agricultural land, while industrial practices that reduce overall pollution will also limit the amount of dust from industry.

4.2. NATIONAL ACTION PLAN TO REDUCE SHORT-LIVED CLIMATE POLLUTANTS

Many of the pollutants that contribute to urban air pollution are also short-lived GHGs. The progress in the implementation of the Federal Government's plan to reduce short-lived climate pollutants (Government of Nigeria 2018) forms part of Nigeria's NDC. Table 4.3 lists the 22 abatement measures included in that plan.

While the NAP applies to the rest of Nigeria as well as Lagos, there is considerable overlap between the planned abatement measures and those discussed in section 4.1. In the transport section, common measures include the renewal of the urban bus fleet in Lagos, introduction of low-sulfur diesel and petrol, elimination of high-emitting vehicles by means of I&M, and reduction of car-based vehicle trips through public transport. The measures proposed for the residential sector in the NAP are of little relevance to Lagos, as they have already been surpassed. Likewise, there is little oil and gas activity and relatively little agriculture in Lagos State so the NAP measures for those sectors have little relevance. Waste management and electric generation, however, are key sectors both for Lagos and the country at large, and the measures included in the NAP are consistent with those recommended here.

TABLE 4.3. ABATEMENT MEASURES IN THE NATIONAL ACTION PLAN (NAP) TO REDUCE SHORT-LIVED CLIMATE POLLUTANTS

Source Sector	SLCP Abatement Measures	Target
Transport	1. Renewal of urban bus fleet in Lagos 2. Adoption of CNG Buses in Nigeria 3. Introduction of low sulphur Diesel and Petrol 4. Elimination of high emitting vehicles that do not meet vehicle emission standards 5. Reduction of vehicle journey's by car through transport modal shifts	5000 new buses in Lagos complete and Danfo buses fully replaced by 2021 25% all Buses converted to CNG by 2030 50 ppm diesel fuel introduced in 2019; 150 ppm petrol introduced in 2021 Euro IV limits met by all vehicles by 2030 500, 000 daily journeys shifted from road to rail & waterways
Residential	6. Increase in population using modern fuels for cooking (LPG, electricity, kerosene, biogas, solar cookers) 7. Replacement of traditional biomass cookstoves with more efficient improved biomass stoves 8. Elimination of kerosene lamps	80% ofH/H using modern fuels for cooking in 2030 20%> H/H using improved biomass stoves for cooking in 2030 All kerosene lighting replaced by solar lamps by 2022
Oil & Gas	9. Elimination of gas faring 10. Fugitive emissions/lecikages Control 11. Methane Leakage Reduction	100%) of gas faring eliminated by 2020 50% Methane Reduction by 2030 50% Methane Reduction by 2030
Industry	12. Improved Energy' Efficiency in industrial Sector	50% improvement in energy' efficiency by 2050
Waste Management	13. Reduction of methane emissions and open burning of waste at open dumpsites through adoption of digesters at dump sites 14. Septic sludge collection 15. Sewerage Systems and Municipal wastewater treatment plants	50% methane recovered from landfills by 2030; 50% reduction in open burning of waste by 2030 Promote Septic sludge collection, treatment and recycling in 37 municipalities Establish, expand Sewerage Systems and municipal wastewater treatment plants in Lagos, Kami and Port Harcourt
Agriculture	16. Increased adoption of intermittent aeration of rice paddy fields (A WD) 17. Reduce open-field burning of crop residues. 18. Anaerobic Digestion (AD) 19. Reduce methane emissions from enteric fermentation	50% cultivated land adopt ABD management system by 2030 50% reduction in the fraction of crop residue burned infields by 2030 50% reduction by 2030 30% reduction in emission intensity bv 2030
Power [Energy]	20. Expansion of National Electricity Coverage 21. Increase share of electricity generated in Nigeria from renewables	90% of the Population have access to electricity grid by 2030 30% electricity generated using renewable energy in 2030
HFCs	22. Elimination of HFC Consumption.	10% of HFCs phased out by 2030, 50% by 2040 and 80% by 2045

Source: Government of Nigeria 2018

4.3. POLICIES AND INVESTMENTS TO IMPROVE AIR QUALITY

From the sectoral air quality interventions outlined earlier, it is possible to sketch out potential AQM scenarios for Lagos to progressively reduce ambient air pollution. Different combinations of policies and actions can be used to reduce $PM_{2.5}$ emissions. Table 4.4 contains a list of key air quality policies recommended for near-term implementation in Lagos based on measured pollution levels, assessed health impacts, readiness for implementation, and consistency with the NAP to Reduce Short-Lived Climate Pollutants.

4.3.1. COSTS OF AIR POLLUTION CONTROL

To assess the **cost** of potential air pollution control measures in Lagos, the financial and economic costs of selected interventions have been estimated, along with their potential to reduce air pollution (measured as avoided tons of $PM_{2.5}$ per year). While it has not been possible to undertake field visits and conduct detailed CBAs for all potential air quality projects in Lagos, a preliminary desk

TABLE 4.4. CLEAN AIR POLICIES FOR LAGOS

Sector	Policies and Actions
Solid Waste	• Solid waste collection strategy to raise the share collected • Recycling, composting, and WTE to reduce MSW landfilled • Ban on open burning of solid waste
Industry	• Monitoring and enforcement of industrial emissions • Clean fuel and “cleaner production” incentives
Transport	• Vehicle emissions testing and display of inspection certificates • Fines and cancellation of certificates of violators • Transition to Euro 3 and 4 vehicle standards
Fuel quality	• Clean fuel import strategy for both diesel and gasoline (Euro 4) • Guaranteed fuel quality among fuel distributors and retailers
Power	• Power sector reform • Genset emissions standards
Other	• LPG for residential and commercial cooking • Ban on field burning during the dry season • Paving, watering, and speed limits on unpaved roads
Administrative	• Installation of air quality monitoring stations • Creation of an air quality monitoring index and information system to alert vulnerable groups to hazardous air days • Installation of automatic pollution-monitoring equipment at major pollution sources (e.g., large industries).

Source: Author’s own elaboration

exercise was undertaken to estimate indicative costs for several high-priority interventions, using data from existing projects in Lagos and elsewhere.

Two sets of costs for reducing air pollution have been evaluated. ***Public costs*** include the building of public infrastructure such as landfills and roads, as well as public administrative costs such as pollution monitoring, regulation, and licensing. The costs of reducing emissions from vehicles, factories, or electric generators to comply with emission standards lie with the owners and are referred to as private ***compliance costs***. Where possible, the net cost (investment minus revenue) of public investments, regulatory costs, and compliance costs have been estimated for selected air quality measures.

The indicative costs of lowering $PM_{2.5}$ concentrations to reach WHO air quality targets have been estimated based on public and private costs. Although on-the-ground analysis of specific air pollution control measures in Lagos for this study was not carried out, available costs of similar interventions from Nigeria and elsewhere have been used. The following control measures account for around three-quarters of potential $PM_{2.5}$ emission reduction measures in Lagos. The cost assumptions for these measures are provided in annex 2.3.

- ***Solid waste burning.*** Control costs include the increased cost of collecting a growing share of MSW, based on private concessionaire costs for Lagos (Aliu et al. 2014). To accommodate the increased amount of MSW, the costs of additional landfills and recycling and composting are included.
- ***Road transport***. Control costs include the costs to upgrade vehicle fleets to Euro 3 and Euro 4 standards, plus the additional costs of cleaner gasoline and diesel.
- ***Industry.*** Control costs include the installation of emission-monitoring equipment on large industrial enterprises and the enforcement of emissions standards. The compliance costs for industrial enterprises have not been estimated.
- ***Electricity generation.*** Control costs include (a) the estimated costs needed to increase the supply and reliability of power from the grid to offset power supplied by backup generators ***or*** (b) the costs of emissions control for backup generators in Lagos.

Using the cost estimates and the health benefits outlined in chapter 3 (Table 3.3), it is possible to create scenarios for lowering air pollution in Lagos to meet WHO interim targets. The results are presented in Table 4.5.

TABLE 4.5. INDICATIVE COSTS AND BENEFITS OF REDUCING AIR POLLUTION

	Air pollution reduction scenarios			
Air quality target	**35 ug/m³**	**25 ug/m³**	**15 ug/m³**	**10 ug/m³**
Reduction in $PM_{2.5}$	−10.0	−20.0	−30.0	−35.0
Cost (public and private) – US$, millions	200–300	350–500	450–600	500–700
Reduction in total mortality	3,598–6,840	7,196–13,680	10,793–20,521	12,592–23,941
Reduction in infant mortality	1,829–3,468	3,657–6,936	5,486–10,404	6,400–12,138
Benefit of reduced mortality (VSL) – US$, millions	890–1,691	1,780–3,381	2,670–5,072	3,115–5,917
Benefit (VSL)/Cost ratio	3.0–8.4	3.6–9.7	4.5–11.3	4.5–11.8
Benefit of reduced mortality – HCA (US$, millions)	235–446	469–891	704–1,337	821–1,559
Benefit (HCA)/Cost ratio	0.8–2.2	0.9–2.5	1.2–3.0	1.2–2.3

Source: Author's own elaboration. See section A4 for cost assumptions.

4.4. FINANCING AIR QUALITY MANAGEMENT

An essential element for improving air quality in Lagos is to identify viable financing resources to support air pollution interventions. Based on discussions with both public and private officials in Lagos, an explicit AQM program in Lagos could be funded through a variety of financing sources, including the state capital budget, private sector interventions, multilateral support, and climate funds (Table 4.6).

Using internal and external resources, Lagos could mobilize and redirect resources between FY21 and FY26 to finance an air quality improvement plan. The LASG has announced plans to issue a green bond of N25 billion (US$60 million), which could be the centerpiece of a broader funding package for air quality that includes private investment, multilateral credit lines, and grant financing.

4.4.1. LASG BUDGET

The LASG has an active debt issuance program, with N100 billion (US$243 million) included in its 2021 appropriations budget. The issuance of a green bond is significantly different from issuing plain vanilla bonds. A key requirement for the issuance of a green bond is the provision of a second-party opinion (SPO), where, in addition to the financial analysis, investors will require a technical plan for meeting the environmental objectives of the project, in this case the lowering of air pollution. The current LASG budget is not well aligned with the priority areas for reducing $PM_{2.5}$ air pollution (Figure 4.2), which is understandable given that Lagos has many important economic and social issues to address. Based on "air quality" projects and activities in the current LASG budget (Table 4.7), a strategic program of policy and regulatory initiatives focused on a broader set of air pollution sources could be developed.

To better align the budget with air quality concerns, the LASG budget should focus on those policies most important to reduce air pollution, expanding beyond public transport to other priority sectors, such as solid waste and power. Priority areas for AQM have been identified in THEMES, an acronym for Lagos' current administration's development agenda that includes projects in transport, health, and the environment.

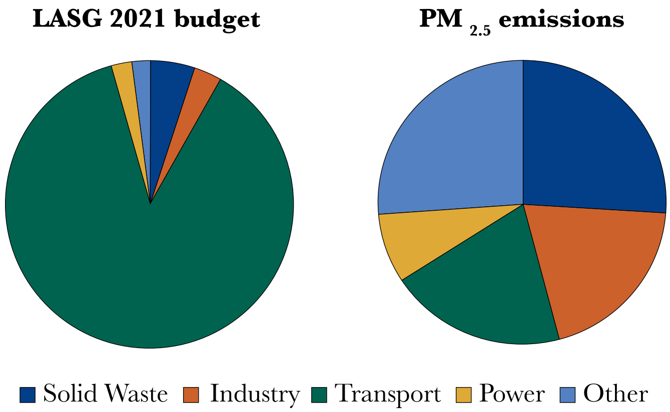
4.4.2. PRIVATE FUNDING

The global market for issuance of green bonds continues to expand (Figure 4.3) and country commitments from COP26 will likely expand those related to climate and air quality. As of 2020, domestic financial institutions had a total of N16 trillion (US$39 billion) in short-term instruments. The local pension funds had over N12 trillion

TABLE 4.6. POSSIBLE FUNDING SOURCES FOR AQM IN LAGOS

Lagos State Budget	The LASG budget is currently financing projects that address air pollution and could be strategically realigned to make a larger contribution to both climate and air quality goals.
Green Bonds	Worldwide, the issuance of environmental finance products continues to grow annually. Lagos' recent announcement of plans to issue a green bond is evidence of the trend. See Figure 4.
Multilateral Lines	Bilateral and Multilateral Development Banks (MDBs) have supported projects that address air pollution, including in areas such as solid waste management, power, and transport.
Climate Funds	Climate funds are available that can support air quality interventions. For example, the World Bank Group's Climate Business Plan has targets and funding commitments within the sectors identified as principal contributors to air pollution in Lagos.

FIGURE 4.2. LASG SECTOR BUDGET COMPARED TO AIR POLLUTION



Source: Own elaboration.

(US$29 billion), with a significant share of those resources invested in green bonds. By being able to develop and design green projects and interventions, the LASG can put itself in a position to access some of these resources through dialogue with the private sector.

4.4.3. MULTILATERAL SUPPORT

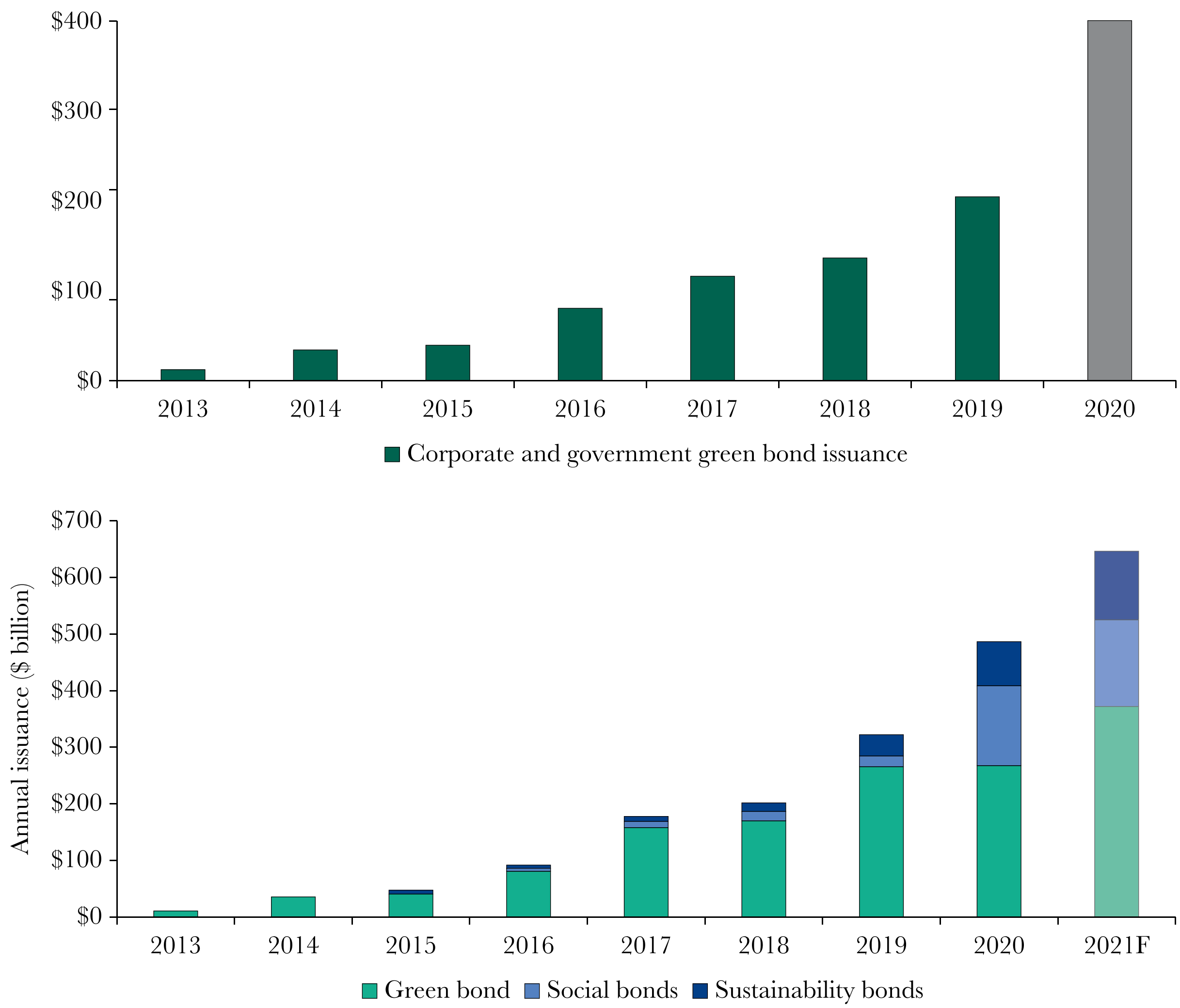
Multilateral development banks (MDBs) have provided financing for interventions to address air pollution from all the key contributing sectors, including solid waste, transport, and power. Although air quality has not been the primary motivation for such projects in Africa, this study demonstrates the seriousness of the problem and could be

TABLE 4.7. "AIR QUALITY" PROJECTS IN THE LASG 2021 BUDGET

WASTE	
Lagos Waste Management Authority (LAWMA)	Reconstruction and upgrading of three solid waste transfer stations.
	Construction of new landfill.
INDUSTRY	
Ministry of Agriculture	Relocation of sawmill from Oko baba to Agbowa timber village.
TRANSPORT	
Lagos Metropolitan Area Transit Authority (LAMATA)	Bus Rapid Transit. High-speed buses operating in segregated lanes.
	2,000 buses to transport passengers from Oshodi to Abuie Egba.
	Completion of 27 km blue line from Okoko to Marina.
	Phase 1 construction of 27 km red line from Agbado to Marina.
	Bike share program.
LAGFERRY	Passenger transport by ferries displacing private road vehicles.
POWER	
Ministry of Energy and Mineral Resources	Light-Up Lagos
	Expansion of LPG in two government estates.
	High-tension power lines, including pilot solar project for hospitals.
	Installation of electricity meters.
OTHER	
LASEPA	Installation of 8 air quality monitoring stations across Lagos State.

Source: Lagos State Ministry of Economic Planning and Budget

FIGURE 4.3. GLOBAL GREEN BOND MARKET



Source: Bloomberg.

the basis of developing an air quality program. Projects specifically related to air quality improvement have been developed by MDBs, and have included sector financing as well as pollution-monitoring equipment and technical assistance for effective AQM (Croitoru, Chang and Kelly 2020). The World Bank has financed numerous air quality improvement projects, including a recent project in Cairo. The financing of environmental improvement has sometimes been through performance-based programs, where financing is provided as pollution-reduction targets are met (World Bank 2016a). The World Bank's "Program-for-Results (PforR)" instrument has been used for social, health, and environment projects. In China, a PforR was developed specifically to address air pollution control in the northern Jing-Jin-Ji Region. Lagos would be an excellent candidate to develop an AQM program with multilateral and bilateral support.

4.4.4. CLIMATE FUNDS

A future AQM plan for Lagos should link with its Climate Action Plan (Lagos State Government 2021) and Nigeria's NDC to mobilize resources. COP26 has created a renewed interest in mobilizing private sector resources toward the US$100 billion per year commitment by developed countries to address climate-related issues.

Leveraging **the Lagos Climate Action Plan.** The Lagos Climate Action Plan targets interventions in sectors that are major contributors to air pollution (Box 4.3). Additional data on baseline numbers and reductions in $PM_{2.5}$ emissions would be needed to list the actions in the financing plan.

Leveraging Nigeria's NDCs. Under the United Nations Framework Convention on Climate Change (UNFCCC), Nigeria has set targets that align with the sectors responsible for air pollution in Lagos. Most of the priority actions for air quality outlined in this chapter are included in Nigeria's NDC (Box 4.4).

4.4.5. SUMMARY OF FUNDING FOR AQM

The amount of funding that is available to address air quality appears well within the reach of Lagos. Table 4.8 provides a 5-year perspective on such a plan that includes green bonds, plain vanilla bonds, multilateral credit lines, and access to grants through climate funds.

Table 4.9 provides a summary of the potential size of such a 5-year program. It could mobilize resources of up to US$1.29 billion (N537 billion) for the state with an increase in the green component of its financial mix. Being able to achieve this mix could likely incentivize access to multilateral lines of US$299 million as well as climate funds of US$190 million.

BOX 4.3. LAGOS CLIMATE ACTION PLAN, 2020–2025

The five-year plan aims to put Lagos on a pathway to zero carbon by 2050, enhance the climate resilience of the city and its population and to maximize the co-benefits of climate action, such as greener and healthier lifestyles. It was developed through a stakeholder engagement process, that allowed the plan to gain broad buy-in from business, civil society and the wider public. The plan envisages a range of actions to reduce GHG emissions in each section, including:

Transport

- Expansion of the BRT network in Lagos.
- Spatial planning to promote transit-oriented development.
- Encourage the uptake of low-emission vehicles.
- Encourage the shift of freight from road to rail.

Energy

- Installing solar PV systems on all schools, hospitals and municipal buildings.
- Reduce emissions in the residential sector by promoting the development of energy storage technologies and incentivizing the deployment of micro-grids in off-grid urban communities.

Waste

- Divert organic waste from landfill by encouraging separation at source and introducing composting technologies.
- Implement composting, waste-to-energy and other waste recovery initiatives in underserved communities.

BOX 4.4. NIGERIA NDC TARGETS AND AIR QUALITY

Sector	Measure
Residential	48 % of population (26.8 million households) using LPG and 13 % (7.3 million households) using improved cookstoves by 2030 Elimination of kerosene lighting by 2030
Energy efficiency	2.5% per year reduction in energy intensity across all sectors
Transport	100,000 extra buses by 2030 Bus Rapid Transport (BRT) will account for 22.1 % of passenger-km by 2035 25 % of trucks and buses using CNG by 2030 All vehicles meet EURO lllemission limits by 2023 and EURO IV by 2030
Electricity generation	30 % of on-grid electricity from renewables (12 GW additional large hydro, 3.5 GW small hydro, 6.5 GW Solar PV, 3.2 GW wind) 13 GW off grid renewable energy (i.e., mini-grids 5.3 GW, Solar Home Systems and street lights 2.7 GW, self-generation 5 GW) Reduce grid transmission and distribution losses to 8% of final consumption of electricity in 2030, down from 15% in 2018. 100% of diesel and single cycle steam turbines replaced with combined cycle Elimination of diesel and gasoline generators for electricity generation by 2030
Oil and gas	Zero gas flaring by 2030 60% reduction in fugitive methane emissions by 2031

TABLE 4.8. FIVE-YEAR AQM FINANCING SCENARIOS

	Program Funding Components									
	2021		2022		2023		2024		2025	
	Allocation (%)	N'B	Allocation (%)	N'B	Allocation (%)	N'B	Allocation (%)	N'B	Allocation (%)	N'B
Borrowing Plan		**100.0**		**125.0**		**125.0**		**130.0**		**140.0**
Multilateral Lines	0.0%	–	25.0%	31.3	30.0%	37.5	30.0%	37.5	30.0%	37.5
Green Bond Issuance	25.0%	25.0	30.0%	30.0	30.0%	30.0	30.0%	30.0	30.0%	30.0
Grant Funding (climate funds)	0.0%	–	0.0%	18.8	0.0%	17.5	0.0%	22.5	0.0%	32.5
LASG Vanilla Bonds	75.0%	75.0	45.0%	45.0	40.0%	40.0	40.0%	40.0	40.0%	40.0

TABLE 4.9. SUMMARY OF POSSIBLE FUNDING INSTRUMENTS TO SUPPORT AIR QUALITY

	Naira (millions)	US$ (millions)
Multilateral credit	143,750	299
Green bond issuance	145,000	302
Grant funding (climate funds)	91,250	190
LASG vanilla bonds	240,000	500
Total	620,000	1,292

REFERENCES

Emagbetere, E., J. Odia, and B. U. Oreko. 2016. "Assessment of Household Energy Utilized for Cooking in Ikeja, Lagos State, Nigeria." *Nigerian Journal of Technology* 35(4): 796–804.

Croitoru, L., J. C. Chang, and A. Kelly. 2020. "The Cost of Air Pollution in Lagos." Washington, DC: World Bank. https://openknowledge.worldbank.org/handle/10986/33038.

Faiz, Asif, Michael Walsh, and Christopher Weaver. 1996. *Air Pollution from Motor Vehicles: Standards and Technologies for Controlling Emissions*. World Bank Press.

Government of Nigeria. 2018. "Nigeria's National Action Plan (NAP) to Reduce Short-Lived Climate Pollutants (SLCPs)." https://www.ccacoalition.org/en/file/6146/download?token=B6o6HXOt.

Gorham, R., B. Eijbergen, and A. Kumar. 2017. "Urban Transport: Lagos Shows Africa the Way Forward (again)." Transport for Development. *World Bank Blogs*. https://blogs.worldbank.org/transport/urban-transport-lagos-shows-africa-way-forward-again.

The Guardian. 2021. "Lagos Revamps Water Transport with High-Capacity Boats." July 9. https://guardian.ng/features/travel/lagos-revamps-water-transport-with-high-capacity-boats/.

Gwilliam, Ken, Masami Kojima, and Todd Johnson. 2004. *Reducing Air Pollution from Urban Transport*. ESMAP/World Bank. https://esmap.org/node/1145.

Hickman, Jonathan E., Niels Andela, Kostas Tsigaridis, Corinne Galy-Lacaux, Money Ossohou, and Susanne E. Bauer. 2021. "Reductions in NO2 Burden over North Equatorial Africa from Decline in Biomass Burning In Spite of Growing Fossil Fuel Use, 2005 to 2017." *Proceedings from the National Academy of Sciences (PNAS)* 118 (7): e2002579118. https://doi.org/10.1073/pnas.2002579118.

IEA (International Energy Agency). 2021. *Nigeria Energy Outlook*. https://www.iea.org/articles/nigeria-energy-outlook.

Jambeck, Jenna, Britta Denise Hardesty, Amy L. Brooks, Tessa Friend, Kristian Telecki, Joan Fabres, Yannick Beaudoin, et al. 2018. "Challenges and Emerging Solutions to the Land-Based Plastic Waste Issue in Africa." *Marine Policy* 96:256–63. https://www.sciencedirect.com/science/article/pii/S0308597X17305286.

Kemper, K., and S. Chaudhuri. 2020. "Air Pollution: A Silent Killer in Lagos." *World Bank Blogs* https://blogs.worldbank.org/africacan/air-pollution-silent-killer-lagos.

Krzyzanowski, K.-D., Birgit Kuna-Dibbert, and Jürgen Schneider. 2005. *Health Effects of Transport-Related Air Pollution*. World Health Organization (WHO). https://www.euro.who.int/__data/assets/pdf_file/0006/74715/e86650.pdf.

Lagos State Waterways Authority. 2017. "Lagos Transport Statistics."

Lagos State Government. 2021. *Second Five-Year Climate Action Plan: 2020–2025*. https://cdn.locomotive.works/sites/5ab410c8a2f42204838f797e/content_entry5ab410faa2f42204838f7990/5ad0ab8e74c4837def5d27aa/files/C40_Lagos_Final_CAP.pdf?1626096978#:~:text=In%202018%2C%20Lagos%20State%20signed,achieving%20carbon%20neutrality%20by%202050.

Mobereola, D. 2009. Africa's First Bus Rapid Transit Scheme: The Lagos BRT-Lite System. Sub-Saharan Africa Transport Policy Program, September 2009. https://documents1.worldbank.org/curated/en/874551467990345646/pdf/534970NWP0DP0910Box345611B01PUBLIC1.pdf

Mufson, S., and S. Kaplan. 2021. "A Lesson in Electric School Buses." *Washington Post*, February 24, 2021. https://www.washingtonpost.com/climate-solutions/2021/02/24/climate-solutions-electric-schoolbuses/.

Omorogbe, Paul. 2021. "Waste-To-Energy Facility: British High Commission, Lagos State Environment Officials on Site Visit." *Nigerian Tribune*, February 14, 2021. https://tribuneonlineng.com/waste-to-energy-facility-british-high-commission-lagos-state-environment-officials-on-site-visit/.

Ozoh, O. B., T. J. Okwor, O. Adetona, A. O. Akinkugbe, C. E. Amadi, C. Esezobor, O. O. Adeyeye, O. Ojo, V. N. Nwude, and K. Mortimer. 2018. "Cooking Fuels in Lagos, Nigeria: Factors Associated with Household Choice of Kerosene or Liquefied Petroleum Gas (LPG)." *Int. J. Environ. Res. Public Health* 15:641. https://doi.org/10.3390/ijerph15040641.

Salau, O., L. Sen, S. Osho, and O. Adejonwo. 2016. "Empirical Investigation of Formal and Informal Sectors in Waste Recycling of the Municipal Waste Management System of Developing Countries: The Case Study of Lagos State." *Journal of Environment and Ecology* 7 (2): 21. https://www.macrothink.org/journal/index.php/jee/article/view/10007.

Schipper, L., J. Guy, M. Balam, N. Kete, J. Mooney, B. Bertelsen, D. Noriega, and C. Weaver. 2006. "Cleaner Buses for Mexico City, Mexico: From Talk to Reality. Transportation Research Record." 1987 (1): 62–72. doi:10.1177/0361198106198700107.

Shah, Jitu, ed. 2003. *Thailand: Reducing Emissions from Motorcycles in Bangkok*. ESMAP/World Bank. https://documents1.worldbank.org/curated/en/908081468782070640/pdf/ESM2750Thailan1ng0Emissions1Bangkok.pdf.

Sofiev, M., J. Winebrake, L. Johansson, E. Carr, M. Prank, J. Soares, J. Vira, R. Kouznetsov, K.-P. Jalkanen, and J. Corbett. 2018. "Cleaner Fuels for Ships Provide Public Health Benefits with Climate Tradeoffs." *Nature Communications* 9 (1): 406. https://doi.org/10.1038/ s41467-017-02774-9.

UNEP (United Nations Environment Programme). 2020. "West African Ministers Adopt Cleaner Fuels and Vehicle Standards." February 20. https://www.unep.org/news-and-stories/story/west-african-ministers-adopt-cleaner-fuels-and-vehicles-standards.

Winkel, R., U. Weddige, D. Johnsen, V. Hoen, and S. Papaefthimiou. 2016. "Shore Side Electricity in Europe: Potential and Environmental Benefits." *Energy Policy* 88:584–93. https://www.sciencedirect.com/science/ article/pii/S0301421515300240.

World Bank. 2010. "EarthCare Solid Waste Composting Project (Carbon Finance)." Project Identification Document. https://documents1.worldbank.org/curated/en/597581468298478449/pdf/533460ISDS0FAX10Box345607B01PUBLIC1.pdf.

World Bank. 2013. "Lagos Urban Transport Project (LUTP). Independent Evaluation Group (IEG)." Implementation Completion Review (ICR).

World Bank. 2014. *Diesel Power Generation: Inventories and Black Carbon Emissions in Nigeria*. Washington, DC: World Bank. https://openknowledge.worldbank.org/handle/10986/28419.

World Bank. 2016a. *Innovative Financing for Air Pollution Control in Jing-Jin-Ji*. https://projects.worldbank.org/en/projects-operations/project-detail/P154669.

World Bank. 2016b. *Sustainable Financing and Policy Models for Municipal Composting*. Urban Development Series Knowledge Papers. https://documents1.worldbank.org/curated/en/529431489572977398/pdf/113487-WP-compostingnoweb-24-PUBLIC.pdf.

World Bank. 2020. *Nigeria – Power Sector Recovery Operation (English)*. Washington, DC: World Bank http://documents.worldbank.org/curated/en/991581593223433078/Nigeria-Power-Sector-Recovery-Operation.

CHAPTER 5
LAWS, REGULATIONS, AND INSTITUTIONAL CAPACITY

A study has been conducted as part of the Lagos PMEH to describe and analyze the regulatory and institutional arrangements for air quality and pollution control objectives in Lagos State in relation to Nigeria's national framework. The outcome of this study, as presented in this chapter, reveals the deficiencies in the legal, regulatory, and institutional frameworks for air quality that currently exist at both the federal and Lagos State levels. Having adopted the national regulations operated by National Environmental Standards and Regulations Enforcement Agency (NESREA), the Lagos State framework operated by LASEPA inherits the federal-level regulatory deficiencies.

Key challenges to air quality governance in Nigeria and Lagos State include the lack of a unified regulatory framework, inadequate and ineffective regulations, deficiencies in the technical and enforcement capacity of regulatory bodies, and budgetary constraints. We therefore make recommendations to strengthen existing legislation and regulations, establish a scientific basis for deriving air quality and emission standards, strengthen the technical capacity of relevant institutions to undertake air quality monitoring and health impact assessments, strengthen the enforcement capacity of regulatory institutions, and ensure adequate funding for the relevant institutions to establish monitoring stations and build other necessary capacity.

5.1. NIGERIAN LEGAL AND REGULATORY FRAMEWORK

The Federal Constitution of Nigeria allows the federal, state, and local governments to legislate with respect to pollution (Suleiman et al. 2017). At the federal level, the key legislation is the 2007 NESREA Act, which established NESREA as the agency under the FMEnv responsible for setting and enforcing environmental regulations,[1] except for the petroleum industry. Another important law is the 1996 Petroleum Act,[2] which assigned responsibility to the Federal Ministry of Petroleum Resources (FMPR) for setting and enforcing the Environmental Guidelines and Standards for the Petroleum Industry in Nigeria (EGASPIN). Also significant is the Environmental Impact Assessment Act of 1992, the scope of which covers any project undertaken by the government (at any level), or which requires a government license or permit, and which could have a significant impact on the environment.

Of potential significance for air quality are directives C/Dir.1/09/20 and C/Dir.2/09/20, of the Commission of the ECOWAS, to set a common fuel sulfur standard for ECOWAS of 50 ppm by weight for both diesel and gasoline fuels, and to establish Euro 4 and Euro 6 emission standards for light-duty vehicles and Euro 6 standards for heavy-duty vehicles, respectively. The directives lay down more stringent standards for motorcycles and tricycles and call for the emission standards to apply to newly imported vehicles—whether new or used—from January 1, 2021. Euro 4 emission standards would apply to both light- and heavy-duty vehicles that are in the *existing* vehicle fleet from January 1, 2025. To date, it does not appear that either directive has been implemented in Nigeria.

5.1.1. EXISTING NATIONAL REGULATIONS ON AIR QUALITY

5.1.1.1. NON-OIL AND GAS REGULATIONS—NESREA ACT

The 2014 Air Quality Control Regulations (Air Regulations) set provisions for the maximum permissible limit values for six criteria pollutants, excluding $PM_{2.5}$. Standards for some pollutants exceed the WHO guidelines threefold. Moreover, the standards do not set limits for population exposure, and it is unclear if their definition was based on scientific country-level studies. Under the Air Regulations, stationary sources and facilities must submit annual emissions reports. However, the emission limits for different source categories—combustion of fossil fuel, industrial operations such as paint manufacturing, textile, quarries—lack clarity, and there is no guidance on the methodologies and protocols to calculate emissions from various sources, such as emissions factors for different emission sources (Ukeh 2021).

The 2011 National Environment Control of Vehicular Emissions from Petrol and Diesel Engines Regulations (Vehicle Emissions Regulations) are aimed at reducing and preventing air pollution from automobiles. The regulations also make provision for citizens' right to clean air and for the improvement of the health of Nigerians, especially in urban settings with high incidences of air pollution caused by the increased number of automobiles. The regulations set standards for specific pollutants for different on-road vehicles manufactured after certain years. However, the implementation of this regulation has run into multiple obstacles, including enforcement of the ban placed on importing two-stroke engines, prohibition of vehicles that do not comply with emissions-reduction technologies, and conducting of annual testing of vehicles for gas emissions (Center for Science and Environment 2013; Ukeh 2021).

The 2009 Permitting and Licensing System Regulations set provisions for the issuance of environmental permits to operators of stationary sources. However, the regulation is not specific on the nature or type of permit, lacks clarity about which phase of the construction or operation of a facility a permit is required, and offers no guidance to prepare and submit an application. Additionally, the few permit requirements in the regulations—such as how to quantify a facility's emissions footprint to determine the type and nature of air permit required, protocols to adopt in determining a facility's emissions footprint, and emissions stack requirements—are not science-based. Moreover, the terms of the permit are vague and unrealistic. Most regulated entities are therefore not motivated or incentivized to prepare and submit air pollution permits. NESREA does not currently implement auditing, monitoring, and evaluation of performance to ensure compliance with permits. Unfortunately, the regulators lack the financial, technical, and human resource capacities to effectively enforce compliance with the permit conditions (Ukeh 2021).

Other regulations under the NESREA Act that have implications for air quality and emissions produced by other mobile and stationary sources are the Pollution Abatement in Industries and Facilities producing Waste Regulations, the Ozone Layer Protection Regulations, and Regulations for Sanitation and Waste Control, and for Energy and Industry. The 2011 Control of Bush or Forest Fire and Open Burning Regulations were enacted to minimize and prevent the destruction of the natural ecosystem owing to fire outbreaks and uncontrolled burning of materials that may affect human health and the environment because of emissions of hazardous and criteria air pollutants.

Despite the existing legal framework, there are increasing environmental problems and air pollution in Nigeria, which are largely due to the lack of compliance with environmental laws. NESREA currently does not have the capacity to monitor pollution or engage in technical discussions with regulated entities to gather the information needed to establish adequate standards, which compels the agency to adopt regulations without knowing emissions levels or existing technologies (Suleiman et al. 2017). The compliance requirements set by the legal and regulatory framework are emphatic about enforcement for noncompliance but not clear about how regulated entities should realistically go about demonstrating compliance, nor about the pathway or timeline to demonstrate compliance. In addition, penalties are rarely calculated and imposed on violators because the regulators lack the resources. In general, enforcement actions are often implemented without proof of violation (Ukeh 2021).

5.1.1.2. OIL AND GAS REGULATIONS—PETROLEUM ACT

Under the 1969 Petroleum Act, the FMPR issued the EGASPIN in 1991, which was revised in 2002, 2016, and 2018. The EGASPIN is operated by the Department of Petroleum Resources (DPR).[3] The EGASPIN establishes robust environmental standards and requirements to be met by operators during project approval, operations, closure, or decommissioning phases (Olawuyi and Tubodenyefa 2018). In relation to air emissions, the EGASPIN sets requirements regarding gaseous point-source emissions, which include their estimation, registration, inventories, the installation of equipment to reduce or prevent them, the implementation of air quality and emissions-monitoring programs, and the installation of appropriate sampling points.

Fuel standards are established through the Nigerian Industrial Standards (NIS) issued by the Standards Organization of Nigeria (SON). In 2003, Nigeria phased out leaded gasoline. In 2017, the Nigerian Industrial Standard for Petroleum Products established a low-sulfur policy through NIS No. 116 and 949. The maximum permissible sulfur content in diesel was set at 50 ppm, 150 ppm for gasoline, and 150 ppm for kerosene. Currently, these standards lack government approval and implementation (Croitoru, Chang and Kelly 2020). In 2020 as part of a high-level meeting of the ECOWAS, Nigeria agreed to set regulations for cleaner fuels and vehicles to permit a maximum of 50 ppm sulfur content for gasoline and diesel by 2021, a minimum of Euro 4 vehicle emissions standard for all vehicles imported, and a plan to improve vehicle efficiency for all vehicles imported (UNEP 2020). The government had committed to adopting such standards by 2020, but the deadline, which was extended to 2021, was not met (SDN 2022). Currently, no specific date has been set. In summary, despite the existence of official standards and formal commitments, fuel quality in Nigeria continues to be poor compared to other African countries, even as the importation of dirty fuels continues (Croitoru, Chang and Kelly 2020).

5.1.1.3. ADDITIONAL ACTS

There are additional acts that also aim at controlling atmospheric and other types of pollution in Nigeria. The Harmful Waste Act prohibits, without lawful authority, the carrying, dumping, or depositing of harmful waste in the air. The Environment Impact Assessment Act details the procedures and sectors required to perform environment impact assessments of potential negative impacts to the environment, including air resources. The Environmental Impact Assessment Act is relevant to assessing the environmental impacts of the oil and gas sector and controls its air emissions.

5.1.1.4. INTERNATIONAL AGREEMENTS

Nigeria is a signatory of multilateral agreements for environmental protection and pollution control. Nigeria ratified the Vienna Convention (1987)[4] and the Montreal Protocol (1988)[5] to protect the O_3 layer, and the Stockholm Convention (2003)[6] that regulates persistent organic pollutants (POPs). Regarding GHGs, Nigeria ratified the Kyoto Protocol (2000) and the Paris Agreement (2016). In 2015, Nigeria submitted an NDC in the form of an unconditional contribution of 20 percent below business-as-usual levels, and a 45 percent contribution conditional on international support by 2030. The government submitted an updated NDC in June 2021 with unconditional contribution still at 20 percent below business as usual, but a slightly more ambitious conditional contribution of 47 percent, with the addition of two new sectors (waste and water) to the existing five: AFOLU, Energy, Oil and Gas, Industry, and Transport. The enhanced NDC will cover short-lived pollutants, including black carbon, an air pollutant with a high incidence of morbidity and premature mortality (Federal Government of Nigeria 2021).

5.1.2. NATIONAL STRATEGIC VISION FOR AQM

Nigeria does not have a stand-alone policy or strategy on pollution control and AQM. However, it has the National Environmental Policy (NEP) of 2016, which sets out the Federal Government's vision for AQM. The NEP contains several policy statements that express the intention of the Federal Government to improve air and atmospheric resources institutional arrangements, strengthen guidelines and standards, enhance enforcement capacity, improve monitoring of emissions, and promote efficient transport systems (Federal Ministry of Environment 2016). However, NEP policy statements lack specific targets, sector abatement measures, responsible parties, timelines, and funding sources. No information was found on the level of implementation of NEP's policy statement.

Nigeria has a comprehensive NAP to Reduce Short-Lived Climate Pollutants covering important air criteria pollutants. In 2019, after a 2-year consultation process, the country's National Council of Ministers approved a cross-sector action plan to reduce short-lived climate pollutants (NAP-SLP). The plan identifies emissions levels and sources for $PM_{2.5}$, SO_2, NO_x, and CO and other air and climate pollutants, and prioritizes 22 abatement measures based on economic and engineering modeling. The plan introduces specific emissions reductions and sector policy targets and is associated with achieving emissions reductions of between 58 and 78 percent for $PM_{2.5}$, SO_2, NO_x, and CO by 2030, if the plan were implemented (Federal Government of Nigeria 2018). The adoption of this action plan elevated the importance of tackling air pollution at the national level. The implementation of the NAP-SLP is coordinated by FMEnv's Climate Change Department. However, because the action plan includes targets and sectoral actions for the reduction of atmospheric pollutants, it is unclear if such policy actions should be headed by the Climate Change unit or the Pollution Control and Environmental Health (PCEH) unit.[7]

5.1.3. FEDERAL INSTITUTIONS

5.1.3.1. FEDERAL MINISTRY OF ENVIRONMENT

The FMEnv leads the governance architecture for the protection of the environment in Nigeria. The ministry administers environmental law and policy and shoulders a key responsibility—to ensure that environmental matters are adequately mainstreamed into all developmental activities in the country. The ministry's mandate was further strengthened by an NAP for the Promotion of Human Rights. NAP recognizes Nigerians' collective rights to a safe, healthy, and ecologically sustainable environment for the present and future generations (Ukeh 2021). However, the ministry does not have a strategic approach to the regulation-making process, or the technical and financial capacity to adopt other policy instruments to guide the country's efforts to improve air quality. In 2021, the FMEnv had allocations corresponding to 0.34 percent of the total budget appropriations act.[8] Air quality does not seem to be a priority within the FMEnv's budget. For example, in 2021 only N33 million (approximately US$8,000) was allocated to air quality monitoring equipment and studies on air pollution.[9] The FMEnv and other ministries, departments and agencies (MDAs) rely heavily on intervention funds from multilateral and bilateral development institutions to battle both short-lived and long-lived air pollutants (Ukeh 2021).

The FMEnv leads a comprehensive set of departments, institutions, and regional offices. The ministry is made up of six technical departments, which include PCEH and Climate Change departments, and seven regulatory agencies, which include NESREA and the National Oil Spill Detection and Response Agency (NOSDRA). The ministry is structured into six zonal operational offices and 36 state-level field offices. The state zonal offices work in partnership with and provide operational guidance to their respective state ministries of environment (Ukeh 2021).

5.1.3.2. NESREA

NESREA has a series of policy instruments to implement environmental policy and air pollution control, composed mainly of enforcement instruments. The NESREA Act empowers the agency with multiple instruments to enforce environmental law. The agency has the power to perform inspections and searches, forbid polluting equipment, issue enforcement notices, establish mobile courts, conduct public investigations, and prosecute and take legal action against citizens or companies violating the law. The NESREA Act has been discussed in Section 5.1.1.1.

5.1.3.3. NOSDRA

NOSDRA is responsible for surveillance and compliance assurance for all existing environmental legislation and regulations in the oil and gas sector. The National Oil Spill Detection and Response Agency Act of 2006 did not give any specific role to the agency with respect to AQM in the oil and gas sector.[10] In 2018, an amendment to the NOSDRA Act was passed by the Nigerian Senate Committee on Environment. Based on a 2018 report of the Senate Committee on Environment, *A Bill for an Act to Amend the National Oil Spill Detection and Response Agency, Act 2006 and for Other Matters Connected Therewith (SB557)*,[11] changes proposed to the functions of NOSDRA which could potentially give the agency jurisdiction for AQM were excluded from the final amended bill. The exclusion suggests that the functions of NOSDRA are intended to be limited to pollution from oil spillage, but not gaseous emissions. Based on this, the roles NOSDRA will play in regulating air quality matters in the oil and gas industry remain unclear when the 2018 NOSDRA Amendment Bill is eventually signed into law.

5.1.3.4. NIMET

The Nigeria Meteorological Agency (NIMET) is involved in air pollution monitoring and currently pursues objectives related to air quality analysis and policy advising. NIMET is an agency under the Federal Ministry of Aviation. Its statutory mandate is continuous observation of national weather and climate and generation of timely meteorological, hydrological, and oceanographic data to support national needs and in fulfilment of relevant international obligations. NIMET maintains 60 weather observation and air quality monitoring stations across the country. In relation to air quality, the agency has a Dobson O_3 spectrophotometer at its Regional Meteorological Training Center in Lagos. It has installed environmental safety monitoring instrument gas analyzers at its observation centers in Abuja, Lagos, Enugu, Kano, and Maiduguri Airports to monitor CO, CO_2, NO_x, $PM_{2.5}$, PM_{10}, and O_3. These gas analyzers are currently not collecting data. BAM gas analyzer was deployed at the National Hospital, Abuja in January 2019 to measure the listed air pollutants. The agency also had a portable Technologies Ozone Monitor Model 202 installed at its headquarters Abuja in 2018 to monitor for tropospheric O_3. The agency has also adopted a comprehensive list of air quality and GHG emissions objectives to be implemented across the country (Ukeh 2021).

5.1.3.5. OTHER INSTITUTIONS

Other institutions with mandates related to air pollution are the FMPR, SON, National Automotive Design and Development Council (NADDC) under the Federal Ministry of Industry, Trade and Development, and the Federal Ministry of Health.

5.2. LAGOS STATE'S LEGAL AND REGULATORY FRAMEWORK

Lagos' institutional air quality framework faces multiple development challenges. The existing legal and regulatory framework lacks certain key elements that are required for adequate AQM. Most regulations in Lagos depend on the national framework, which itself is inadequate. AQM plans have not been developed, nor have jurisdictional monitoring and reporting requirements been implemented. Although the LASEPA under the Lagos State Ministry of Environment has the statutory role of regulating air quality in the state, multiple institutions have duplicative or overlapping functions related to pollution control—which blurs the lines of accountability—while coordination, enforcement, and implementation capacities remain weak.

Lagos has adopted environmental legislation and established a Lagos State Ministry of Environment and Water Resources (LMoE) as well as several parastatal agencies with environmental responsibilities. The key environmental legislation in Lagos State is the Environmental Management Protection Law of 2017[12], which consolidated and expanded the previous environmental laws. Part VI of that law establishes LASEPA as a parastatal agency within LMoE, with a board comprising a chairman, three public members, and eight ex officio members: the permanent secretaries of the Ministries of Health, Agriculture, Works and Infrastructure, Transportation, Finance, and Local Government and Community Affairs; the Director of Environmental Services, Sewage and Water of the MoE; and the General Manager of LASEPA.

The 2017 law gives LASEPA broad powers to, among others, "monitor and control all forms of environmental degradation from agricultural, industrial and government operations; set, monitor and enforce standards and guidelines on vehicular emissions; survey and monitor surface, underground and potable water, air, land and soil environments in the state to determine pollution levels in them and collect baseline data; and prepare a periodic master plan to enhance capacity building for the Agency and for the environment and natural resources management." The law also establishes that "the funds of the Agency shall consist of: (a) such monies as may be appropriated to the Agency by the state; and (b) all subscriptions from the charge, fees and charges for services rendered by the Agency." Thus, the law specifically provides for the agency to supplement its appropriated funding with (for example) permit fees, emission fees, and other charges paid by the organizations it regulates.

Nigeria's federal structure implies that state legislation may equip state agencies with powers and functions duplicative of the Federal Government. For example, both NESREA and LASEPA are empowered to monitor and control industrial pollution and to set standards on vehicular emissions. This creates the potential for duplication of effort and even conflicting standards. At present, coordination between NESREA and LASEPA appears satisfactory, possibly because both the Federal President and the Governor of Lagos State are from the same political party. Lagos State has not yet established its own standards and currently abides by federal air quality and fuel standards.

Another issue is the challenges that LASEPA encounters in regulating the operations of federal establishments that operate within Lagos State. For instance, LASEPA is unable to regulate fuel quality within Lagos, which has impacts on vehicular emissions. This is due to the inability of Lagos State to determine the quality of refined petroleum product imports and the distribution of the imported products within the state.

Second, Lagos State's existing legislation does not require LASEPA to adopt specific plans to achieve air quality standards and control pollution, a shortcoming of the federal regulations adopted by LASEPA (Center for Science and Environment 2013). This further renders actions by LASEPA in air pollution control ineffective and results in the inefficient allocation of resources. An AQM plan is just being developed for Lagos State through the PMEH intervention.

Third, the adopted legal and regulatory framework does not have air quality and emissions monitoring requirements for specific jurisdictions, or requirements to report compliance with national air quality standards. Fourth, airshed delineation or transboundary air management is not mandated or incentivized by existing regulations. As a result, LASEPA does not have an understanding of the airshed responsible for air pollution within Lagos. This effectively limits any collaborative efforts among EPAs across geographical boundaries to monitor and manage transboundary air pollution.

Finally, current legislation is heavy on enforcement mechanisms but is less developed on other policy tools to incentivize compliance, tools such as market-based instruments like voluntary certification programs, pollution taxes and emissions trading systems, which when combined with enforcement tools would likely yield better policy results.

5.3. ORGANIZATIONS INVOLVED IN LAGOS STATE

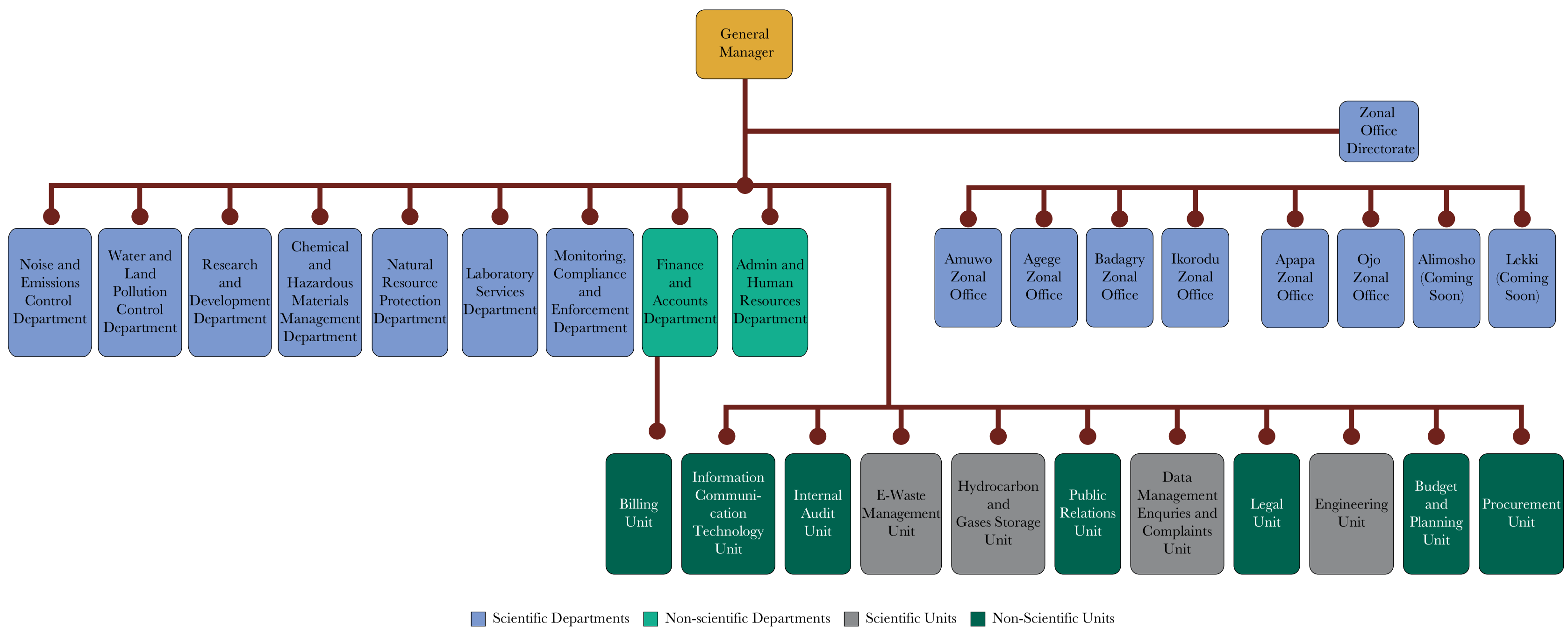
In Lagos State, LMoE is charged with securing a cleaner, healthier, and more sustainable environment conducive to tourism, economic growth, and the wellbeing of all citizens. It serves as the coordinating ministry for all the offices and parastatals under Environment. The key objective of the ministry is to ensure that environmental matters are adequately mainstreamed into all developmental activities in the state. LMoE is made up of two offices and seven parastatal agencies. LASEPA is the parastatal with statutory responsibility for AQM in the state. The Lagos State Waste Management Agency (LAWMA) is responsible for solid waste management, and the Lagos State Waste Water Management Office (LASWMO) is responsible for sewage collection and treatment.

LASEPA was established in 1996 to enforce measures to combat environmental degradation on manufacturing premises. Figure 5.1 shows the present organization chart, which comprises seven scientific offices, eight zonal offices, four scientific units, and seven non-scientific units. In 2021, it was slated to receive only the equivalent of US$1.25 million from the state budget. That means that most of LASEPA's funding has to come from fees and an annual Environmental Development Charge on industry.

Under the Lagos Environmental Management Protection Law of 2017, LASEPA has the legal authority to enforce emission standards on industrial, agricultural, and government sources and on generating plants in residential and commercial areas, to set and enforce vehicle emission standards, and to set up an air quality monitoring network. However, it mostly lacks the technical capacity and staff to do so effectively. Training and capacity building, as well as additional staff and equipment investments, are needed for LASEPA to effectively fulfill its statutory role in AQM. This will require an increase in budget. As a parastatal, the agency has the capacity to be self-funding and already derives a large fraction of its budget from fees, fines, and the Environmental Development Charge.

In Lagos, the discharge of injurious gases that cause air pollution is an offence, and individuals and corporate bodies can be fined for causing pollution. Over time, LASEPA has demonstrated the capacity to enforce regulations on noise pollution in Lagos. However, the agency lacks the instruments and training to effectively control emissions of air pollutants and GHGs. A key objective of the PMEH program is to enhance the capacity of LASEPA to effectively monitor and regulate air pollution. To realize this objective, the PMEH has engaged LASEPA personnel in on-field and classroom capacity-building sessions on the various components of AQM.

FIGURE 5.1. ORGANIZATION CHART FOR LAGOS STATE EPA



Along with NESREA, several other federal MDAs are stakeholders with interest and influence in AQM in Lagos. The Nigerian Ports Authority, which controls the two ports of Apapa and Tin Can Island, the Airports Authority, and the Nigerian Railway Corporation, reports to the Federal Ministry of Transportation. Under the FMPRs, the NNPC has exclusive authority to import refined petroleum products, which are distributed across the country by its subsidiary, the Pipelines and Product Marketing Company (PPMC) (Ehinomen and Adeleke 2012). Tertiary-level hospitals report to the Federal Ministry of Health. In the past, LASEPA has been limited in its ability to enforce regulations at federal institutions located in Lagos due to jurisdictional conflicts with NESREA.

5.4. EXISTING REGULATIONS IN LAGOS STATE

LASEPA has largely adopted the NESREA standards and regulations rather than establish its own. Table 5.1 looks at the Lagos State and national AQM policies, regulations, and standards from the perspective of recommended international AQM systems aimed at realizing the five strategic AQM goals.[13]

5.5. STRENGTHENING THE SCIENTIFIC BASE FOR AQM

To effectively manage air quality requires systematic, ongoing measurements of ambient air pollution levels (**air quality monitoring**), a detailed understanding of the sources of air pollution (**emissions inventory**), and the ability to predict the effects of changes in the emission inventory on ambient levels of pollution (**air quality modeling**). Until now, none of these three capabilities have been in operation in Lagos and Nigeria. A previous effort at developing an emissions inventory in Nigeria highlighted critical missing links in the development of an emissions inventory infrastructure in a typical Nigerian environment (Fagbeja et al. 2017). As documented in chapter 2, the World Bank PMEH program has taken the first steps to fill these gaps in Lagos by (a) sponsoring one year of continuous data collection at six selected locations in Lagos State, (b) funding the development of an emissions inventory for the state, and (c) funding initial efforts to model specific episodes during the year of monitoring to compare those results with the measured data. The LASG should build on these initial steps.

Ground-based air quality information in Nigeria is sparse. The FMEnv and other MDAs own air quality monitoring stations, but there is little information on their location, functionality, and datasets and whether the generated data are actually informing public decisions. Until this project, analyses of air quality had been based on irregular, short-term, sampling efforts. This precluded the country and cities like Lagos from developing a longer-term understanding of the dynamics of air pollution.

Due to the lack of consolidated information on air quality, most national and international studies use satellite observations, aircraft observations, and simulation models to understand pollution sources and the concentrations. Robust studies of other pollutants, such as particulate matter, require near-source measurements, which are limited in the country.

LASEPA still needs to work on the following priority areas to enhance its AQM information system: conduct long-term monitoring of pollutants, including $PM_{2.5}$ in several representative locations, collaborate with the LSMoH to centralize city health data, extend and improve the present emissions inventory, conduct refined source apportionment studies, and establish a platform for public dissemination of air quality information. This will require funding for the procurement of new equipment and the maintenance of existing infrastructure and datasets, integration of new technologies such as satellite data and machine learning to augment ground-based monitoring, establishment of standards for measuring pollutant emissions from sources and for monitoring air quality, and improvement of the community's acceptance of public air monitoring infrastructure to decrease vandalism of monitoring equipment.

TABLE 5.1. AQM LAWS, REGULATIONS, POLICIES, AND INSTITUTIONS AT LAGOS STATE AND FEDERAL LEVELS

Policy, regulation, standard	Lagos State level	National level
1. Ambient Air Quality Standards (AAQS)	a. Part VI of Lagos State Environmental Regulations, 2017 (LMoE – LASEPA) references and recognizes the NAAQS consistent with the federal regulations. b. Lagos environmental regulations adopts the languages of the federal (NESREA) air quality regulations.	Part VI of National Air Quality Control Regulations, 2014 (FMEnv – NESREA), established the NAAQS.
2. Ambient Air Quality Monitoring and Modeling Program	a. Part VI of Lagos State Environmental Regulations, 2017 (LMoE – LASEPA) referenced air quality monitoring requirements. b. Lagos State adopts most of the federal (NESREA) air quality regulations.	a. National Air Quality Control Regulations, 2014 (FMEnv – NESREA). b. EGASPIN, 1991, Revised 2002, 2016, 2018 (FMPR – DPR).
3. Standards for Stationary Sources	a. Part VI of Lagos State Environmental Regulations, 2017 (LMoE – LASEPA). b. Lagos State adopts most of the federal (NESREA) air quality regulations. c. Industrial Guidelines – LASEPA.	a. Part II of National Air Quality Control Regulations, 2014 (FMEnv – NESREA). b. National Environmental (Control of Bush or Forest Fire and Open Burning) Regulations, 2011 (FMEnv – NESREA).
4. Standards for Mobile Sources	a. Part VI of Lagos State Environmental Regulations, 2017 (LMoE – LASEPA). b. Lagos State adopts most of the federal (NESREA) air quality regulations.	a. Part III of National Air Quality Control Regulations, 2014 (FMEnv – NESREA). b. Control of Vehicular Emissions from Petrol and Diesel Engines (2011).
5. Compliance Requirements and Penalties	a. Part VI of Lagos State Environmental Regulations, 2017 (LMoE – LASEPA). b. Lagos State adopts most of the federal (NESREA) air quality regulations.	Part VII and X of National Air Quality Control Regulations, 2014 (FMEnv – NESREA).
6. Operating Permit Program	a. Part VI of Lagos State Environmental Regulations, 2017 (LMoE – LASEPA). b. Lagos State adopts most of the federal (NESREA) air quality regulations.	Part IX of National Air Quality Control Regulations, 2014 (FMEnv – NESREA)
7. Continuous Emissions Monitoring	No emissions monitoring regulations exist.	No emissions monitoring regulations exist.
8. Area Designation for Air Quality Planning	No related policies or legislation found.	No related policies or legislation found.
9. Climate Change Program	Lagos State adopts the National Policy on Climate Change.	National Policy on Climate Change – 2012.
10. Energy and Alternative Energy	No related policies or legislation found.	Part IV of National Environmental (Energy Sector) Regulations (2014).
11. Emissions Trading Policy	No emission trading policy found.	No emission trading policy found.

5.6. NEW REGULATORY AND ENFORCEMENT STRUCTURES

The current air quality regulatory framework in Lagos State and Nigeria is insufficient to tackle increasing pollution challenges. This is due to the identified institutional and legislative deficiencies. Therefore, the Lagos State and Federal Governments need to modify the existing legal and regulatory framework to promote adequate governance structures and more effective enforcement of pollution control. The following four recommendations are aimed at establishing new regulatory and enforcement structures.

Strengthen current ambient air quality standards established in the 2014 Federal Air Quality Control Regulations. A standard for $PM_{2.5}$ needs to be established based on scientific studies, and other standards need to be revised based on scientific knowledge. LASEPA should create a schedule for the adoption of lower concentration limits to comply with the WHO's recommendations, and a national exposure reduction target for key pollutants such as $PM_{2.5}$. This will represent the realities in the state and provide a basis for improving the existing regulations.

Amend the NESREA Act to establish clear and differentiated institutional roles and responsibilities. Federal institutions and state institutions need to have differentiated and complementary roles and responsibilities to enforce air quality control measures with regulated entities and to implement air quality policy in a way that avoids the duplication of effort. Lagos State Management Protection Law also needs to be revised accordingly and clarify roles and responsibilities.

Amend the NESREA Act, and by extension the Lagos State Environmental Protection Laws, to require planning and monitoring at the federal and state levels. The amendment should have a requirement for the Federal Government to lead a multi-stakeholder discussion and adoption of a National Air Quality Strategy with clear emissions reductions targets, sectoral actions, and budget allocations. The NESREA Act amendment should also mandate federal and state governments to work together to delineate regional airsheds. State governments should be required to establish air zones for air quality monitoring and management purposes based on airshed dynamics. The NESREA Act amendment should exhort the Federal Government to develop an AQI methodology to be adopted by state governments. Finally, the proposed amendment should include demanding state governments to comply with air monitoring and reporting requirements, develop air pollutant emission inventories, and disclose information to the public on the state of air quality. Lagos State must therefore amend its regulatory framework to also foster cooperation within the state. LASEPA, through its regional offices, can then coordinate with the local government on the adoption of state implementation plans (SIPs) and air zone monitoring and management plans incentivizing transboundary cooperation.

Strengthen NESREA, LASEPA, and other state EPAs enforcement capacities. With the support of international institutions, NESREA should work with LASEPA and other state EPAs to devise measures to enhance national and state institutional capacities to (a) develop sound air quality regulations; (b) determine realistic emissions standards across different emissions source categories; and (c) develop practical enforcement mechanisms, such as through the use of incentives and market-based instruments, with adequate science-based infrastructure, including research and development and meteorological observation technologies. Regulated institutions, including LASEPA, should implement a robust staff-training program to promote professionalism, integrity, consistency, and transparency for AQM. LASEPA should explore collaboration with international donor agencies to fund a technical service consultancy to equip and train LASEPA personnel on air quality enforcement strategies.

5.7. THE HEALTH SYSTEM SHOULD BE AN ACTIVE ACTOR

The health sector in Lagos should proactively tackle the health impact of air pollution and act with a strong advocacy voice to promote urgent intervention actions to reduce air pollution emissions and population exposure, perform continuous health impact evaluation, improve and expand the system of health information collection, and initiate epidemiologic research on air pollution.

There is a major need for the health sector in Lagos to be better informed about the health hazards of air pollution. Air pollution is a powerful causative factor of mortality and morbidity. This association is not widely acknowledged within the Lagos health care community and appropriate education on the scientific evidence for it should be pursued. There is a major need to educate personnel on how pollution exposure is driving the rise of NCD because air pollution impedes the formation of new human capital and undermines the prospects of future development by causing damage across the entire population. This is particularly true in children. It has been shown that the two periods when pollution exposure is the most critical to the health status of an individual at later stages in life are during gestation and during the first few years after birth. As the WHO recommends, member countries should "*enable health systems, including health protection authorities, to take a leading role in raising awareness in the public and among all stakeholders of the impacts of air pollution on health and of opportunities to reduce or avoid exposure*" (WHO, 2015).

Health systems have a key role in monitoring and responding to air pollution health risks and should raise their voice. The Lagos State Ministry of Health (LMoH), together with other relevant health institutions, should recognize the growing danger of ambient air pollution and engage health care personnel (doctors and nurses), the civil society, and the public to take bold, evidence-based actions to stop pollution at source as a key public health measure for health prevention. It is essential to build multisectoral partnerships. Pollution prevention strategies that hold great promise include a transition to less-polluting renewable energy sources, a reduction in the reliance on fossil fuels, promotion of less-polluting public transport, proper management of wastes, and incorporation of pollution prevention into all forward planning.

HIA is a critical element of air quality assessment, management, and planning. The institutional and policy framework for HIA and health monitoring of air pollution needs to be improved. HIA provides a basis to draw policy recommendations that should be considered in the AQM plan for Lagos. The Lagos health sector should be informed about the results of air pollution monitoring and should be able to perform the necessary HIA to quantify the health benefits of changes in air pollution levels. Appropriate education of technical personnel should be undertaken to equip them with the necessary professional skills, and the health information system should be upgraded.

The health information system needs to be fundamentally reshaped. There is a lack of knowledge of the most important health events occurring in the Lagos population because the current health information system covers only the public sector. The system should be redesigned to enable it to acquire timely and reliable information on the most important health events taking place in the entire population, including vital statistics such as births and deaths.

Promote research and build research capacity on air pollution, human health, and the economy in Lagos/Nigeria research institutions. Support for research will build long-term, local scientific and technical capacity and strengthen the national economy. The creation of a research infrastructure is an investment in the future, and it will be of particular value to start epidemiologic studies and derive ERFs for the Lagos/Nigeria population.

REFERENCES

Center for Science and Environment. 2013. "Stakeholder Workshop on Air Quality and Transportation Challenges in Nigeria and Agenda for Clean Air Action Plan." https://www.cseindia.org/stakeholder-workshop-on-air-quality-and-transportation-challenges-in-nigeria-and-agenda-for-clean-air-action-plan-6130.

Croitoru, L., J. C. Chang, and A. Kelly. 2020. "The Cost of Air Pollution in Lagos." Washington, DC: World Bank. https://openknowledge.worldbank.org/handle/10986/33038.

Ehinowen, C., and A. Adeleke. 2012. "An Assessment of the Distribution of Petroleum Products in Nigeria." *E3 Journal of Business Management Economics* 3(6): 234–241.

Fagbeja, M. A., J. L. Hill, T. L. Chatterton, J. W. S. Longhurst, J. E. Akpokodje, G. I. Agbaje, and S. A. Halilu, 2017. Challenges and opportunities in the design and construction of a GIS-based emissions inventory infrastructure for the Niger Delta region of Nigeria. Environmental Science and Pollution Research 24(8): 7788–7808.

Federal Government of Nigeria. 2018. "Nigeria's National Action Plan (NAP) to reduce Short-Lived Climate Pollutants."

Federal Government of Nigeria. 2021. "Nigeria's Nationally Determined Contribution." https://www4.unfccc.int/sites/ndcstaging/PublishedDocuments/Nigeria%20First/NDC%20INTERIM%20REPORT%20SUBMISSION%20-%20NIGERIA.pdf.

Federal Ministry of Environment. 2016. "National Policy on the Environment."

Olawuyi, D. S., and Z. Tubodenyefa. 2018. "Review of the Environmental Guidelines and Standards for the Petroleum Industry in Nigeria (EGASPIN)." https://www.iucn.org/sites/dev/files/content/documents/2019/review_of_the_environmental_guidelines_and_standards_for_the_petroleum_industry_in_nigeria.pdf.

Stakeholder Democracy Network (SDN). 2022. "Dirty fuel imports continue to pose a serious health risk in Nigeria." https://www.stakeholderdemocracy.org/dirty-fuel.

Suleiman, R. M., M. O. Raimi, and H. O. Sawyerr. 2017. "A Deep Dive into the Review of National Environmental Standards and Regulations Enforcement Agency (NESREA Act)."

Ukeh, Felix. 2021. "Stakeholders and Institutional Assessment Study, Air Quality Management Program in Lagos, Nigeria."

UNEP (UN Environment Programme). "West African Ministers Adopt Cleaner Fuels and Vehicle Standards." https://www.unep.org/news-and-stories/story/west-african-ministers-adopt-cleaner-fuels-and-vehicles-standards.

World Health Assembly, 68. (2015). Health and the environment: addressing the health impact of air pollution. World Health Organization. https://apps.who.int/iris/handle/10665/253237.

CHAPTER 6
RECOMMENDED AIR QUALITY MANAGEMENT STRATEGY FOR LAGOS STATE

6.1. INSTITUTIONAL DEVELOPMENT

The State of Lagos, and indeed Nigeria, needs a new policy vision for AQM that is supported by regulatory changes. The regulatory changes discussed in section 5.5 will provide a more stable basis for the implementation of Lagos State's and Nigeria's new policy on air quality. The following seven recommendations, however, can be worked in parallel to the proposed regulatory modifications.

LASEPA to undertake a holistic assessment of Lagos State's AQM challenges and opportunities as identified by the PMEH program and develop a policy strategy to engage stakeholders drawn from the relevant MDAs, private sector, academia, and the civil society. The main purpose of this engagement is to chart the State Air Quality Strategy with air pollution reduction goals, specifically for the pollutants of concern. The strategy should also have an implementation plan with specific cross-sectoral actions, responsible actors, budget allocations, and a monitoring plan. The strategy will develop a principal framework for the state and local government efforts to protect air quality across the state, giving considerations to the existing national laws and regulations guiding air quality. It will focus on enhancing the capacity to respond to criteria and climate change air pollutants with adequate science-based infrastructure, including research and development initiatives and meteorological observation technologies. The strategy will also focus on strengthening the collection and reporting of data by the relevant public and private institutions, which will be useful for estimating and inventorying emissions of air pollutants and GHGs. The policy should have a broad communication strategy and its level of implementation be periodically reported to the State Executive Council.

Ensure that the Lagos State air quality institutions work collaboratively with federal air quality institutions. The State Air Quality Strategy should devise mechanisms to promote collaboration between the state and federal institutions to achieve their respective mandates with limited overlap and duplication of efforts. LASEPA should establish clear, measurable objectives with long-term roadmaps, including mechanisms for information dissemination, data sharing between agencies, and periodic assessment of health and economic impacts. The process should consolidate and streamline air quality regulatory, monitoring, and enforcement functions of various state agencies to minimize duplication and overlap and ensure better use of public resources, minimize burden on regulated entities, and maximize effectiveness. The State Air Quality Plan should also leverage Nigeria's signatory status to multilateral agreements for environmental protection and pollution control—the Vienna Convention (1987),[35] the Montreal Protocol (1988),[36] and the Stockholm Convention (2003)[37]—to explore the co-benefits of air quality and GHG emissions monitoring to support Nigeria's reporting on the NDC. Nigeria's updated NDC should cover short-lived pollutants including black carbon, an air pollutant with high morbidity and premature mortality incidence (Federal Government of Nigeria 2021).

Work toward establishing internationally standardized air quality research facilities in LASEPA and other state-owned educational institutions to develop an air pollutant database across sectors. The institutions should partner with NESREA to delineate the air quality regions (airsheds) into which the state falls within Nigeria for enhancing cross-boundary collaboration with relevant states to improve air quality planning within Lagos. The air pollutant database developed by the institutions should support setting realistic targets for the state's air pollution reduction strategies and provide support for setting national air pollution reduction targets. An SIP designed by LASEPA should encourage the establishment of policies, regulations, standards, research, technologies, and so on.

Assess current state monitoring capabilities, and develop and implement a strategy to establish air quality information systems. The Lagos State Ministry of Environment should assess actual air quality monitoring capacities, identifying the state, location, and integrity of air monitoring equipment, laboratories, and data. Based on results, design and fund a plan to establish an air quality information system based on a consolidated air monitoring network, capable of reporting real-time data and responsive to state and federal assessment and monitoring criteria. The Governments of Lagos State and Nigeria should join efforts to build partnerships with national and international research institutions to plant the seed for the future development of air quality forecast systems. Lagos State should work on the following priority areas to enhance its AQM information system: conduct long-term monitoring of pollutants, including $PM_{2.5}$, in several representative locations, centralize city health data, implement an emissions inventory of air pollutants, and conduct refined source apportionment studies.

Work with civil society organizations (CSOs) and the media. By implementing training workshops for journalists and public sensitization campaigns, the Lagos State Ministry of Environment can collaborate to increase the general public's knowledge about air pollution and its health effects. Working with CSOs to increase the citizenry's awareness of its rights to clean air, and the existing mechanisms to sanction violations, will improve citizens' accountability and engagement.

Strengthen courts to effectively rule against individuals and corporations that violate air pollution control legislation. This can be effectively achieved through training programs for judges, the sharing of case studies of effective rulings, and increasing LASEPA's prosecution capacities.

Strengthen the financial capabilities of LASEPA by enhancing funding through line charges, taxes, and levies, in addition to statutory budgetary allocations. This will position LASEPA to acquire the necessary equipment and build human and infrastructure capacity to implement the State Air Quality Strategy without recourse to support from polluters. This will also enhance LASEPA's capacity to effectively enforce established regulations.

6.2. PUBLIC INVOLVEMENT—AQI

The development of an Air Quality Index provides a platform for public awareness and information dissemination that essentially ensures that the public understands the level of air quality within their vicinity and participates in protecting public health. An AQI unifies the complicated science of pollution composition, exposure rates-based health severity, ambient standards, measurement and standard protocols and breaks it down into simple, color-coded bins that give people an instant visual grasp of pollution levels in their surroundings, enabling them to develop the necessary alertness.

While the methods to monitor air pollution and estimate its health impacts are becoming standardized across the globe, this is not the case for methods used for calculating an AQI and the AQI nomenclature. These methods, and the degree of alertness disseminated by health alert systems, vary depending on different countries' interpretation of thresholds for regulatory purposes and background conditions.

FIGURE 6.1. COMPARISONS OF THE VARIATIONS IN BREAKPOINTS AND INDEX NOMENCLATURE ACROSS SPECIFIC COUNTRIES

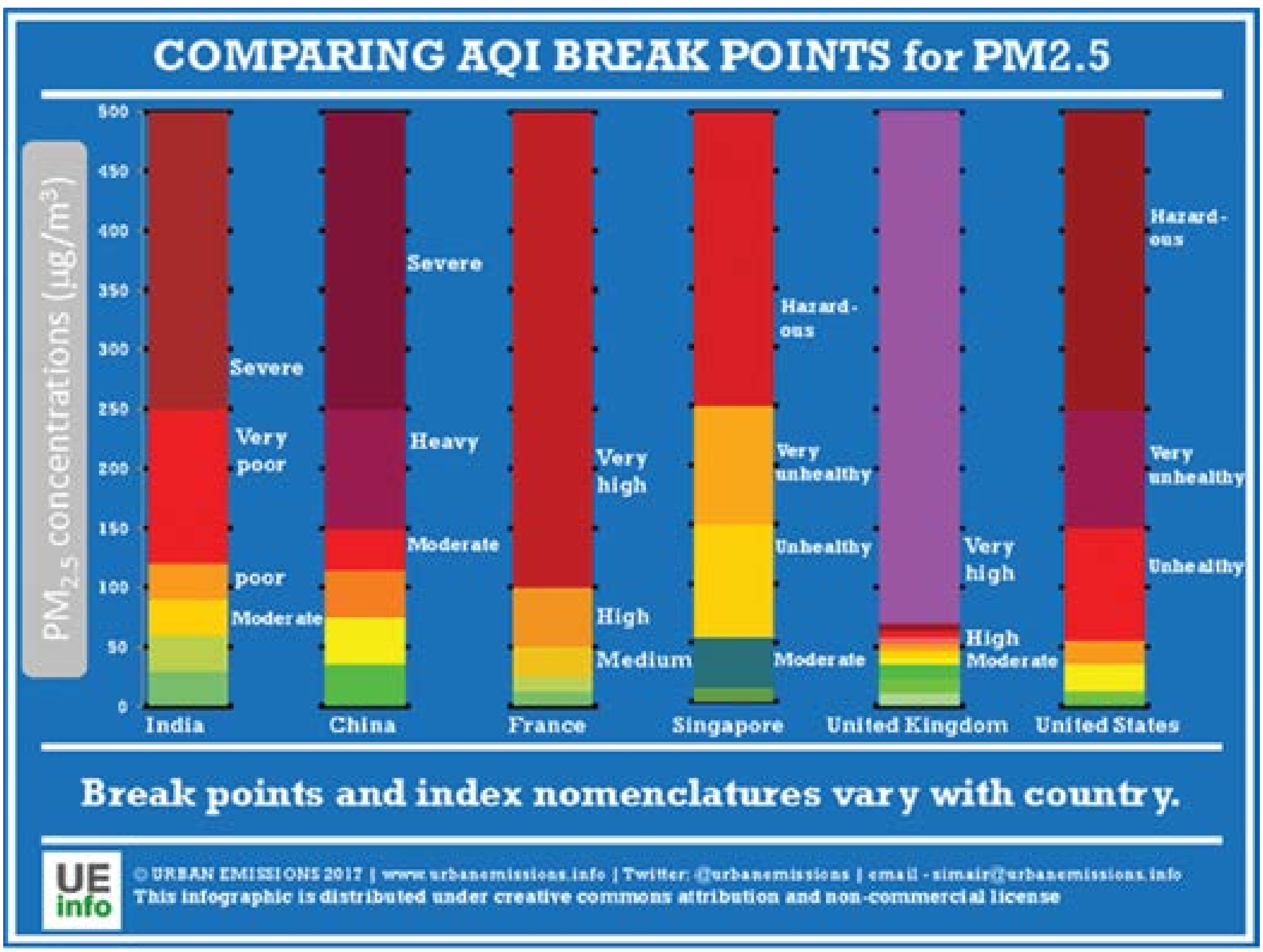
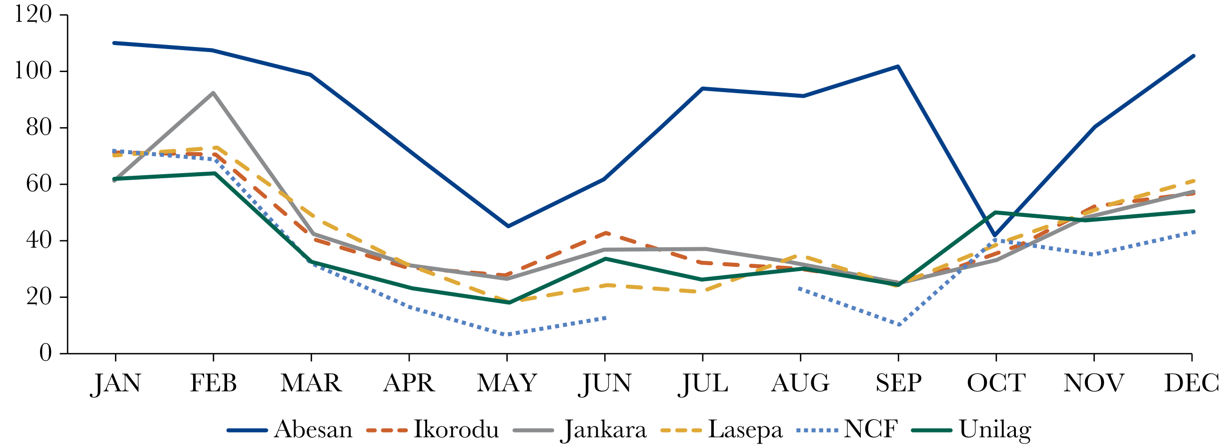


FIGURE 6.2. SEASONAL CYCLE OF $PM_{2.5}$ MONITORED FROM SIX STATIONS IN LAGOS, AUGUST 2020 TO JULY 2021



Based on a review of methodologies from seven countries—the US, the EU, the UK, India, China, Republic of Korea, and Singapore— to develop an AQI centered on air quality breakpoints and timescale variations, comparative AQIs for Lagos State have been developed. The AQI for Lagos used the 12-month air quality monitoring data from the six monitoring stations in the state. The process relies on the average seasonal and diurnal cycles of the concentrations of $PM_{2.5}$, PM_{10}, and the other pollutants monitored from the sites (Figure 2). The data were available at 5-minute intervals for 1 year, spanning August 2020 to July 2021. A summary of monthly $PM_{2.5}$ concentrations is presented in Figure 2. Wintertime highs and rainy season lows are immediately evident in the data, with highs around 120 $\mu g/m^3$ and lows under 20 mg/m^3. The presence of higher commercial and industrial activity in the Abesan area is represented in its higher averages, compared to the other five stations.

Figure 6.3 shows a Microsoft Excel-based AQI calculator developed to explore the methodologies and their interpretations for an application using the ambient-monitoring data from the Lagos network.

Table 6.1 presents a summary of an application of the seven methodologies for the City of Lagos, using the data collected from the six ambient-monitoring stations. The results are binned and colored according to the respective country specifications. The general understanding is that GREEN refers to good air quality and BROWN and PURPLE indicate severe air quality.

The most used/adapted methodology in the world is from the US. According to this methodology, taking $PM_{2.5}$ as the limiting pollutant, between August 2020 and July 2021, the City of Lagos experienced only 2 percent of days in category GOOD, 29 percent of days in category MODERATE, 45 percent of days in category UNHEALTHY FOR SENSITIVE PEOPLE, 23 percent of days in category UNHEALTHY, and 2 percent of days in category VERY UNHEALTHY. There were no SEVERE alert days.

There is no evidence that the current national air quality standards operational in Lagos State, and in Nigeria, have been developed based on extensive monitoring, emissions inventory development, and modeling. Consequently, in developing the methodology for an AQI in Lagos, there has to be a scientific basis to establish new standards. This will establish clearly defined breakpoints and an AQI range for each pollutant, centered on evidence-based health and economic impacts of local air quality. The recommendation is for LASEPA to build on the outcomes of the PMEH study and ensure expanded, continuous air-quality monitoring across Lagos State.

FIGURE 6.3. AQI CALCULATOR PAGE

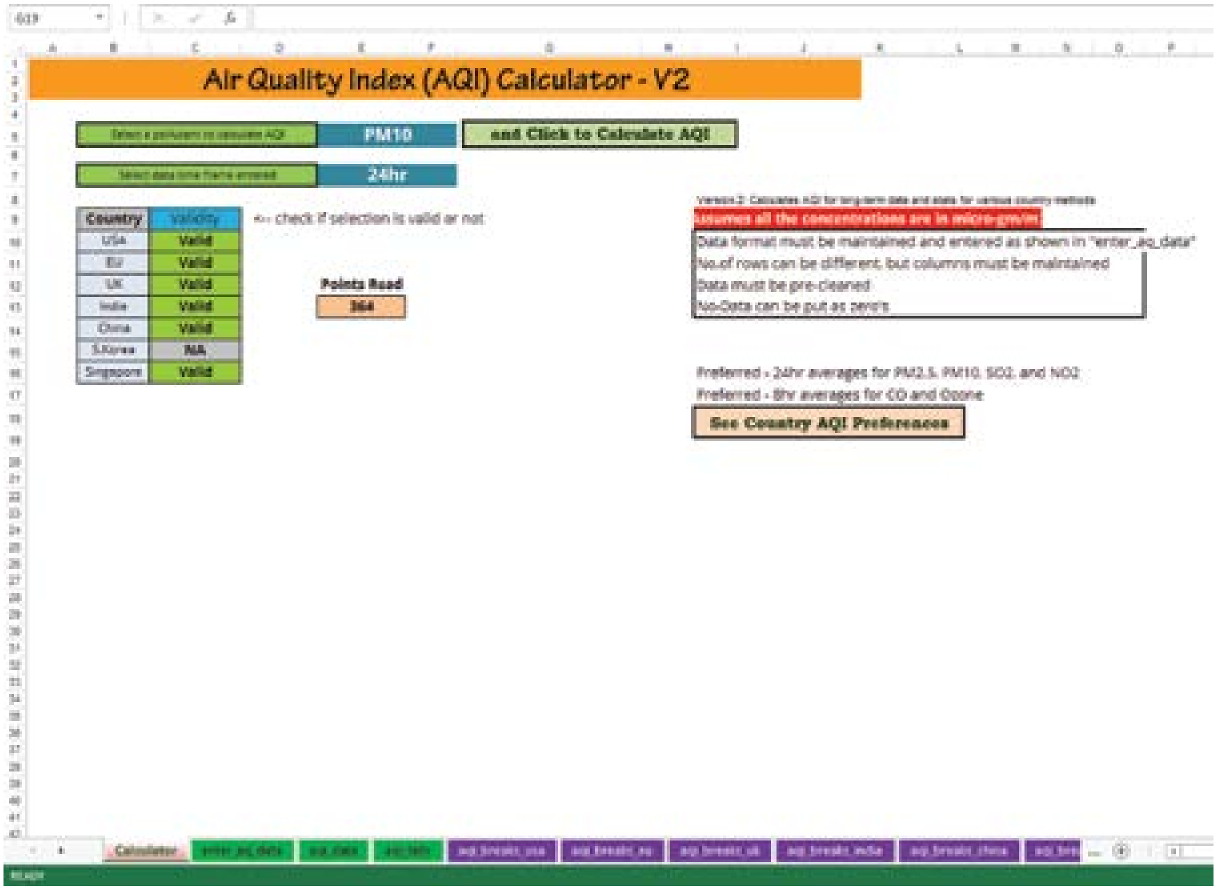


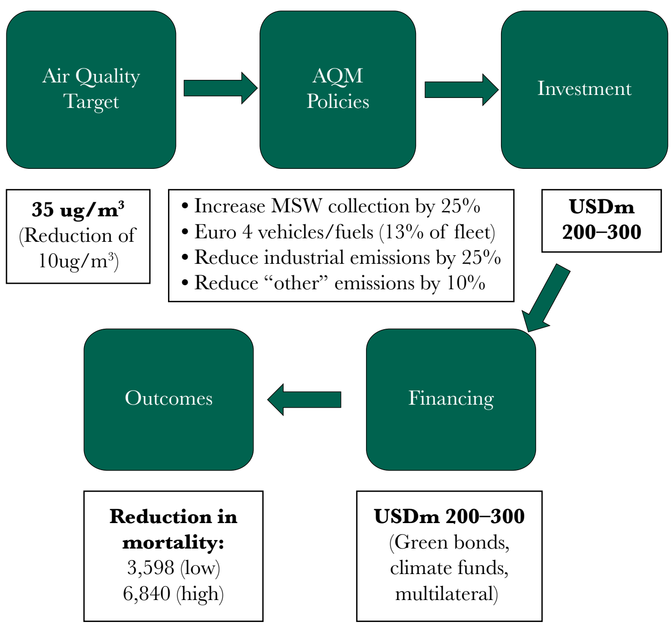
TABLE 6.1. COMPARISON OF AQI RESULTS DERIVED FOR LAGOS

$PM_{2.5}$						
			% points in each bin			
USA	**EU**	**UK**	**India**	**China**	**S.Korea**	**Singapore**
2%	1%	1%	21%	30%	0%	2%
29%	6%	9%	63%	63%	0%	73%
45%	5%	20%	11%	4%	0%	23%
23%	54%	15%	3%	1%	0%	2%
2%	27%	14%	2%	2%	0%	0%
0%	7%	13%	0%	0%	0%	0%
		10%				
		7%				
		4%				
		8%				

TABLE 6.1. *(Continued)*

PM_{10}						
% points in each bin						
USA	**EU**	**UK**	**India**	**China**	**S.Korea**	**Singapore**
10%	1%	0%	9%	9%	2%	9%
80%	4%	2%	40%	80%	29%	80%
7%	4%	6%	49%	10%	39%	10%
1%	40%	4%	1%	1%	25%	1%
1%	39%	5%	1%	1%	3%	1%
1%	12%	7%	1%	0%	2%	0%
		7%				
		9%				
		7%				
		51%				

FIGURE 6.4. RECOMMENDED AQM ACTIONS FOR LAGOS



6.3. RECOMMENDED AQM ACTIONS

Given the large health impacts associated with air pollution that have been estimated for Lagos, immediate action is needed. An initial goal would be to lower ambient $PM_{2.5}$ air pollution by 10 μg/m^3, which could reduce annual premature mortality by 3,598–6,840 deaths, over half of which are infant deaths. Such premature mortality is valued at US$235–1,691 million or between 0.33–2.35 percent of Lagos' GDP.

Poor air quality is an urgent public health problem in Lagos and requires an urgent response. Recommended actions to address air pollution in Lagos include the following:

Within 1 year

Air quality monitoring

1. Resume air quality monitoring at the six sites for which a monitoring record already exists, and begin planning an expanded network.
2. Train and equip LASEPA staff to carry out emission measurements on industrial sources, and begin such testing with the largest and worst emitters.

Health

3. Start education, training, and lifelong learning of health personnel on the health effects of air pollution.

Regulation and enforcement

Solid waste management

4. Redouble efforts to collect and dispose of solid waste by landfill, recycling, composting, and/or incineration with emission controls, and enforce prohibitions on open burning of waste and biomass.

Industries

5. Locate and shut down any lead smelting or battery recycling operations in Ikorodu, measure lead levels in soil and in the blood of the affected population, and take remedial action as necessary.

Transport

6. Implement ECOWAS Directive C/Dir.1/09/20, limiting sulfur in gasoline and diesel fuel to 50 ppm by weight; enforce this by collecting and analyzing fuel samples at the ports and at retail stations, with fines or the loss of retail licenses for noncompliance.
7. Begin implementation of ECOWAS Directive C/Dir.2/09/20 by notifying vehicle importers and implementing inspections and testing to confirm that newly imported light-duty vehicle (whether new or used) meet Euro 4 emission standards and Euro 6 standards for heavy-duty vehicles.

Energy

8. Set and enforce emission standards for backup generators.

Air quality financing

9. Consider allocating a percentage of existing or new emission fees or other charges as line charges for LASEPA to sustainably support increased staffing and equipment.
10. Consider multilateral financing and/or an air quality green bond to support needed investments in emission controls, air quality monitoring infrastructure, emissions measurement capabilities, and capacity building for air quality enforcement and management.

Within 3 years

Air quality monitoring

11. Establish 8 to 12 additional air quality monitoring sites, including upwind and downwind locations as well as sites influenced by the ports, traffic, and industrial areas, to better monitor population-based exposure and to strengthen the basis for air quality modeling.
12. Strengthen the scientific basis for AQM by continuing to develop the emissions inventory, strengthening oversight of the emissions auditing process, and strengthening the reporting of health and economic statistics.

Health

13. Strengthen the scientific basis for health impact assessment, expand the system of health information collection, and initiate epidemiological research on air pollution.
14. Engage public opinion by adopting an AQI and routinely providing air quality data and forecasts to the media and on LASEPA's website.

Regulation and enforcement

Transport

15. Strengthen the existing vehicle inspection and maintenance system to enforce the requirement of

ECOWAS Directive C/Dir.2/09/20 that vehicles in circulation meet Euro 4 emission standards from January 2025.

16. Replace the existing *danfo* (microbus) fleet with larger minibuses, preferably plug-in hybrid-electric vehicles with advanced emission control, and restructure the routes to coordinate with the BRT. By charging from the power grid when it is available and from their on-board engine when not, plug-in hybrids could provide reliable service in the near term while retaining the ability to switch to all-electric operation in the future.
17. Consider measures to phase out engine-driven taxi-cabs, *okada* motorcycle taxis, and *keke* NAPEP tricycle taxis in favor of BEVs.

Energy

18. Increase the capacity and reliability of the electric-generating system to reduce the need for backup generators, and consider retrofitting the Egbin power plant for combined cycle operation with low-NO_x gas turbines.
19. Consider grouping small power users into "mini grids" of a few hundred kilowatts incorporating solar photovoltaic panels and diesel-generating sets with advanced emission controls.

ANNEX 1

ESTIMATING THE HEALTH AND MORTALITY EFFECTS OF AIR POLLUTION IN LAGOS

KEY MESSAGES

- » Current levels of $PM_{2.5}$ ambient air concentration (47 µg/m^3 weighted by population) pose a serious, but preventable, public health hazard, especially in children under 5 years.
- » The morbidity burden is especially high in children, including 180,000 to 350,000 ALRI (primarily cases of pneumonia) and infant mortality (8,000 to 15,000 deaths, or one-half of the total mortality burden).
- » Lead exposure contributes to a high loss of IQ in young children (especially those younger than 6 years), with a mean loss of 6.2 IQ points per child, and up to 1 million IQ points lost at the population level.
- » Current $PM_{2.5}$ pollution is responsible for 16,000 to 30,000 premature deaths annually, or 18 percent of all natural deaths, in Lagos State. An additional 250 to 500 deaths are attributable to PM_{10} exposure during the *Harmattan* season and 300 to 400 excess cardiovascular deaths in adults from exposure to lead.
- » Reducing the $PM_{2.5}$ concentration to the WHO-recommended IT 1 (35 µg/m^3) would reduce premature mortality by 28 percent (4,300 deaths among infants and adults), and additionally prevent 64,000 lower respiratory infections in children under 5 years.
- » Additional efforts to collect baseline health data, including mortality statistics and data on hospital admissions, are necessary to improve the HIA.

A1.1. INTRODUCTION

Air pollution, in particular particulate matter ($PM_{2.5}$ and PM_{10}), is the leading environmental risk factor worldwide. Globally, among 20 major risk factors evaluated in the GBD study, ambient and household air pollution together currently rank 4th for attributable disease and mortality—after hypertension, smoking, and dietary factors (GBD 2020). The estimates indicate that around 7 million deaths,[1] mainly from NCDs, are attributable to the joint effects of ambient and household air pollution, with the greatest attributable disease burden seen in LMICs (89 percent of the global total, with low-income and lower-middle-income countries alone contributing around 40 percent of the total impact). Higher estimates than these have been published (Burnett et al. 2018). A recent report indicated 10.2 million premature deaths from fossil fuels use (Vohra et al. 2021). Regions with large anthropogenic contributions had the highest attributable deaths, suggesting substantial health benefits from replacing traditional, fossil fuel-based energy sources as well as taking actions on the other different anthropogenic sources such as industry, transport, and agriculture practices (McDuffie et al. 2021).

The recent literature indicates there is strong evidence of a causal relationship between $PM_{2.5}$ air pollution exposure and all-cause mortality as well as ALRI (acute lower respiratory infections), IHD (ischemic heart disease), stroke, COPD (chronic obstructive pulmonary disease), and lung cancer (GBD 2020). A growing and suggestive body of evidence also reports causal relationships between $PM_{2.5}$ air pollution and type II diabetes and its effects on neonatal mortality from low birth weight and short gestation as well as neurologic effects in both children and adults (Thurston et al. 2017).

$PM_{2.5}$ mass has been generally used as the index pollutant for quantifying the impact of outdoor air pollution. First, previous studies have demonstrated that mortality from long-term exposure to $PM_{2.5}$ dominates the overall impact of air pollution. Second, there is a vast set of published studies from around the world linking $PM_{2.5}$ to mortality in humans (Chen and Hoek 2020). Third, the $PM_{2.5}$ effects observed in epidemiologic studies are supported by toxicological and human clinical studies (US EPA 2019). Fourth, concentrations of $PM_{2.5}$ can be obtained from monitors, chemical transport models, and/or satellite data. Finally, $PM_{2.5}$ is ubiquitous and is generated from many different sources in Lagos, including fuel combustion from mobile sources (cars, buses, trucks, and motorcycles) and stationary sources (for example, power plants, port emissions, diesel- or gasoline-powered electrical generators, industrial boilers, and factories), biomass burning, cooking, waste combustion, and road dust. This set of factors sets $PM_{2.5}$ apart from all other air pollutants.

The approaches and the methods of HIA (health impact assessment) of air pollution are well documented. A publication from WHO (WHO Regional Office for Europe 2016) provides the basic concepts and general principles of air pollution health risk assessment for various scenarios and purposes. In fact, both estimation of the burden of diseases attributable to air pollution, and evaluation of policy scenarios and CBAs, are possible. The present report illustrates the methods and input data for the HIA of particulate-matter air pollution in Lagos, Nigeria, as of 2020–2021.

A1.2. DEFINITION AND APPLICATIONS OF HIA OF AIR POLLUTION

There are four main steps in the health impact assessment (HIA) that combine expertise in exposure science, epidemiology, and public health. They are:

1. Estimate the exposure of the population under consideration to specific air pollutants. Ground-level monitoring data, together with air quality modeling and satellite data, are currently used to evaluate

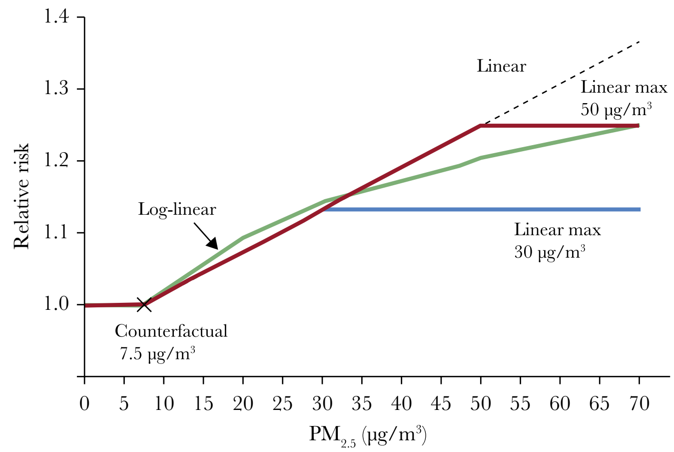
current (or past) exposure or to predict levels in future scenarios, provided that future emission inventories are available.

2. Select the counterfactual (or cut-off value) of the specific pollutant above which the estimate of the health impact is actually performed.
3. Assess the health impact associated with the estimated exposure to air pollution in the specific population. Both the appropriate exposure-response functions (ERFs) from epidemiological studies and the baseline local health statistics are required. The results are reported as numbers of premature deaths, cases of disease, years of life lost, disability-adjusted life years, or change in life expectancy attributable to exposure, or a change in exposure to air pollution.
4. Finally, a critical evaluation of the uncertainties and potential errors involved in the calculation is an essential step of the assessment, which is also carried out through sensitivity analyses.

There are historical landmarks in risk assessment of air pollution. In 1998, Ostro and Chestnut were the first to propose a methodology to quantify the health benefits of potential nationwide reductions in ambient PM_{10} in the US (Ostro and Chestnut 1998). Kunzli et al. (2000) evaluated the impact of outdoor and traffic-related air pollution on public health in Austria, France, and Switzerland. In the same period, two WHO documents (WHO 2000, 2001) provided guidance on several aspects related to air pollution HIAs.

Cohen et al. (2004) published the first GBD evaluation for 2000. Population-weighted annual average concentrations of $PM_{2.5}$ and PM_{10} were estimated, and the two health outcomes for adults were mortality from cardiopulmonary disease and mortality from lung cancer, using risk coefficients from the large American Cancer Society cohort study of adults in the US (Pope et al. 2002). Cohen and colleagues assumed that the risk of death increased linearly over a range of annual average concentrations of $PM_{2.5}$, between a counterfactual concentration of 7.5 μg/m^3 and a maximum of 30 μg/m^3, the highest observed concentration at the time of any cohort study of $PM_{2.5}$, with no additional increase in the health risk assumed for concentrations beyond 30 μg/m^3. Sensitivity analyses were

FIGURE A1.1. ERFS OF THE GBD 2000 STUDY



Source: Cohen et al. 2004.

conducted assuming a linear association from the same counterfactual to 50 μg/m^3, with no additional risk change above this value. A risk model based on the logarithm of concentration was also considered. These risk associations are depicted in Figure A1.1.

A1.3. AVAILABLE ERF MODELS

A1.3.1. LINEAR (LOG-LINEAR) ERFS

In 2013, the WHO Regional Office for Europe coordinated two projects (REVIHAAP – Review of evidence on health aspects of air pollution, and HRAPIE – Health risks of air pollution in Europe) to provide the European Commission and its stakeholders with evidence-based advice on the adverse effects of ambient air pollution. In particular, the documents provide the health outcomes and ERFs that could be used for risk assessment of short- and long-term exposure on morbidity and mortality in the European context (WHO 2013a, 2013b).

HRAPIE experts recommended estimation of the impact of long-term (annual average) exposure to $PM_{2.5}$ on natural cause[2] mortality in adult populations (age 30+ years) for cost-effectiveness analysis. A linear ERF[3], with a relative risk RR[4] of 1.062 (95 percent CI = 1.040, 1.083) per increment of 10 μg/m^3, was recommended. The recommended risk coefficient was based on a meta-analysis of all cohort studies published before January 2013 by Hoek et al. (2013) and included 11 different studies conducted in adult populations of North America and Europe. The review conducted by Hoek et al. (2013) also provided meta-analyses for cardiovascular mortality with a stronger and statistically significant effect (RR of 1.11, 95 percent CI = 1.05, 1.16 per 10 μg/m^3, based on 11 studies). The effect of $PM_{2.5}$ on respiratory mortality (excluding mortality from lung cancer) was weaker and with a large uncertainty (RR of 1.029, 95 percent CI = 0.94, 1.126 per 10 μg/m^3, based on six studies).

Following the review by Hoek et al. (2013), several additional cohort studies have been published on $PM_{2.5}$ (or PM_{10}) all-cause or cause-specific mortality. In particular, in the most recent update of the WHO Air Quality Guidelines (WHO 2021), three relevant systematic reviews on short- and long-term exposure to air pollutants and mortality have been conducted (Chen and Hoek 2020 on long-term effects of PM; Huangfu and Atkinson (2020) on long-term effects of NO_2; and Orellano et al. (2020) on short-term effects of several pollutants).

Below is a short list of the strengths and limitations of the application of a linear (or log-linear) function to estimate the all-cause mortality attributable to air pollution.

STRENGTHS

- Applicability, because mortality statistics on all-cause mortality are generally available worldwide with a greater accuracy than cause-specific mortality.
- Effect estimates are robust as they are based on several studies.
- Effects estimates are all based on studies involving mean $PM_{2.5}$ outdoor air pollution in the range of 2 to 30–40 μg/m^3.
- The mathematical modeling is relatively simple:

$$\textit{Health Impact} = \textit{Exposed population} \times \textit{Background rate of mortality or morbidity} \times \textit{Concentration-Response function, CRF} \times \textit{Change in pollution}$$

LIMITATIONS

- All-cause or natural-cause mortality is influenced by other conditions than chronic diseases, and the percentage of NCDs varies across countries.
- The application is difficult outside the exposure ranges of the original studies; in particular, the use of the log-linear model poses a problem for assessments in any place with high levels of outdoor $PM_{2.5}$. Extrapolating log-linear model coefficients derived from studies in low-exposure, high-income countries to much greater levels of outdoor $PM_{2.5}$ results in implausibly large estimates of relative risk and attributable deaths in LMICs.

A1.3.2. INTEGRATED EXPOSURE RESPONSE (IER) FUNCTIONS OF THE GBD

Pope et al. (2009) assessed the shape of the exposure-response relationship between cardiovascular mortality and fine particulates from cigarette smoke and ambient air pollution in the American Cancer Society cohort. They found that there were substantially increased cardiovascular mortality risks at low levels of active cigarette smoking, and smaller but nevertheless significant excess risks even at the much lower exposure levels associated with secondhand cigarette smoke and ambient air pollution. Based on these findings, Burnett et al. (2014) suggested a more complex shape to describe the association between $PM_{2.5}$ concentrations and mortality, with no association below some concentration (counterfactual), a near-linear association for low to moderate concentrations, and a diminishing change in risk as concentration increases over the global range of $PM_{2.5}$. Burnett et al. incorporated information on risk from other sources of $PM_{2.5}$ such as secondhand and active smoking and exposure to indoor sources of $PM_{2.5}$ from the burning of biomass for cooking and heating (Pope et al. 2009). Concentrations from these sources are much larger than those observed in cohort studies of ambient air pollution that have been conducted largely in North America and Western Europe (Hoek et al. 2013). The Burnett et al. (2014) approach provided a method to estimate risk over the global range of ambient concentrations.

The GBD project has included ambient air pollution in its evaluation since its 2010 release. For the project, IER functions for fine particulate matter were derived from the pivotal study of Burnett et al. (2014) that considered evidence from different combustion sources. To apply the GBD framework, IER functions were developed that estimate the impact of ambient fine particulate matter on mortality and morbidity within selected disease categories (including cardiovascular and respiratory mortality and lung cancer) prespecified as part of the overall GBD comparative risk assessment project.

The GBD project has released several updates since 2010. The underlying assumptions and the methodology are described in a paper by Burnett et al. (2014) and have been applied in subsequent years by the GBD collaborators. The last report in the GBD series was published in 2020 (GBD 2020).

Since its introduction, the IERs have been accepted as the state-of-the art model, now used by various organizations, including WHO, to estimate the burden of disease and examine strategies to improve air quality at global, national, and subnational scales for outdoor-air, fine-particulate pollution and household pollution from the use of solid fuels for heating and cooking. The estimates of the IERs continue to evolve, changing with the incorporation of new data and fitting methods. Due to recent studies providing estimates of high levels of fine particulate pollution in China, new estimators based solely on outdoor, fine-particulate air pollution evidence have been proposed which require fewer assumptions than the IER, and yield larger relative risk estimates (Burnett and Cohen 2020; Burnett et al. 2018).

A1.3.3. GLOBAL EXPOSURE MORTALITY MODEL (GEMM)

The most recent innovation in the GBD approach was the introduction of a new model known as the GEMM (Burnett et al. 2018), based on 41 cohort studies of exposure to only ambient air $PM_{2.5}$ concentrations in populations predominantly in Europe and North America, but also in Asia. The approach has more flexible parameters such that the change in relative risk at higher concentrations declines as concentration increases, thus limiting the magnitude of the relative risk for the most polluted parts of the world where few studies have been conducted. The attributable number of deaths due to $PM_{2.5}$ exposure worldwide was about twice that predicted by the IER, in part because the GEMM considers natural causes of mortality, specifically, NCDs plus adult lower respiratory infections, and in part because the IER incorporates additional types of exposure, such as active smoking, that have lower relative risks per unit $PM_{2.5}$ than ambient air pollution (Burnett and Cohen 2020).

In summary, there are three types of relative risk models proposed for assessing the population mortality burden due to outdoor $PM_{2.5}$ exposure: linear (or log-linear), the IER approach in GBD, and the GEMM approach. Each of these model specifications has strengths and limitations that have implications depending on the specific analytic objectives and the study area. The work by Burnett and Cohen (2020) provides an illustration of the differences among these models for areas that are at lower outdoor concentrations, and over the global range.

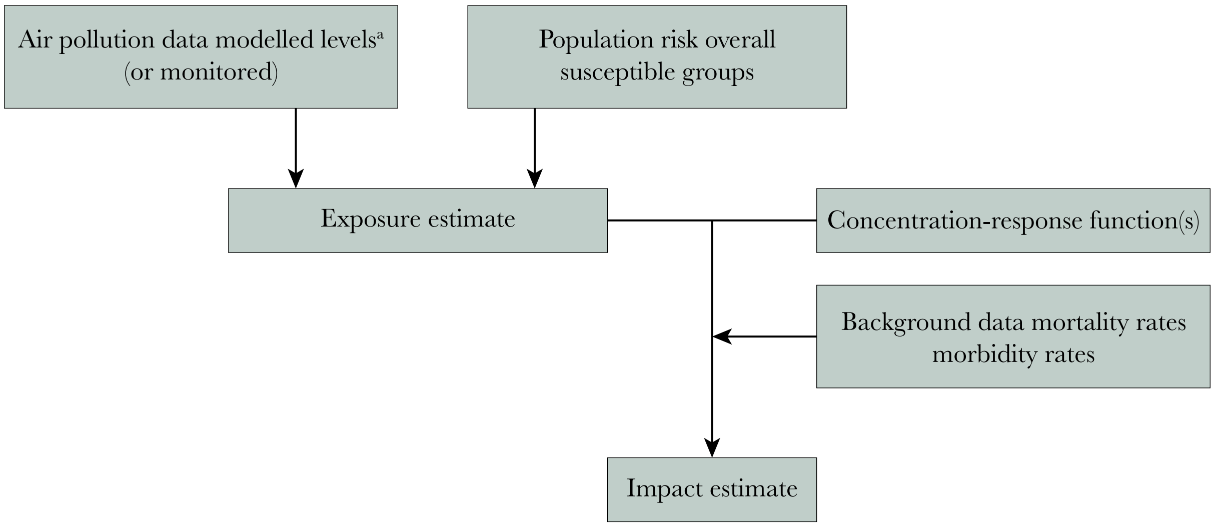
A1.4. METHODS AND INPUT DATA FOR THE HIA IN LAGOS

Figure A1.2 illustrates the main steps for calculating the burden of mortality and morbidity in Lagos.

A1.4.1. AIR POLLUTION DATA

In estimating the burden of disease, it is desirable to assess the current exposure of the population to an index pollutant, traditionally $PM_{2.5}$ and PM_{10}, based on either ground-level monitors, remote-sensing satellites, land-use regression models, chemical transport models, or some combination of the above. Ideally, these concentrations are based on several recent years of complete data (to reduce the influence of an atypical year or season) from monitors that are reasonably representative of local

FIGURE A1.2. SCHEMATIC PRESENTATION OF THE MAIN STEPS OF THE HIA



[a]If modelled data are used, the approach can be used to assess the impact of emission reduction strategies on different health outcomes.

population exposure. At a minimum, 1 year of data are necessary for the HIA to make sure that seasonal patterns are incorporated into the annual average (this is the case for the Lagos study). The monitors should not be unduly influenced by local sources such as a nearby highway, factory, or power plant but should rather reflect average exposures over a wide impact area. Typically, ground-based, population-oriented monitors have been averaged across a metropolitan area to characterize air quality in epidemiological studies. These concentrations are then combined with population data to obtain PWEs.

We have used the 1-year concentration data of $PM_{2.5}$ and PM_{10} measured during the period of the project. The continuous and filter-based monitoring of air pollutants was limited to six sites located across the City of Lagos between August 2020 and July 2021, giving one full year of monitored data. The annual data from the six monitors were used to assign an annual exposure value for the population of each LGA in Lagos State where the monitor was located. For the LGAs without monitors, we have used the results of a dispersion model covering five distinct episodes distributed throughout the monitoring period to derive adjustment factors between the LGAs served with the monitors and those not served with the monitors. For this exercise, data from the recent emission inventory were used as inputs to the dispersion analysis. We first estimated a provisional PWE (population-weighted exposure) for each LGA (Lagos government area) using the results of the dispersion analysis coupled with a high-resolution map of the population density distribution within each LGA to calculate an accurate representation of the LGA-specific PWE. We then derived the PWE for the entire Lagos State, weighing each LGA by its population size. Average annual exposure for Lagos State and each LGA was used in the assessment. This calculation was repeated for both $PM_{2.5}$ and PM_{10} exposures, with the latter index being more appropriate to estimate the impact of the *Harmattan* season.

The adjustment factor and LGA PWE estimates were calculated using the following equations:

$$\text{LGA Adjustment factor} = \frac{\text{PWE dispersion result for LGA interst}}{\text{PWE dispersion result for LGA with monitor}}$$

$$\begin{matrix}\text{Non-}\\ \text{monitored}\\ \text{LGA exposure}\end{matrix} = \begin{matrix}\text{Cloest}\\ \text{monitoring}\\ \text{station to LGA}\\ \text{of interst}\end{matrix} \times \begin{matrix}\text{LGA}\\ \text{Adjustment}\\ \text{factor}\end{matrix}$$

In a sensitivity analysis, we used the simplest solution, that is, to assign to the LGA without a monitor the average concentration of the closest LGA (see results in the Supplementary Material).

A1.4.2. POPULATION DATA

As illustrated in Figure A1.2, the HIA requires input data on demographics and baseline rates for mortality and morbidity. Table A1.1 shows two alternative population compositions by quinquennial age group for Lagos State in 2018, while Table A1.2 presents the population distribution by LGA. Figure A1.3 shows a map of LGA districts.

TABLE A1.1. ESTIMATES OF LAGOS STATE POPULATION BY AGE GROUP, 2018

Age (years)	Base case	Sensitivity
0–4	1,591,424	3,065,496
5–9	1,437,766	2,769,515
10–14	1,292,164	2,489,349
15–19	1,269,198	2,445,056
20–24	1,492,935	2,875,657
25–29	1,529,662	2,946,225
30–34	1,233,580	2,375,555
35–39	1,049,921	2,021,579
40–44	761,198	1,465,616
45–49	543,296	1,045,888
50–54	386,546	744,286
55–59	232,479	447,515
60–64	168,103	323,732
65–69	99,570	191,740
70–74	78,318	150,863
75–79	42,736	82,335
80–84	42,969	82,824
85+	47,982	92,471
Total	**13,299,845**	**25,615,703**

Source: Author's own elaboration.

Figure A1.4 depicts the two population distributions and their temporal evolution between 2006, the year of the last national census, and 2018. For the base case, the total population is projected out to 2018, assuming a 3.2 percent mean annual growth (LBS 2019). For each age group, a differential growth is applied. This age-adjusted rate is computed from the national level all-age population growth using the following expression: All-age population growth × μ, where μ is a multiplier equal to the growth in a particular age group, divided by the all-age population growth in Nigeria (Figure A1.5). As an example, for ages 0–4 years, the multiplier is 2.3 percent/2.7 percent = 0.85; for ages 75–79 years, the multiplier is 3 percent/2.7 percent = 1.11, and so on. The sensitivity case represents the population distribution in 2018 using the approach in LBS (2019)—multiplying each age group in the 2006 census by 1.926 and then adjusting for the annual population growth since 2006. The base case population is about half as large as that of the sensitivity case. Figure A1.4 also shows the LBS 2018 projected population (dotted red line). Compared to the sensitivity case (dash gray curve), the Lagos Bureau of Statistics (LBS) curve is shifted to younger ages.

A1.4.3. MORTALITY AND MORBIDITY DATA

There is a paucity of local data on mortality (and morbidity). Whatever information is currently available is incomplete at best and has not been fully vetted. Regarding hospitalizations, we have evaluated the summary statistics of inpatient admissions (hospitalized patients and their mortality) and outpatient care (emergency room visits and their mortality) for 2017 (see data in the Supplemental Material). These statistics are derived from 184 public health care facilities, but data for the remaining 1,927 care facilities across the state are not available. In addition, for most of the deaths occurring at home, there is no medical certification, and, therefore, the mortality statistics could not be compiled.

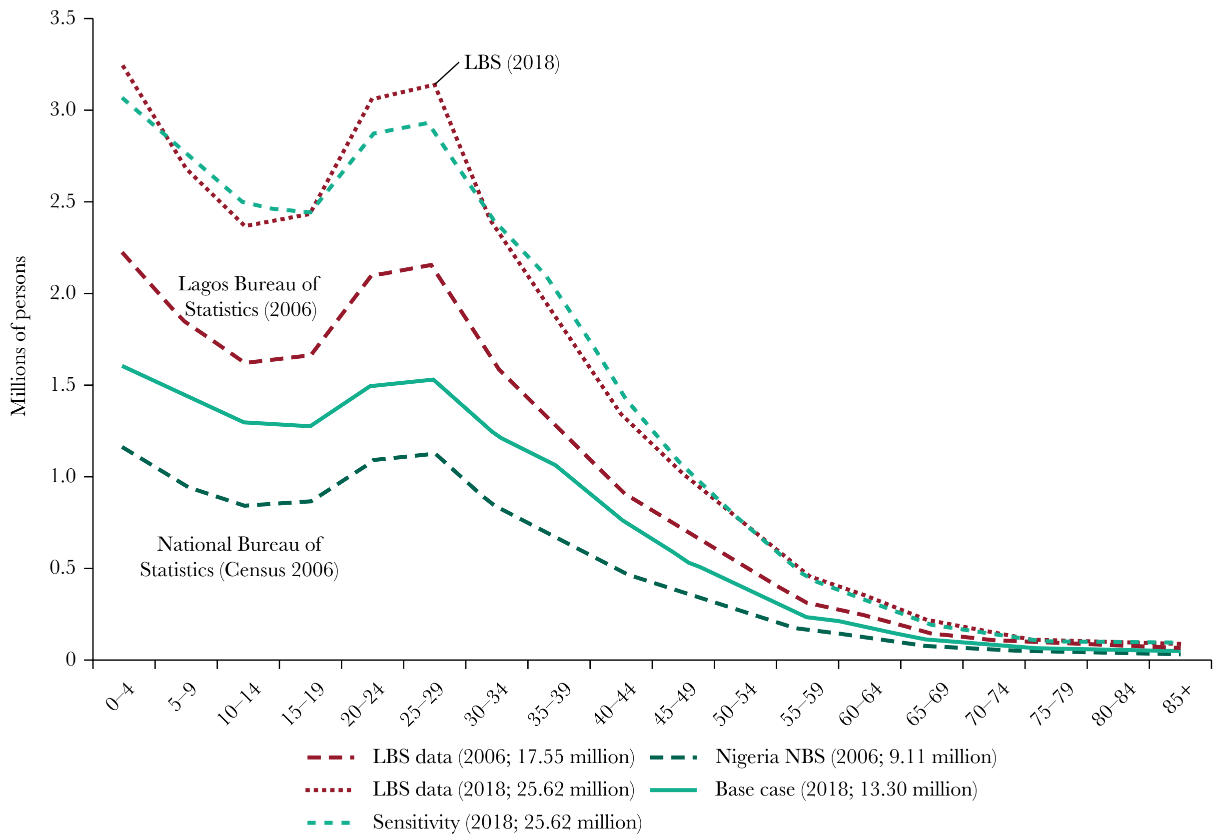
TABLE A1.2. ESTIMATES OF LAGOS STATE POPULATION BY LGA

	2006 Population		2018 Projected population[a]	
LGA	Census[†]	LBS[‡]	Base Case	Sensitivity
Agege	461,743	1,033,064	673,840	1,507,591
Ajeromi-Ifelodun	687,316	1,435,295	1,003,027	2,094,583
Alimosho	1,319,571	2,047,026	1,925,702	2,987,306
Amuwo-Odofin	328,975	524,971	480,086	766,111
Apapa	222,986	522,384	325,412	762,336
Badagry	237,731	380,420	346,930	555,162
Epe	181,734	323,634	265,212	472,292
Eti-Osa	283,791	983,515	414,147	1,435,282
Ibeju/Lekki	117,793	99,540	171,900	145,263
Ifako-Ijaye	427,737	744,323	624,214	1,086,220
Ikeja	317,614	648,720	463,507	946,703
Ikorodu	527,917	689,045	770,410	1,005,551
Kosofe	682,772	934,614	996,396	1,363,919
Lagos Island	212,700	859,849	310,402	1,254,812
Lagos Mainland	326,700	629,469	476,766	918,609
Mushin	631,857	1,321,517	922,094	1,928,542
Ojo	609,173	941,523	888,990	1,374,002
Oshodi-Isolo	629,061	1,134,548	918,014	1,655,691
Shomolu	403,569	1,025,123	588,944	1,496,003
Surulere	502,865	1,274,362	733,851	1,859,727
Lagos State	**9,113,605**	**17,552,942**	**13,299,845**	**25,615,703**

[†] National Population Commission, https://catalog.ihsn.org/index.php/catalog/3340/download/48521
[‡] Lagos Bureau of Statistics population composition (LBS 2019)
[a] Mean annual growth rate is 3.2% (Nigeria National Bureau of Statistics & LBS; the rate is 3.22% according to United Nations World Urbanization Prospects, https://population.un.org/wup/)
Source: Author's own elaboration.

FIGURE A1.3. MAP OF LAGOS STATE SHOWING LGAS

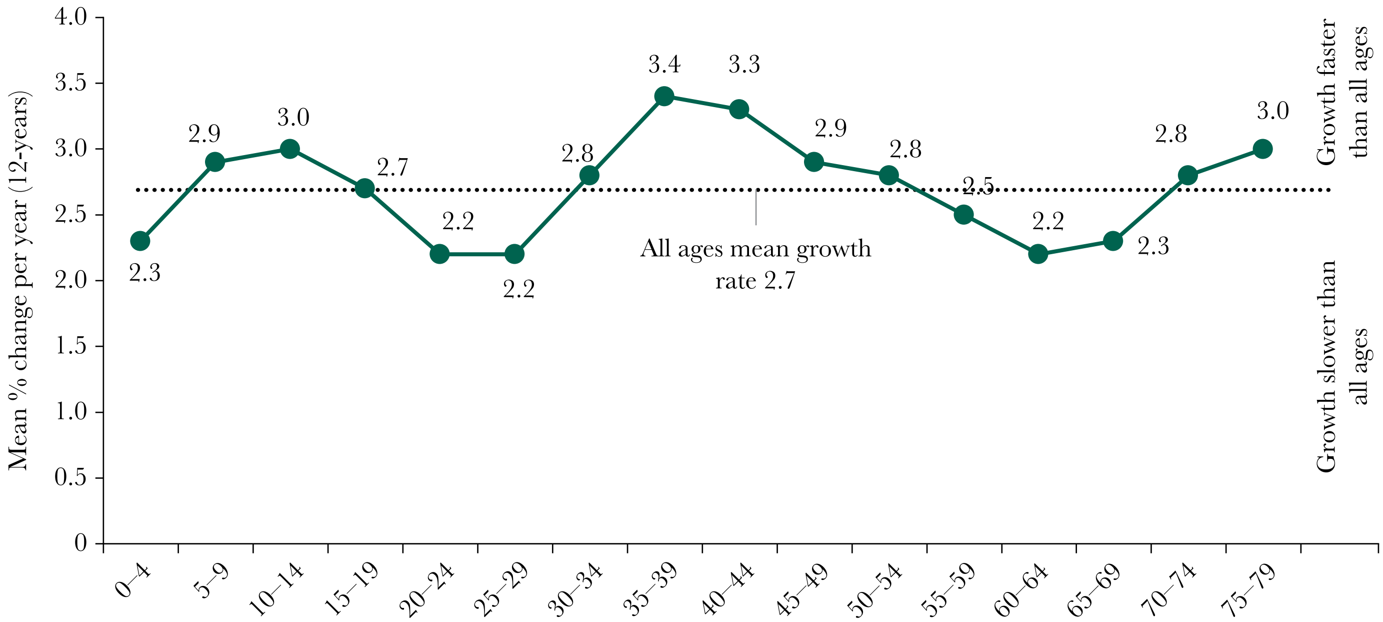
FIGURE A1.4. LAGOS STATE POPULATION IN 2006 AND 2018



Source: Author's own elaboration.

Note: The LBS (2018) curve is biased to younger ages if compared to the sensitivity line composition. Moreover, the curve is shifted up by a fixed factor equal to 1.459, which represents the 12-year total population growth at 3.2 percent.

FIGURE A1.5. NIGERIA POPULATION LONG-TERM GROWTH RATE BY AGE GROUP, 2006–2018



Source: Author's own elaboration with data from the UN World Population Prospects 2019, https://population.un.org/wpp.

For the estimation of the mortality data for the HIA, two international sources were consulted to derive the required information for the base and sensitivity case scenarios: these are the GHDx database of the GBD database (IHME 2021), and the GHE database (WHO 2021). The all-cause and cause-specific deaths (both sexes) are summarized in table A1.3 (base case) and Table A1.4 (sensitivity case) for calculations based on the GHDx inputs. Figure A1.6 depicts the data shown in table A1.3. Values calculated based on data from GHE are presented in Table A1.5 (base case) and Table A1.6 (sensitivity case). The number of deaths for each age group is calculated as the product of the Nigerian hazard rate (number of deaths for a particular outcome per 100,000 population from the GHDx or GHE database; Table A1.7) and the age-specific population size from Table A1.1. Estimates at the LGA level are calculated assuming the same age composition in each LGA. The results are shown in Table A1.8 for the base case and Table A1.9 for the sensitivity case. For the long-term $PM_{2.5}$ exposure, the following health endpoints were considered:

» Mortality due to NCDs and specific GBD categories, including lower respiratory infections, stroke, COPD, lung cancer, diabetes, and IHD.
» Infant mortality (age less than 1 year) from the same sources (GBD and WHO). The infant mortality rate stands at 6.7 percent and 7.5 percent, respectively, for GBD and WHO databases.
» Lower respiratory tract infections for children under age 5 (mainly pneumonia). The baseline rate (incidences per 1,000 children is 302, with a 95 percent CI: 160–538) was obtained from the study by McAllister et al. (2019).
» Incidence of chronic bronchitis in adults 27 years and older (3.9 cases per 1,000 individuals, based on the rate from HRAPIE, WHO 2013b).
» Incidence of restricted activity days in the population of all ages (19 days per year) was taken from HRAPIE (WHO 2013b). Hospital admissions were subtracted to calculate the net PM attributable restricted activity days.
» RHAs and emergency room visits (including pneumonia, bronchitis, and asthma). The baseline

TABLE A1.3. LAGOS STATE MORTALITY (BOTH SEXES) BY CAUSE OF DEATH AND AGE, BASE CASE 2018

Age (years)	Persons	All causes	NCD	IHD	Stroke	COPD	ALRI	LC	DM
0–4	1,591,424	36,702	3,642	0	64	3	6,145	0	0
5–9	1437,766	1,508	247	0	9	0	75	0	0
10–14	1,292,164	853	205	0	11	0	36	0	0
15–19	1,269,198	1,243	284	9	10	5	36	0	6
20–24	1,492,935	1,976	417	17	26	2	56	1	3
25–29	1,529,662	2,821	619	20	35	7	85	2	8
30–34	1,233,580	3,185	727	49	46	8	82	5	15
35–39	1,049,921	3,797	949	84	76	9	97	7	13
40–44	761,198	3,694	1,161	116	124	11	100	10	34
45–49	543,296	3,507	1,326	174	150	I8	112	18	63
50–54	386,546	3,425	1,601	238	226	36	136	29	95
55–59	232,479	2,866	1,520	220	214	34	129	28	90
60–64	168,103	3,178	1,875	305	302	59	160	39	122
65–69	99,570	2,824	1,776	337	295	75	160	41	127
70–74	78,318	3,616	2,270	482	407	117	233	53	145
75–79	42,736	3,025	2,129	440	400	101	221	39	144
80–84	42,969	4,630	3,348	713	618	148	392	42	215
85+	47,982	8,453	6,167	1,395	1,047	280	857	43	349
Total	**13,299,845**	**91,302**	**30,263**	**4,600**	**4,061**	**914**	**9,112**	**357**	**1,429**

Source: Author's own elaboration.

Note: LC = Lung cancer; DM = Diabetes mellitus.

Estimates derived from GHDx national hazard rates applied to the projected population based on 2006 census.

statistics for the entire Lagos State were estimated based on public hospital data, assuming that the private hospitals had a similar load of patients (2017 data). For RHAs, the incidences in children under 5, who account for 12 percent of the total population and contribute 85 percent of total cases (according to LMoH inpatient records for 2017), are 302 LRI cases per 1,000 children, of which 2.09 percent (range: 0.91–4.79 percent) require hospitalization (McAllister et al. 2019). Further, this increases by 32 percent to include other respiratory illnesses, such as COPD and asthma (according to inpatient statistics from the LMoH inpatient records for 2017).

» CHAs and emergency-room visits consist of disease-specific categories such as IHD, which includes heart attacks, heart failure, and stroke. The baseline statistics for the entire Lagos State

TABLE A1.4. LAGOS STATE MORTALITY (BOTH SEXES) BY CAUSE OF DEATH AND AGE, SENSITIVITY CASE 2018

Age (years)	Persons	All causes	NCD	IHD	Stroke	COPD	ALRI	LC	DM
0–4	3,065,496	70,698	7,015	0	124	7	11,837	0	0
5–9	2,769,515	2,905	476	0	17	0	145	0	0
10–14	2,489,349	1,643	395	0	22	0	70	1	0
15–19	2,445,056	2,394	548	17	19	9	69	1	11
20–24	2,875,657	3,807	804	33	50	3	108	1	6
25–29	2,946,225	5,433	1,192	39	67	13	163	3	16
30–34	2,375,555	6,133	1,401	94	88	16	159	9	28
35–39	2,021,579	7,312	1,827	162	146	17	187	14	26
40–44	1,465,616	7,112	2,235	223	238	21	192	20	66
45–49	1,045,888	6,752	2,552	335	288	35	216	34	122
50–54	744,286	6,595	3,083	458	436	69	262	55	184
55–59	447,515	5,517	2,926	424	412	66	248	54	172
60–64	323,732	6,120	3,611	588	582	114	307	76	235
65–69	191,740	5,438	3,421	649	568	144	308	79	244
70–74	150,863	6,965	4,372	928	784	225	449	102	279
75–79	82,335	5,828	4,102	848	771	194	425	76	277
80–84	82,824	8,924	6,453	1,375	1,191	286	755	80	415
85+	92,471	16,291	11,885	2,688	2,018	540	1,651	82	672
Total	**25,615,703**	**175,865**	**58,297**	**8,861**	**7,823**	**1,761**	**17,553**	**687**	**2,752**

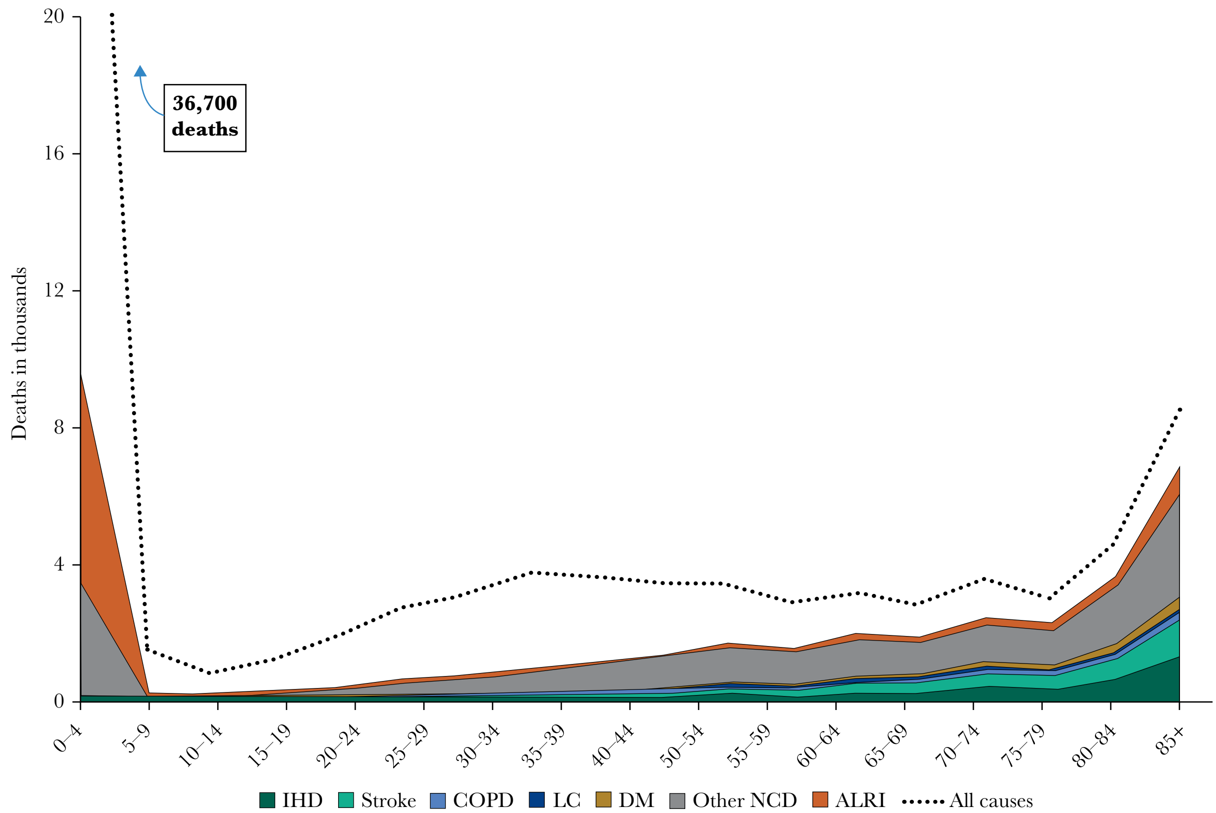
Source: Author's own elaboration.

Note: LC = Lung cancer; DM = Diabetes mellitus estimates derived from GHDx national hazard rates applied to the projected population based on LBS (2006).

were estimated based on the available public hospital data, assuming that the private hospitals had a similar load of patients (2017 data). For CHAs, we assumed most cases occur among adults, and based on Sub-Saharan Africa data presented in Etyang and Scott (2013) (table S2), the baseline rate is 2.6 times higher than the adult RHA incidence rate (adults account for 15 percent of the all-age RHA cases).

We also estimated the impact of short-term exposure to PM_{10} on daily overall mortality due to the *Harmattan* season. In the specific situation of Lagos, daily population exposure to PM_{10} has importance and, in some instances, it does not correlate well with that of $PM_{2.5}$. This happens on days when the *Harmattan* winds blow, between the end of November and mid-March. It is a dry and dusty wind from the North-East originating from the Sahara Desert, and it involves a large size

FIGURE A1.6. LAGOS STATE MORTALITY (BOTH SEXES) BY CAUSE OF DEATH AND AGE, BASE CASE 2018



Note: Estimates derived from GHDx national hazard rates (table A1.3).

increase of particles in the air, especially the coarse fraction (that is between 2.5 and 10 microns in diameter). The health effects of this type of source have been suspected (De Longueville et al. 2010) but never well studied. On the other hand, there is ample evidence of the acute health effects of Saharan dust from other locations (Querol et al. 2019), although the overall short-term effect of particles on mortality is much lower in comparison to the overall effect of chronic exposure. For the assessment of the short-term burden on mortality due to the *Harmattan* season, we applied the short-term ERF for PM_{10} from Orellano et al. (2020).

A1.4.4. EXPOSURE-RESPONSE FUNCTIONS (ERF)

The ERFs from the epidemiological literature that quantitatively relate exposure to $PM_{2.5}$ to the risk of the specific health effect have been reviewed in the first part of the document. The epidemiological studies provide an estimate of the percent change in risk that might be expected per each unit change in air pollution. For example, for ambient air $PM_{2.5}$ concentrations below 30–40 μg/m^3, current studies of long-term exposure indicate that a 10 μg/m^3 change is expected to result

TABLE A1.5. LAGOS STATE MORTALITY (BOTH SEXES) BY CAUSE OF DEATH AND AGE, BASE CASE 2018

Age (years)	Persons	All causes	NCD	IHD	Stroke	COPD	ALRI	LC	DM
0–4	1,591,424	38,158	3,237	0	62	3	7,936	0	9
5–9	1,437,766	3,137	519	0	24	1	216	0	6
10–14	1,292,164	1,715	402	0	31	1	101	0	8
15–19	1,269,198	1,174	190	7	7	4	26	0	6
20–24	1,492,935	1,888	301	13	20	1	42	0	6
25–29	1,529,662	2,710	449	14	23	4	53	1	10
30–34	1,233,580	3,044	645	37	34	6	62	2	19
35–39	1,049,921	3,647	946	64	56	6	73	4	19
40–44	761,198	3,542	1,107	88	92	8	75	6	36
45–49	543,296	3,345	1,231	134	118	14	86	13	52
50–54	386,546	3,282	1,434	199	194	30	116	14	85
55–59	232,479	2,720	1,562	238	231	37	139	12	103
60–64	168,103	3,003	1,911	338	335	66	177	9	142
65–69	99,570	2,668	1,888	403	353	89	191	6	157
70–74	78,318	3,397	2,391	591	499	139	286	5	184
75–79	42,736	2,843	2,048	497	453	112	248	3	166
80–84	42,969	4,320	3,075	772	674	154	425	3	234
85+	47,982	8,131	5,771	1,528	1,166	298	883	3	382
Total	**13,299,845**	**97,724**	**29,107**	**4,923**	**4,373**	**975**	**11,134**	**81**	**1,623**

Note: Estimates derived from GHE national hazard rates applied to the projected population based on 2006 census.

in an 8 percent increase in the risk of premature death from all natural causes of death (Chen and Hoek 2020). However, for the high levels of $PM_{2.5}$ pollution recorded in Lagos—well above the range of the concentration levels observed in most of the studies—the best approach has been to apply the IER functions used by GBD to assess the ambient air $PM_{2.5}$ cause-specific mortality (for example, Croitoru, Chang, and Akpokodje 2020). In this study, we used the most recent IER functions (GBD 2020) as well as the GEMM relationship (Burnett et al. 2018) for the NCDs plus lower respiratory illnesses. For infant mortality, we used the novel paper by Heft-Neal et al. (2018). They found that a 10 μg/m^3 increase in $PM_{2.5}$ concentration was associated with a 9.2 percent (95 percent CI: 4–14 percent) rise in infant mortality based on a large study carried out in Africa. Figure A1.7 is a graphical representation of the ERFs that have been used in this work.

The concentration of lead in $PM_{2.5}$ and PM_{10} observed in Ikorodu LGA is particularly elevated (see section 2.2)

TABLE A1.6. LAGOS STATE MORTALITY (BOTH SEXES) BY CAUSE OF DEATH AND AGE, SENSITIVITY CASE 2018

Age (years)	Persons	All causes	NCD	IHD	Stroke	COPD	ALRI	LC	DM
0–4	3,065,496	73,502	6,235	0	120	6	15,287	0	18
5–9	2,769,515	6,043	1,001	0	46	1	417	0	12
10–14	2,489,349	3,305	775	0	60	1	194	0	15
15–19	2,445,056	2,261	366	13	14	7	51	0	11
20–24	2,875,657	3,637	580	25	38	2	81	1	11
25–29	2,946,225	5,219	865	28	45	8	101	2	20
30–34	2,375,555	5,861	1,243	72	66	12	119	5	36
35–39	2,021,579	7,021	1,822	124	107	12	140	8	37
40–44	1,465,616	6,821	2,131	169	178	16	143	12	70
45–49	1,045,888	6,440	2,369	258	227	28	166	25	100
50–54	744,286	6,320	2,761	383	374	58	224	28	163
55–59	447,515	5,237	3,006	457	444	71	267	22	198
60–64	323,732	5,784	3,679	651	644	126	340	18	274
65–69	191,740	5,137	3,636	777	680	172	369	11	303
70–74	150,863	6,544	4,606	1,138	961	268	550	9	353
75–79	82,335	5,478	3,947	957	872	216	479	5	319
80–84	82,824	8,326	5,927	1,489	1,300	298	819	5	452
85+	92,471	15,669	11,122	2,945	2,247	574	1,701	7	736
Total	**25,615,703**	**178,605**	**56,070**	**9,485**	**8,424**	**1,878**	**21,448**	**157**	**3,127**

Source: Author's own elaboration

Note: LC = Lung cancer; DM = Diabetes mellitus.

Estimates derived from GHE national hazard rates applied to the projected population based on LBS (2006).

compared to the US EPA 2016 standard (0.15 μg/m^3). Lead exposure in children has been linked to severe brain damage, leading to loss of intelligence (IQ), and adverse behavioral outcomes such as learning disabilities, school failure, and conduct disorder (Lanphear et al. 2005; Pew Charitable Trusts 2017; Ruckart et al. 2021). In adults, lead exposure can affect the cardiovascular system by increasing the likelihood of high blood pressure and, consequently, increasing cardiovascular mortality (Brown et al. 2020; US EPA 1999). To estimate the impact of lead exposure on the Ikorodu population—the LGA with the highest lead exposure exceedance (1.35 μg/m^3 air lead) as compared to the US standard—the air concentration has been converted into blood levels using a conversion factor of 4 for children 0–6 years and 2 for adults (US EPA 1999). Based on the estimated blood lead levels, the impact

TABLE A1.7. NIGERIA MORTALITY RATES (PER 100,000, BOTH SEXES) BY CAUSE OF DEATH AND AGE

	All causes		NCD		IHD		Stroke		COPD		ALRI		LC		DM	
Age group	**GBD**	**WHO**	**GBD**	**WHO**	**GBD**	**WHO**	**GBD**	**WHO**	**GBD**	**WHO**	**GBD**	**WHO**	**GBD**	**WHO**	**GBD**	**WHO**
0–4	2,306	2,398	229	203	0	0	4	4	0	0	386	499	0	0	0	1
5–9	105	218	17	36	0	0	1	2	0	0	5	15	0	0	0	0
10–14	66	133	16	31	0	0	1	2	0	0	3	8	0	0	0	1
15–19	98	92	22	15	1	1	1	1	0	0	3	2	0	0	0	0
20–24	132	126	28	20	1	1	2	1	0	0	4	3	0	0	0	0
25–29	184	177	40	29	1	1	2	2	0	0	6	3	0	0	1	1
30–34	258	247	59	52	4	3	4	3	1	1	7	5	0	0	1	2
35–39	362	347	90	90	8	6	7	5	1	1	9	7	1	0	1	2
40–44	485	465	153	145	15	12	16	12	1	1	13	10	1	1	4	5
45–49	646	616	244	227	32	25	28	22	3	3	21	16	3	2	12	10
50–54	886	849	414	371	62	51	59	50	9	8	35	30	7	4	25	22
55–59	1,233	1,170	654	672	95	102	92	99	15	16	55	60	12	5	39	44
60–64	1,890	1,787	1,116	1,137	182	201	180	199	35	39	95	105	23	5	73	85
65–69	2,836	2,679	1,784	1,897	339	405	296	355	75	90	161	192	41	6	127	158
70–74	4,617	4,338	2,898	3,053	615	754	519	637	149	178	297	365	68	6	185	234
75–79	7,078	6,653	4,982	4,793	1,030	1,162	937	1,059	235	262	517	581	92	6	337	387
80–84	10,774	10,053	7,792	7,156	1,660	1,798	1,439	1,570	346	359	912	989	97	6	501	545
85+	17,617	16,945	12,852	12,027	2,907	3,185	2,182	2,430	584	621	1,786	1,839	89	7	727	796
All ages	742	766	225	206	32	31	30	29	6.6	6.3	81	103	2.9	0.6	11	11

Sources: Author's own compilation of mortality data from GHDx (IHME 2021) and GHE (WHO 2021).

Note: Both databases provide similar mortality rates for the selected group of diseases. Lung cancer is a notable exception, for which the WHO estimate is much lower than the GBD value (up to a factor of 15 times smaller for ages 75 and older, and by a factor of 4.5 times smaller when considering all ages).

TABLE A1.8. LAGOS STATE MORTALITY (GHDX HAZARD RATES, BOTH SEXES) BY LGA, 2018

Local Government Area, LGA	All causes		NCD		IHD		Stroke		COPD		ALRI		LC		DM	
	Base case	Sensitivity	Base case	Sensitivity	Base case	Sensitivity	Base case	Sensitivity	Base case	Sensitivity	Base case	Sensitivity	Base case	Sensitivity	Base case	Sensitivity
Agege	4,626	10,350	1,533	3,431	233	522	206	460	46	104	462	1,033	18	40	72	162
Ajeromi-lfeiodun	6,886	14,380	2,282	4,767	347	725	306	640	69	144	687	1,435	27	56	108	225
Alimosho	13,220	20,509	4,382	6,799	666	1,033	588	912	132	205	1,319	2,047	52	80	207	321
Amuwo-Odofin	3,296	5,260	1,092	1,744	166	265	147	234	33	53	329	525	13	21	52	82
Apapa	2,234	5,234	740	1,735	113	264	99	233	22	52	223	522	9	20	35	82
Badagry	2,382	3,811	789	1,263	120	192	106	170	24	38	238	380	9	15	37	60
Epe	1,821	3,243	603	1,075	92	163	81	144	18	32	182	324	7	13	28	51
Eti-Osa	2,843	9,854	942	3,266	143	497	126	438	28	99	284	983	11	38	44	154
Ibeju/Lekki	1,180	997	391	331	59	50	52	44	12	10	118	100	5	4	18	16
Ifako-ijaye	4,285	7,457	1,420	2,472	216	376	191	332	43	75	428	744	17	29	67	117
Ikeja	3,182	6,500	1,055	2,155	160	327	142	289	32	65	318	649	12	25	50	102
Ikorodu	5,289	6,904	1,753	2,288	266	348	235	307	53	69	528	689	21	27	83	108
Kosofe	6,840	9,364	2,267	3,104	345	472	304	417	68	94	683	935	27	37	107	147
Lagos island	2,131	8,615	706	2,856	107	434	95	383	21	86	213	860	8	34	33	135
Lagos Mainland	3,273	6,307	1,085	2,091	165	318	146	281	33	63	327	629	13	25	51	99
Mushin	6,330	13,240	2,098	4,389	319	667	282	589	63	133	632	1,321	25	52	99	207
Ojo	6,103	9,433	2,023	3,127	307	475	271	420	61	94	609	942	24	37	95	148
Oshodi-lsolo	6,302	11,367	2,089	3,768	317	573	280	506	63	114	629	1,135	25	44	99	178
Shomolu	4,043	10,271	1,340	3,405	204	518	180	457	40	103	403	1,025	16	40	63	161
Surulere	5,038	12,768	1,670	4,232	254	643	224	568	50	128	503	1,274	20	50	79	200
All LGA	**91,302**	**175,865**	**30,263**	**58,297**	**4,600**	**8,861**	**4,061**	**7,823**	**914**	**1,761**	**9,112**	**17,553**	**357**	**687**	**1,429**	**2,752**

Source: Author's own elaboration.

Note: LC = Lung cancer; DM = Diabetes mellitus.

Estimates derived from GHDx national hazard rates assuming the same age profile in each LGA. Projected population based on 2006 census (base case) and LBS (2006) (sensitivity).

TABLE A1.9. LAGOS STATE MORTALITY (GHE HAZARD RATES, BOTH SEXES) BY LGA, 2018

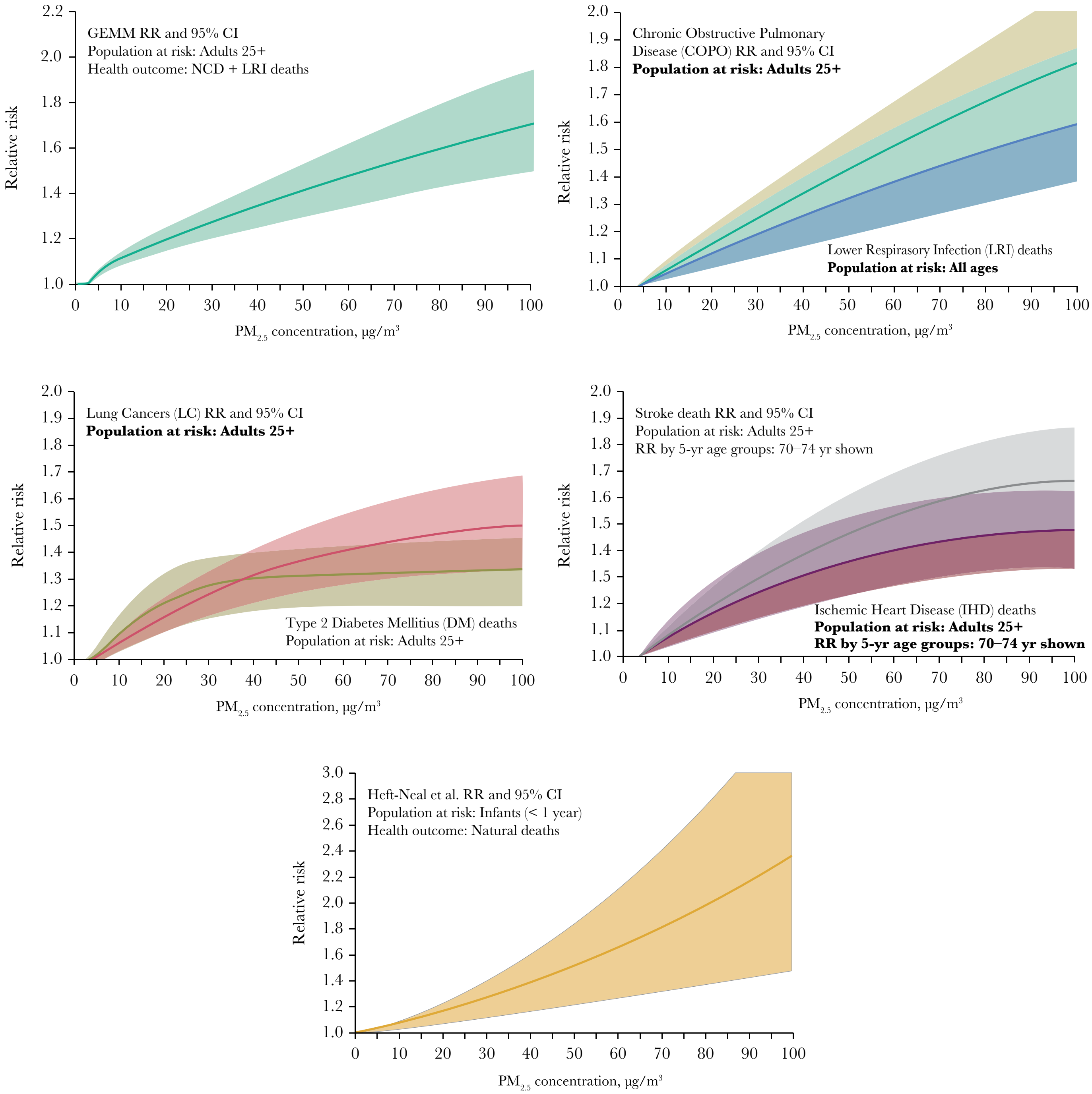
Local Government Area, LGA	All causes		NCD		IHD		Stroke		COPD		ALRI		LC		DM	
	Base case	Sensitivity	Base case	Sensitivity	Base case	Sensitivity	Base case	Sensitivity	Base case	Sensitivity	Base case	Sensitivity	Base case	Sensitivity	Base case	Sensitivity
Agege	4,698	10,512	1,475	3,300	249	558	222	496	49	111	564	1,262	4	9	82	184
Ajeromi-lfeiodun	6,993	14,604	2,195	4,585	371	776	330	689	74	154	840	1,754	6	13	122	256
Alimosho	13,426	20,829	4,214	6,539	713	1,106	633	982	141	219	1,612	2,501	12	18	235	365
Amuwo-Odofin	3,347	5,342	1,051	1,677	178	284	158	252	35	56	402	641	3	5	59	94
Apapa	2,269	5,315	712	1,669	120	282	107	251	24	56	272	638	2	5	40	93
Badagry	2,419	3,871	759	1,215	128	206	114	183	25	41	290	465	2	3	42	68
Epe	1,849	3,293	580	1,034	98	175	87	155	19	35	222	395	2	3	32	58
Eti-Osa	2,887	10,007	906	3,142	153	531	136	472	30	105	347	1,202	3	9	51	175
Ibeju/Lekki	1,198	1,013	376	318	64	54	57	48	13	11	144	122	1	1	21	18
Ifako-ljaye	4,352	7,574	1,366	2,378	231	402	205	357	46	80	523	939	4	7	76	133
Ikeja	3,231	6,601	1,014	2,072	172	351	152	311	34	69	388	793	3	6	57	116
Ikorodu	5,371	7,011	1,686	2,201	285	372	253	331	56	74	645	842	5	6	94	123
Kosofe	6,947	9,510	2,181	2,985	369	505	328	449	73	100	834	1,142	6	8	122	167
Lagos island	2,164	8,749	679	2,747	115	465	102	413	23	92	260	1,051	2	8	38	153
Lagos Mainland	3,324	6,405	1,043	2,011	176	340	157	302	35	67	399	769	3	6	58	112
Mushin	6,429	13,447	2,018	4,221	341	714	303	634	68	141	772	1,615	6	12	113	235
Ojo	6,198	9,580	1,946	3,008	329	509	292	452	65	101	744	1,150	5	8	109	168
Oshodi-lsolo	6,400	11,544	2,009	3,624	340	613	302	545	67	121	769	1,386	6	10	112	202
Shomolu	4,106	10,431	1,289	3,275	218	554	194	492	43	110	493	1,253	4	9	72	183
Surulere	5,116	12,967	1,606	4,071	272	689	241	612	54	136	614	1,557	4	11	90	227
All LGA	**92,724**	**178,605**	**29,107**	**56,070**	**4,923**	**9,485**	**4,373**	**8,424**	**975**	**1,878**	**11,134**	**21,448**	**81**	**157**	**1,623**	**3,127**

Source: Author's own elaboration.

Note: LC = Lung cancer; DM = Diabetes mellitus.

Estimates derived from GHE national hazard rates assuming the same age profile in each LGA. Projected population based on 2006 census (base case) and LBS (2006) (sensitivity).

FIGURE A1.7. ERFS FOR THE LAGOS HIA



Note: Estimates derived from GHDx national hazard rates (table A1.3).

of lead exposure on children's IQ has been estimated (as a decrease in children's IQ equal to 1.15 points per 1 μg/dl (microgram per deciliter) blood lead increase; Pew Charitable Trusts 2017), as has the impact of lead on cardiovascular mortality in adults (Brown et al. 2020).

A $PM_{2.5}$ counterfactual concentration has been used to estimate the burden of disease. The GBD (2020) study assumed a uniformly distributed value between 2.4 and 5.9 μg/m^3 $PM_{2.5}$, whereas GEMM assumes 2.4 μg/m^3, and the same counterfactual is applied for infant mortality. Furthermore, multiple targets have been examined, such as the new WHO Air Quality guideline of 5 μg/m^3 or the WHO interim targets (35, 25, 15, 10 μg/m^3 $PM_{2.5}$) to quantify the health benefits that could be achieved from exposure reductions.

A1.5. RESULTS

A1.5.1. $PM_{2.5}$ PREMATURE MORTALITY AND MORBIDITY (BASE AND SENSITIVITY SCENARIOS)

Table A1.10 and Figure A1.8 show the estimates of $PM_{2.5}$ PWE by LGAs in Lagos. The estimation is based on fixed monitor data (for LGAs with such a monitoring station) and the results of the air dispersion analysis for five episodes between August 2020 and July 2021. The overall values for the entire Lagos are 47 μg/m^3 and 114 μg/m^3 for $PM_{2.5}$ and PM_{10}, respectively (base case). Only a small difference has been estimated when using the sensitivity population (46 μg/m^3 and 116 μg/m^3 for $PM_{2.5}$ and PM_{10}, respectively). The population living in Ikorodu, Shomolu, Mushin, and Oshodi are exposed to particularly high values of ambient pollution ($PM_{2.5}$ values of 97, 85, 71, and 60 μg/m^3, respectively). The alternative calculations, based on the closest monitors, provide similar estimates (see results in the Supplemental Material).

Table A1.11 shows the results of the calculation of the attributable burden in Lagos for mortality (calculated using GEMM for adults and Heft-Neal et al. for infants) and morbidity (calculated using HRAPIE). Figure A1.9 summarizes the findings for both the base and sensitivity case populations. For the base case population, the estimated annual mortality attributable to $PM_{2.5}$ is 15,850 deaths, of which 7,790 are infant deaths, or around 50 percent of the total mortality. In total, 182,400 annual cases of lower respiratory infections in children up to 5 years were estimated, together with 14,700 new cases of chronic bronchitis in adults, 46 million restricted activity days, and 1,490 hospital admissions for cardiovascular and respiratory diseases. The table provides 95 percent CIs around these estimates. Alimosho, Ikorodu, and Oshodi are the LGAs with the greatest impact. The estimates are doubled (Table A1.12) when considering the sensitivity population: the annual mortality attributable to $PM_{2.5}$ is 30,350 deaths (14,890 infant deaths), 349,000 annual cases of lower respiratory infections in children up to 5 years, 28,300 new cases of chronic bronchitis, 88 million restricted days, and 2,840 hospital admissions. In the sensitivity population calculation, the LGAs that had the greatest impact were Alimosho, Mushin, Shomolo, and Oshodi.

Figure A1.10 shows the attributable cases of premature mortality by cause of death applying the IER functions proposed by GBD in 2020. Mortality results have been adjusted for co-exposure to indoor air pollution, assuming that 40 percent of the population in the following LGAs use solid fuel for cooking purposes: Amuwo-Odofin, Badagry, Epe, Eti-Osa (NCF), Ibekju/Lekki, and Ojo (Croitoru, Chang and Kelly 2020). The adjustment for indoor air pollution follows the GBD 2020 recommended proportional population attributable fraction (PAF) approach (*Source*: GBD 2020, SI appendix 1, 11). The calculations were done on the base case population and using baseline mortality rates from GHDx-IHME and GHE-WHO. The results were similar using the two databases and indicated that mortality from lower respiratory infections, IHD, and stroke had the greatest impact.

Figure A1.11 presents the age-specific mortality results for the base case population (top) and sensitivity case population (bottom). The total mortality is calculated as the sum of infant mortality (Heft-Neal et al. 2018), deaths from lower respiratory infections for ages 1–25 (GBD 2020), and adult mortality (ages 25+) according to GEMM.

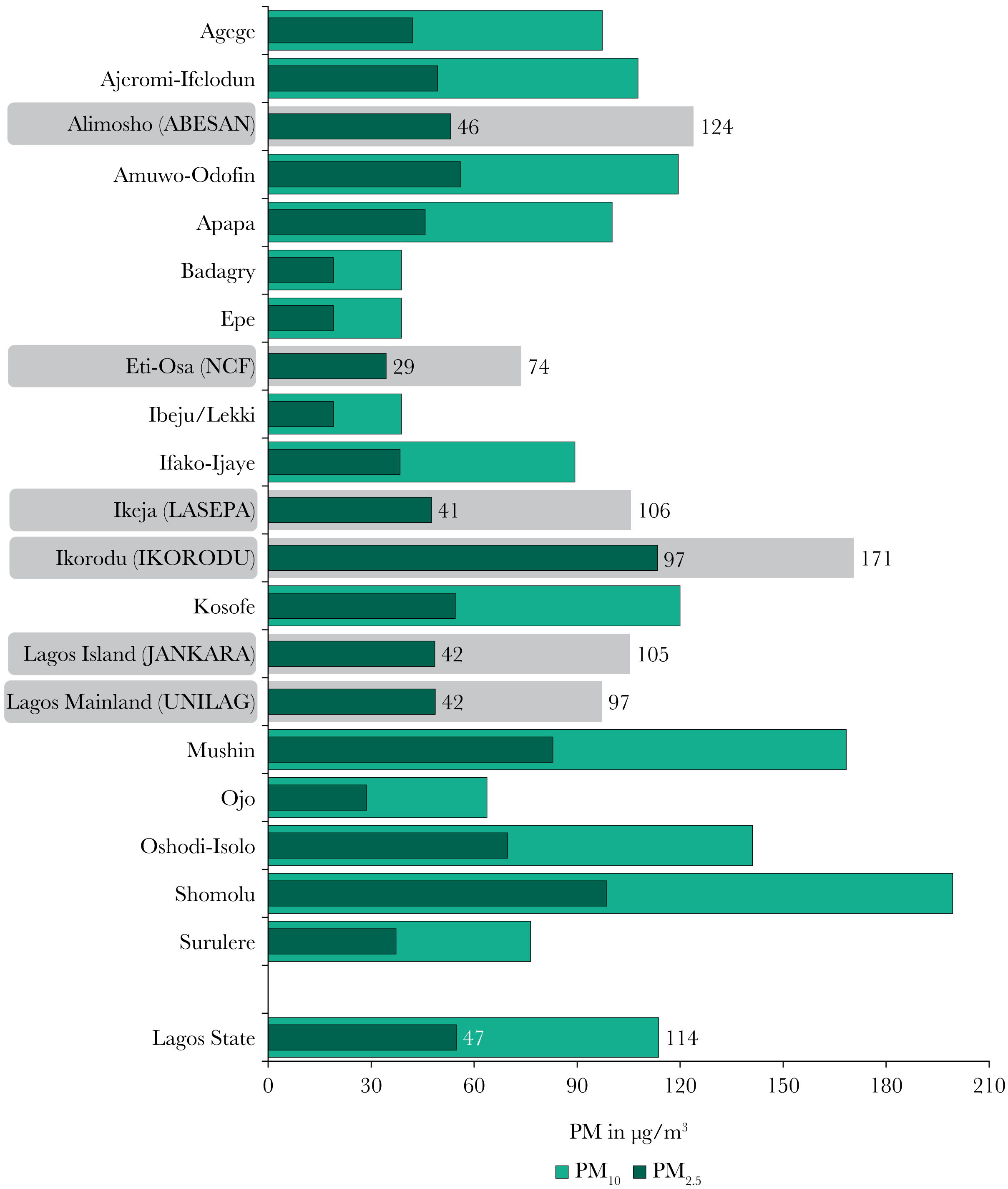
TABLE A1.10. ANNUAL PM PWE BY LGA

Local Government Area (LGA)	Closest monitoring station	$PM_{2.5}$ Adj factor	PM_{10} Adj factor	PWE, µg/m³	
				$PM_{2.5}$	PM_{10}
Agege	Mean of Ikeja & Alimosho	0.84	0.85	36	97
Ajeromi-lfelodun	Lagos Island	1.02	1.02	42	108
Alimosho*				46	124
Amuwo Odofin	Eti-Osa	1.63	1.62	48	119
Apapa	Lagos Island	0.94	0.95	39	100
Badagry	Same as Epe	0.55	0.53	16	39
Epe	Eti-Osa	0.55	0.53	16	39
Eti-Osa*				29	74
Ibeju-Lekki	Same as Epe	0.55	0.53	16	39
Ifako-ljaye	Mean of Ikeja & Alimosho	0.76	0.78	33	89
Ikeja*				41	106
Ikorodu*				97	171
Kosofe	Ikeja	1.15	1.14	47	120
Lagos Island*				42	105
Lagos Mainland*				42	97
Mushin	Lagos Mainland	1.70	1.73	71	168
Ojo	Eti-Osa	0.83	0.86	25	64
Oshodi	Lagos Mainland	1.43	1.45	60	141
Shomolu	Lagos Mainland	2.03	2.05	85	199
Surulere	Lagos Mainland	0.77	0.79	32	76
Lagos State (Base Case population)				**47**	**114**
Lagos State (Sensitivity population)				**46**	**113**

* LGAs where air monitors are located (mean monitored concentration over period Aug 2020 to Jul 2021).

Source: Author's own elaboration.

FIGURE A1.8. AMBIENT AIR QUALITY FOR LAGOS STATE AND LGAS



Source: Author's own elaboration

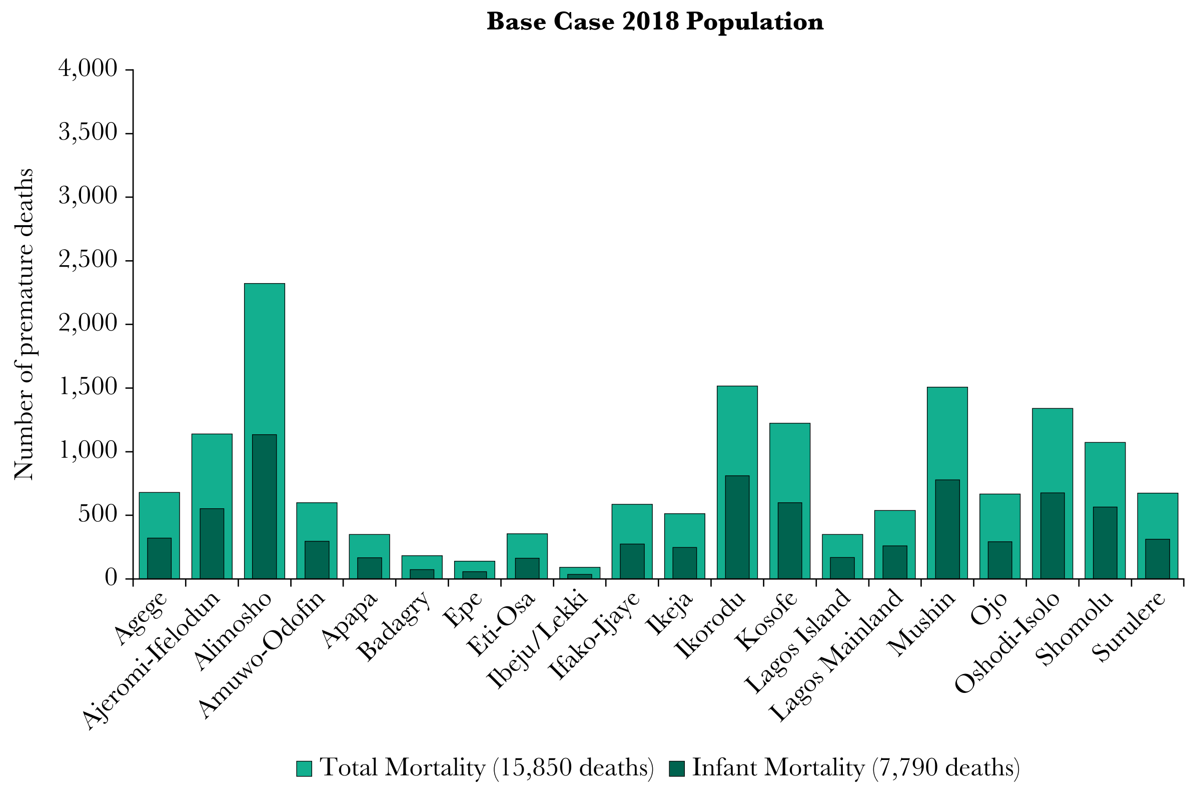
Note: The six LGAs where daily ambient concentrations were monitored during the monitoring campaign between August 2020 and July 2021 are highlighted by the gray boxes along the y-axis on the left.

TABLE A1.11. $PM_{2.5}$ ATTRIBUTABLE HEALTH BURDENS FOR THE BASE CASE POPULATION

Local Government Area (LGA)	Infant Mortality	Total Mortality* (all ages)		Lower Respiratory Infections Children under 5-years		Onset Chronic Bronchitis Adults over 27-years		Restricted Activity Days All ages (in thousands)		Hospital Admissions All ages, cardiovascular and respiratory	
	Deaths	**Deaths**	**95%CI**	**Cases**	**95%CI**	**Cases**	**95%CI**	**Cases**	**95%CI**	**Cases**	**95%CI**
Agege	**320**	**680**	430–890	**7,670**	2,280–14,210	**710**	340–880	**1,840**	1,660–2,040	**58**	2–115
Ajeromi-Ifelodun	**550**	**1,140**	720–1,490	**13,080**	3,970–23,380	**1,120**	550–1,370	**3,190**	2,880–3,550	**102**	3–201
Alimosho	**1,130**	**2,320**	1,470–3,020	**26,730**	8,220–46,890	**2,320**	1,180–2,760	**6,580**	5,950–7,310	**211**	6–415
Amuwo Odofin	**300**	**600**	380–780	**6,950**	2,160–12,040	**570**	290–680	**1,720**	1,560–1,910	**55**	2–109
Apapa	**170**	**350**	220–460	**3,980**	1,200–7,240	**350**	170–430	**960**	870–1,070	**31**	1–60
Badagry	**70**	**180**	120–250	**1,810**	500–3,810	**180**	70–250	**410**	370–460	**13**	0–25
Epe	**60**	**140**	90–190	**1,390**	380–2,910	**140**	50–190	**310**	280–350	**10**	0–19
Eti-Osa	**160**	**350**	220–470	**3,920**	1,130–7,560	**360**	160–470	**920**	830–1,030	**29**	1–57
Ibeju-Lekki	**40**	**90**	60–120	**900**	250–1,890	**90**	40–130	**200**	180–230	**6**	0–13
Ifako-Ijaye	**270**	**590**	370–780	**6,560**	1,920–12,370	**620**	290–790	**1,550**	1,400–1,730	**49**	1–97
Ikeja	**250**	**510**	330–670	**5,860**	1,770–10,570	**510**	250–630	**1,420**	1,290–1,580	**45**	1–89
Ikorodu	**810**	**1,520**	1,000–1,860	**18,210**	6,710–25,370	**1,060**	610–1,190	**5,170**	4,730–5,670	**177**	6–334
Kosofe	**600**	**1,220**	780–1,590	**14,120**	4,360–24,620	**1,180**	600–1,410	**3,490**	3,160–3,880	**112**	3–220
Lagos Island	**170**	**350**	220–460	**4,000**	1,210–7,170	**340**	170–420	**970**	880–1,080	**31**	1–61
Lagos Mainland	**260**	**540**	340–700	**6,160**	1,870–11,030	**500**	240–630	**1,500**	1,350–1,670	**48**	1–94
Mushin	**780**	**1,510**	980–1,900	**17,890**	6,040–27,660	**1,270**	720–1,430	**4,740**	4,310–5,230	**157**	5–302
Ojo	**290**	**670**	420–890	**7,080**	2,010–14,080	**700**	300–930	**1,630**	1,470–1,830	**51**	2–102
Oshodi	**680**	**1,340**	860–1,710	**15,740**	5,100–25,650	**1,170**	620–1,370	**4,040**	3,660–4,470	**132**	4–256
Shomolu	**570**	**1,070**	700–1,330	**12,810**	4,530–18,700	**860**	520–930	**3,520**	3,210–3,870	**119**	4–226
Surulere	**310**	**670**	420–890	**7,490**	2,190–14,220	**660**	300–860	**1,770**	1,600–1,970	**56**	2–111
Lagos State	**7,790**	**15,850**	10,130–20,450	**182,400**	57,770–311,400	**14,710**	7,440–17,770	**45,920**	41,600–50,900	**1,490**	46–2,910

Note: * Baseline rates obtained from the WHO GHE database for 2018.

FIGURE A1.9. $PM_{2.5}$ ATTRIBUTABLE MORTALITY BY LGA AND MORBIDITY FOR LAGOS STATE



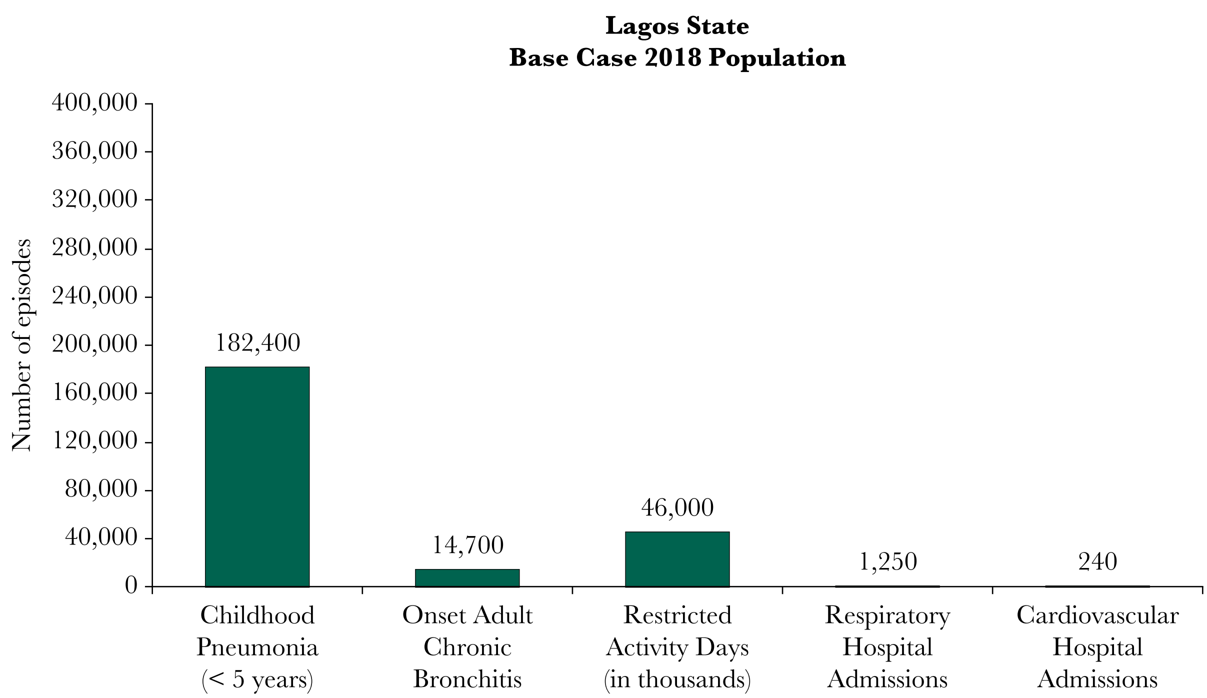
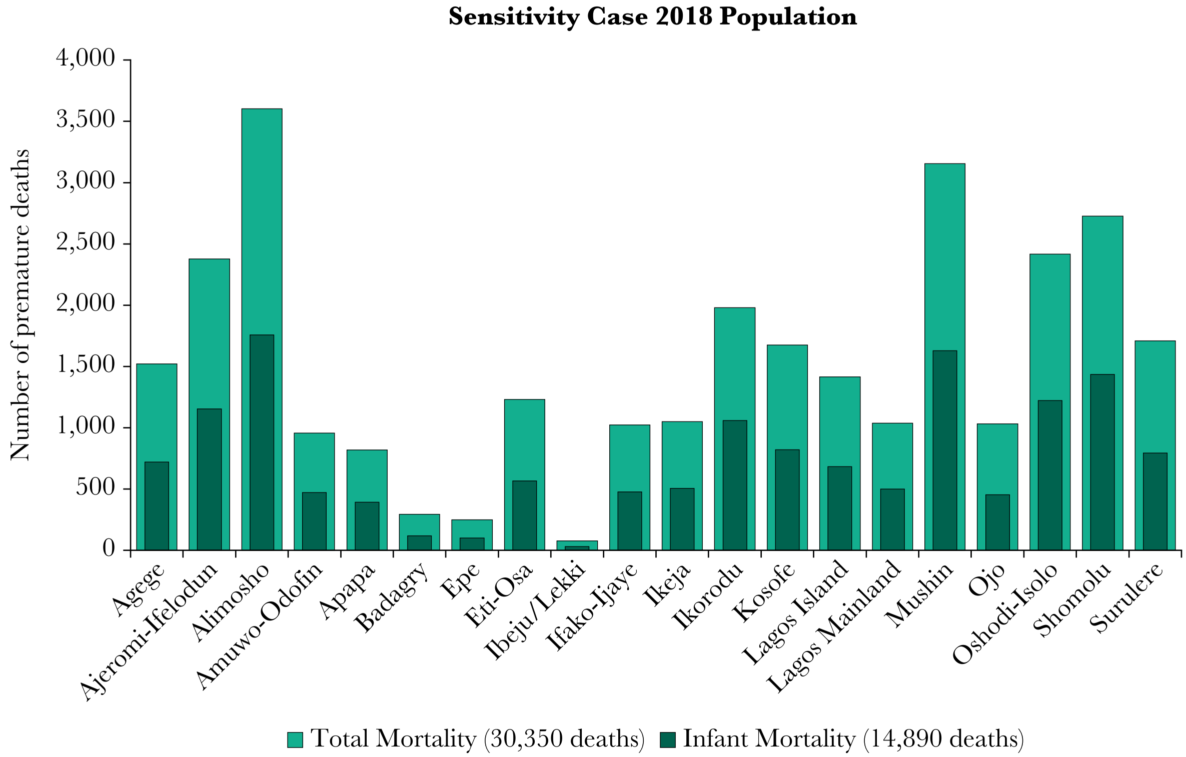
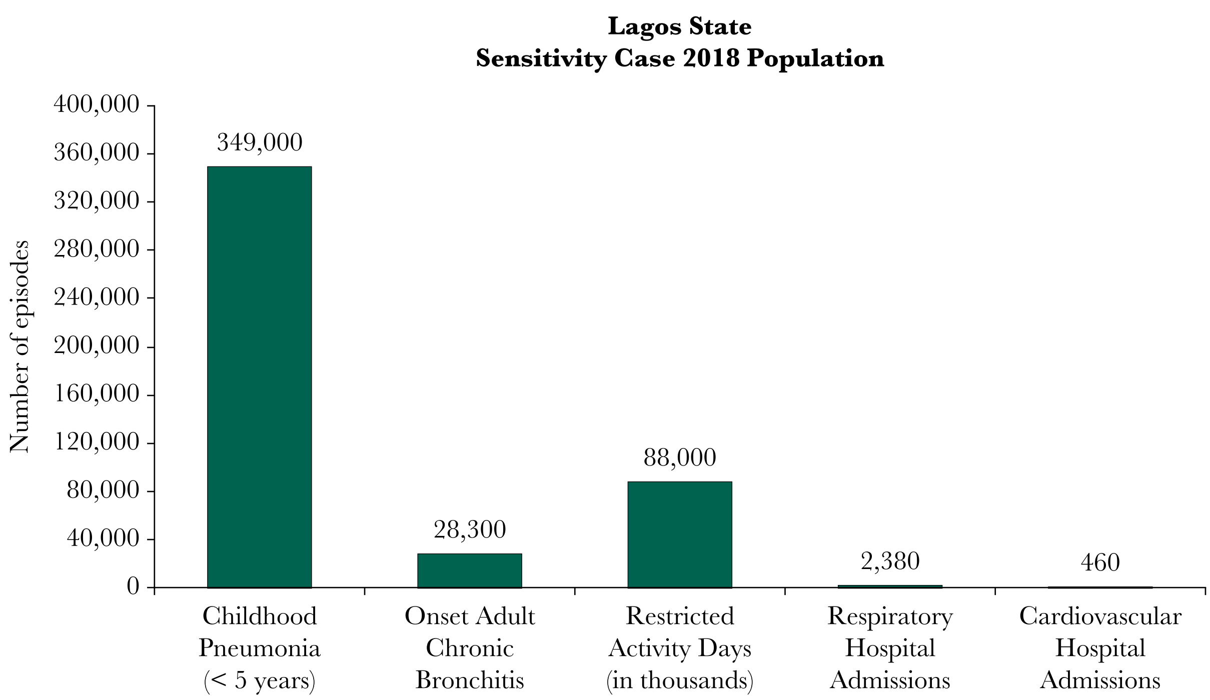


FIGURE A1.9. *(Continued)*





Source: Author's own elaboration

Note: Adult mortality quantified using GEMM and infant mortality using Heft-Neal et al. (2018). Baseline rates obtained from the WHO GHE database for 2018.

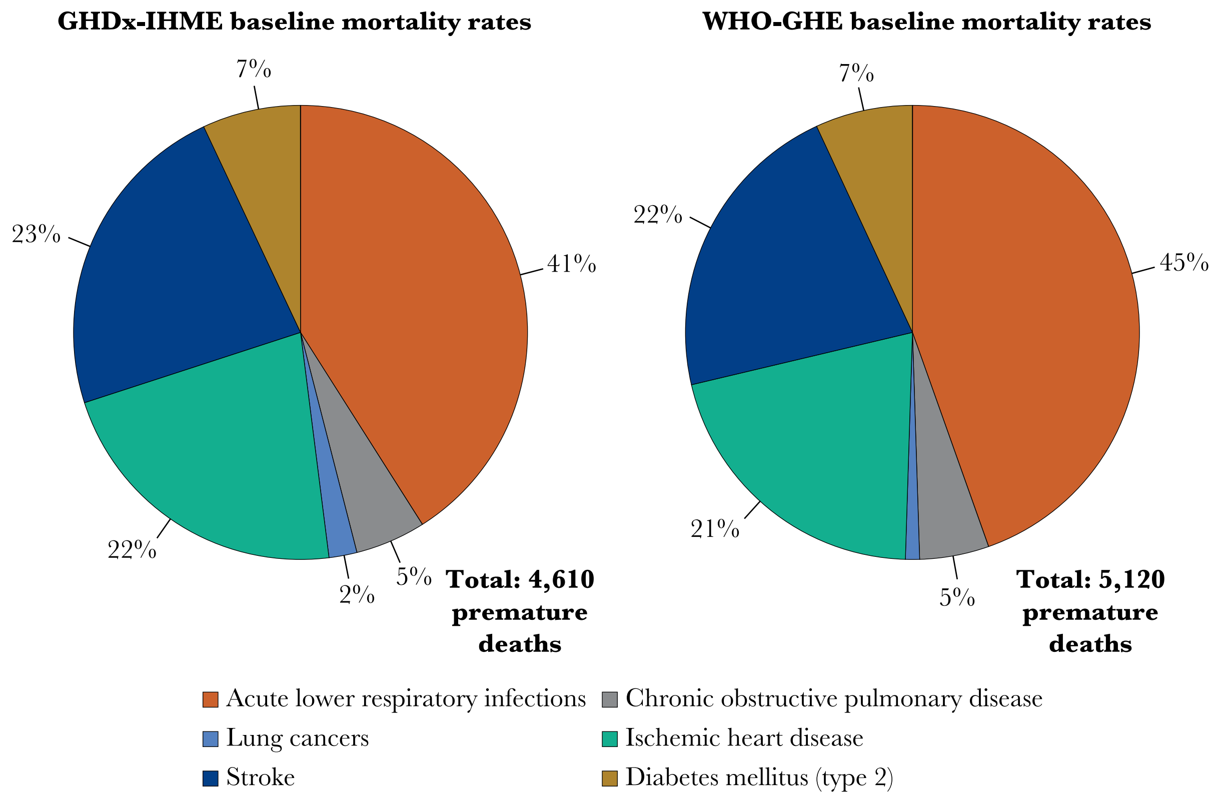
TABLE A1.12. $PM_{2.5}$ ATTRIBUTABLE HEALTH BURDENS FOR THE SENSITIVITY CASE POPULATION

Local Government Area (LGA)	Infant Mortality	Total Mortality* (all ages)		Lower Respiratory Infections Children under 5-years		Onset Chronic Bronchitis Adults over 27-years		Restricted Activity Days All ages (in thousands)		Hospital Admissions All ages, cardiovascular and respiratory	
	Deaths	Deaths	95%CI	Cases	95%CI	Cases	95%CI	Cases	95%CI	Cases	95%CI
Agege	**720**	**1,520**	960–2,000	**17,170**	5,090–31,800	**1,590**	750–1,980	**4,110**	3,710–4,570	**130**	4–258
Ajeromi-lfelodun	**1,150**	**2,370**	1,500–3,110	**27,330**	8,300–48,830	**2,340**	1,140–2,860	**6,660**	6,020–7,410	**212**	6–419
Alimosho	**1,760**	**3,610**	2,290–4,680	**41,470**	12,750–72,750	**3,590**	1,830–4,280	**10,200**	9,230–11,340	**327**	10–644
Amuwo Odofin	**470**	**960**	610–1,240	**11,090**	3,440–19,210	**900**	460–1,090	**2,750**	2,490–3,050	**88**	3–174
Apapa	**390**	**820**	520–1,070	**9,330**	2,800–16,970	**820**	390–1,010	**2,250**	2,040–2,510	**71**	2–142
Badagry	**120**	**290**	190–400	**2,900**	800–6,090	**290**	110–410	**650**	590–730	**20**	1–41
Epe	**100**	**250**	160–340	**2,470**	680–5,180	**240**	100–340	**550**	500–620	**17**	1–34
Eti-Osa	**570**	**1,230**	770–1,630	**13,590**	3,930–26,200	**1,260**	560–1,640	**3,180**	2,870–3,550	**100**	3–199
Ibeju-Lekki	**30**	**80**	50–100	**760**	210–1,590	**70**	30–110	**170**	150–190	**5**	0–11
Ifako-ljaye	**480**	**1,030**	640–1,350	**11,410**	3,340–21,530	**1,080**	500–1,370	**2,700**	2,440–3,010	**85**	3–169
Ikeja	**510**	**1,050**	660–1,370	**11,970**	3,610–21,580	**1,050**	510–1,280	**2,900**	2,630–3,230	**92**	3–183
Ikorodu	**1,060**	**1,980**	1,310–2,420	**23,770**	8,760–33,120	**1,390**	790–1,560	**6,740**	6,170–7,400	**231**	7–435
Kosofe	**820**	**1,670**	1,060–2,170	**19,340**	5,970–33,700	**1,610**	810–1,940	**4,780**	4,320–5,300	**153**	5–301
Lagos Island	**680**	**1,410**	900–1,850	**16,150**	4,890–28,970	**1,380**	670–1,700	**3,930**	3,550–4,370	**125**	4–247
Lagos Mainland	**500**	**1,040**	660–1,360	**11,860**	3,590–21,260	**970**	460–1,200	**2,890**	2,610–3,210	**92**	3–182
Mushin	**1,630**	**3,160**	2,040–3,970	**37,430**	12,620–57,850	**2,650**	1,500–2,980	**9,910**	9,020–10,940	**328**	10–632
Ojo	**450**	**1,030**	650–1,380	**10,950**	3,100–21,770	**1,080**	470–1,440	**2,530**	2,270–2,820	**79**	2–158
Oshodi	**1,220**	**2,420**	1,550–3,090	**28,390**	9,200–46,270	**2,120**	1,130–2,460	**7,280**	6,610–8,060	**238**	7–462
Shomolu	**1,430**	**2,720**	1,790–3,380	**32,540**	11,500–47,520	**2,170**	1,310–2,370	**8,930**	8,150–9,830	**301**	10–574
Surulere	**790**	**1,710**	1,080–2,260	**18,990**	5,540–36,050	**1,670**	750–2,170	**4,480**	4,040–5,000	**141**	4–281
Lagos State	**14,890**	**30,350**	19,380–39,190	**348,900**	110,100–598,200	**28,280**	14.270–34,210	**87,610**	79,410–97,150	**2,840**	87–5,550

Source: Author's own elaboration

Note: *Baseline rates obtained from the WHO GHE database for 2018. Numbers may not add up due to rounding off errors.

FIGURE A1.10. $PM_{2.5}$ ATTRIBUTABLE CAUSE-SPECIFIC MORTALITY FOR LAGOS STATE



Source: Author's own elaboration.

Note: Mortality quantified using the IER functions of the GBD (2020). Baseline rates obtained from the WHO GHE database for 2018.

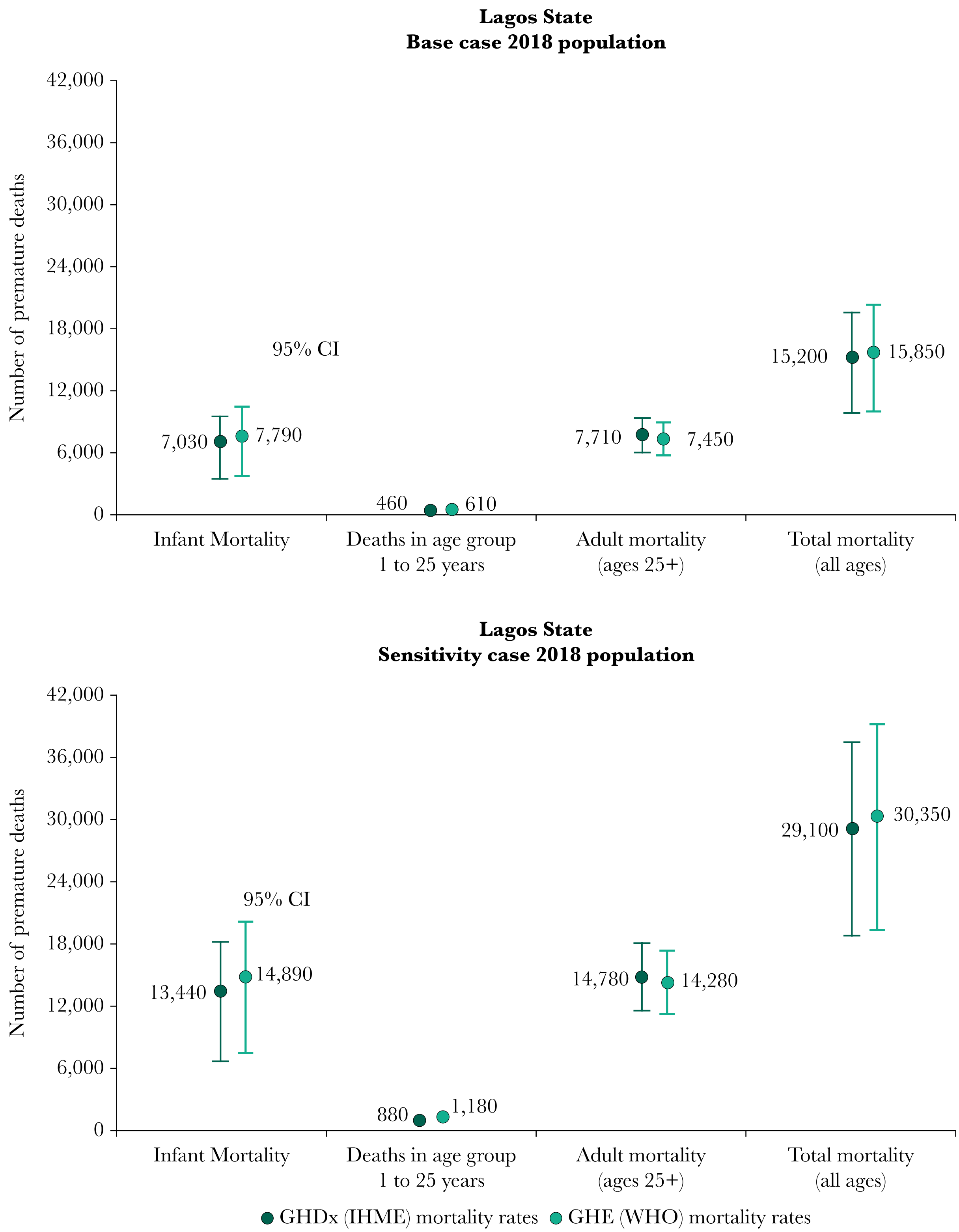
A1.5.2. *HARMATTAN* HEALTH BURDEN

Table A1.13 presents the results of attributable mortality from short-term exposure to PM_{10} during the 2 months of January and February. We have assumed an excess PM_{10} exposure equal to the difference of the average concentration for January–February and the average of the shoulder months December and March. In January and February, the excess PM_{10} concentration was 88 μg/m^3 PM_{10} for the base-case population and 90 μg/m^3 for the sensitivity-case population with a total of 250 and 500 premature deaths, respectively. These numbers are not included in the overall impact assessment performed for $PM_{2.5}$ long-term exposure.

A1.5.3. HEALTH BENEFIT ANALYSIS FROM IMPROVEMENTS IN AIR QUALITY

Figure A1.12 shows the benefits of reducing $PM_{2.5}$ concentration in Lagos. Progressively reaching the different WHO $PM_{2.5}$ interim targets, IT 1 (35 μg/m^3), IT 2 (25 μg/m^3), IT 3 (15 μg/m^3), IT 4 (10 μg/m^3), and the WHO air quality guideline (5 μg/m^3) would avert 29 percent, 46 percent, 66 percent, 77 percent, and 90 percent of the estimated attributable premature deaths (green curve).

FIGURE A1.11. $PM_{2.5}$ ATTRIBUTABLE MORTALITY BY AGE GROUP FOR LAGOS STATE



Source: Author's own elaboration.

TABLE A1.13. PM_{10} ATTRIBUTABLE SHORT-TERM MORTALITY DUE TO THE *HARMATTAN* SEASON

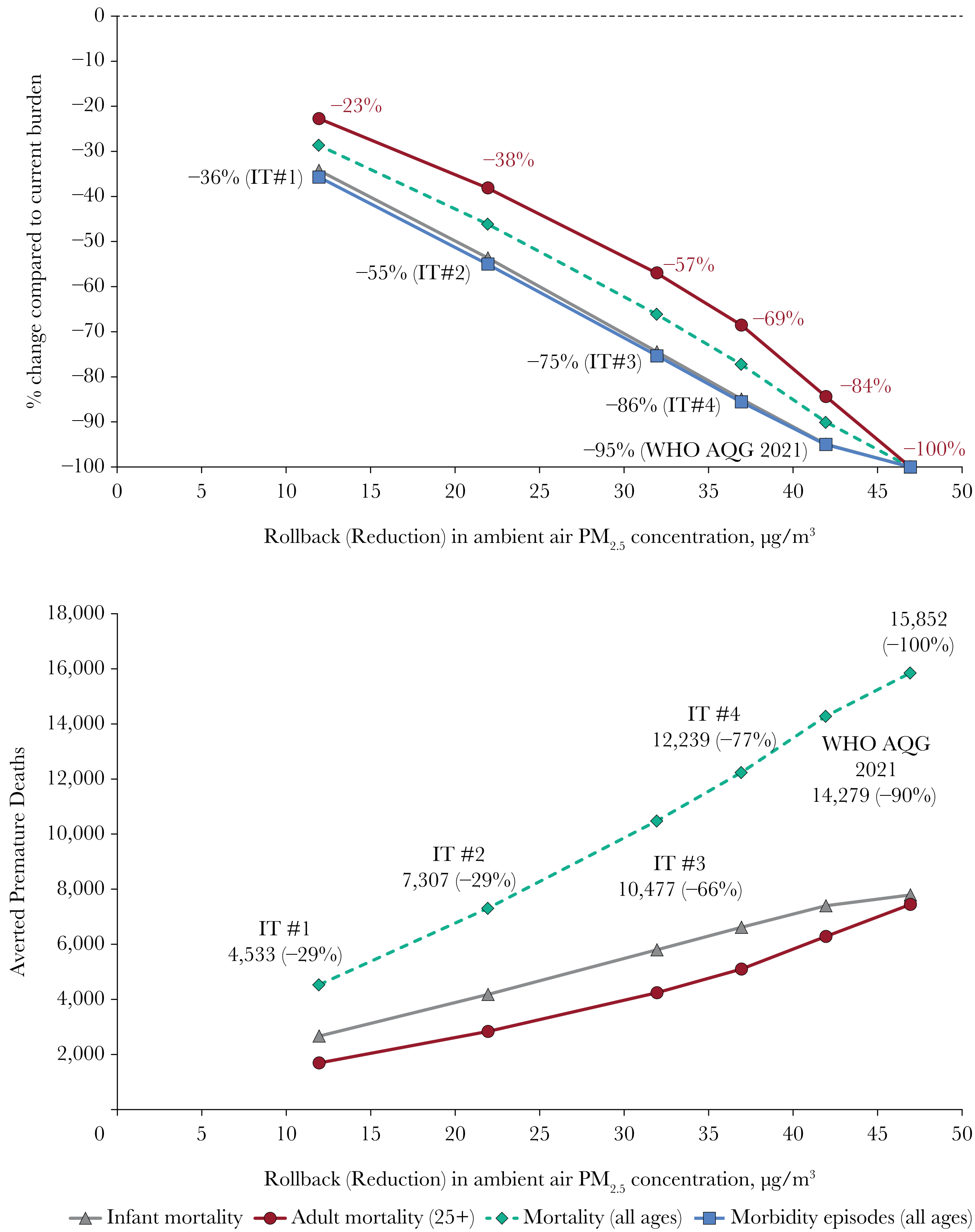
Local Government Area (LGA)	Population (aged 25+)		PM_{10} excess exposure $\mu g/m^3$	Mortality†			
				Base Case population		Sensitivity Case population	
	Base Case	Sensitivity		Deaths	95%CI	Deaths	95%CI
Agege	314,953	704,522	70	**10**	9–12	**23**	19–27
Ajeromi-Ifelodun	468,816	978,832	91	**20**	16–24	**41**	34–49
Alimosho*	900,075	1,396,016	86	**36**	30–43	**56**	46–66
Amuwo Odofin	224,393	358,016	131	**13**	11–16	**22**	18–26
Apapa	152,098	356,252	85	**6**	5–7	**14**	12–17
Badagry	162,155	259,436	42	**3**	3–4	**5**	4–6
Epe	123,960	220,710	42	**2**	2–3	**4**	4–5
Eti-Osa*	193,573	670,731	81	**7**	6–9	**25**	21–30
Ibeju-Lekki	80,346	67,884	42	**2**	1–2	**1**	1–2
Ifako-Ijave	291,758	507,608	64	**9**	7–10	**15**	13–18
Ikeja*	216,643	442,409	79	**8**	7–10	**16**	14–19
Ikorodu*	360,090	469,910	37	**6**	5–7	**8**	7–10
Kosofe	465,716	637,381	90	**19**	16–23	**27**	22–32
Lagos Island*	145,082	586,394	89	**6**	5–7	**24**	20–29
Lagos Mainland*	222,841	429,281	82	**8**	7–10	**16**	14–19
Mushin	430,987	901,239	142	**28**	23–33	**59**	49–70
Ojo	415,515	642,093	70	**13**	11–16	**21**	17–25
Oshodi	429,080	773,731	119	**23**	20–28	**42**	35–50
Shomolu	275,273	699,106	168	**21**	18–25	**54**	45–64
Surulere	343,002	869,080	64	**10**	9–12	**26**	22–31
Lagos State (Base Case)	**6,216,358**		**88**	250	210–300		
Lagos State (Sensitivity)		**11,970,630**	**90**			500	420–590

Source: Author's own elaboration.

Note: *LGAs where air monitors are located (mean monitored concentration over August 2020 to July 2021).

†Short-term mortality (based on the ERF by Orellano et al. 2020) during the 2-month period of January and February, assuming an excess PM_{10} exposure equal to the difference of the average concentration for the months January and February and the average of the shoulder months December and March.

FIGURE A1.12. HEALTH BENEFITS FOR A REDUCTION IN $PM_{2.5}$ AIR POLLUTION ACROSS LAGOS STATE



Source: Author's own elaboration

Note: The top figure shows the relative mortality reduction compared to the current state, while the figure below shows the averted deaths for the base-case population and GHE baseline mortality rates. The absolute benefit is roughly doubled for the sensitivity-case population.

TABLE A1.14. IMPACT ASSESSMENT OF AIR LEAD CONTAMINATION IN IKORODU

Population scenario	Lead (Pb) air concentration µg/m3	Children (under 6 years old)				Adults (over 40 years)				
		Population	Pb blood	IQ loss		Cardiovascular deaths	Pb blood	Pb attributable mortality		
			µg Pb/dL	Child	Total		µgPb/dL	Deaths	95%CI	
Base Case	1.35	125,499	5.4	6.21	779,349	475	2.7	285	*191*	*346*
Sensitivity Case	1.35	163,824	5.4	6.21	1,017,347	621	2.7	373	*250*	*453*

Source: Author's own elaboration.

A1.5.4. IMPACT OF LEAD EXPOSURE ON CHILDREN IQ AND CARDIOVASCULAR MORTALITY

Table A1.14 illustrates the results of the impact assessment of lead contamination in Ikorodu based on measured air contamination (1.35 µg/m³ air lead). We estimated that every child in Ikorodu (125,500 according to the base case and 163,800 according to the sensitivity population) is significantly affected by lead exposure. The calculated loss of intelligence by each child is 6.21 IQ points, which represents a huge physical burden on the current generation and potentially a significant loss of future income. The total loss in IQ points for the two populations is 780,000 and 1,017,000, respectively. Also, the impact of lead on cardiovascular mortality is remarkably high: the attributable premature mortality is 285 and 373 deaths, according to the base case and the sensitivity population, respectively.

A1.6. DISCUSSION AND CONCLUSION

The estimation of the health burden of disease in Lagos, Nigeria, indicates that air pollution from $PM_{2.5}$ poses a serious public health hazard, especially among children younger than 5 years. The PWE is high, reaching 47 µg/m³, a value nearly 10 times higher than the new recommended WHO air quality guideline of 5 µg/m³ (WHO 2021). Urgent action to reach the WHO IT 1 (35 µg/m³) is therefore recommended. The overall impact on mortality across the population of Lagos State is responsible for 15,850 to 30,350 premature deaths per year, with the largest contribution from infant mortality (between 7,800 and 14,900 infant deaths). For adult mortality, the impact is larger for cardiovascular diseases. The impact on morbidity, especially pneumonia and other acute respiratory conditions, in children 0–5 years (between 182,000 and 349,000) is particularly worrisome. Other outcomes were also estimated and they contribute to increasing the overall burden.

Two additional critical contributions should be added to the estimates' loss of life from long-term exposure to $PM_{2.5}$: (a) the impact of the daily high levels of PM_{10} during the *Harmattan* period, particularly during January and February and (b) industrial air pollution in Ikorodu with the relevant lead contamination, which accounts for a sizable loss of intellectual capacity in children (a total of 780,000 to more than 1 million IQ points at the population level) and a high attributable cardiovascular mortality in that particular LGA (285 to 373 premature cardiovascular deaths). The quantified health burdens should be interpreted as conservative estimates because the additional impact from direct exposure to other critical pollutants (for example, gaseous air pollutants such as NO_2 and SO_2) has not been quantified in this work. A preliminary estimate of the potential attributable burden on mortality from direct NO_2 exposure, for example, could add a further 10 percent to the $PM_{2.5}$ mortality. The adverse health effects from exposure to secondary inorganic aerosols (a component of PM) created through chemical transformation of NO_2 and SO_2 precursor emissions are already included in the $PM_{2.5}$ impact assessment.

The exposure assessment, one of the most important contributions of this study, is based on an extensive monitoring program of air pollution that has been set up in several locations and with standardized procedures and quality controls. The results of the monitoring program have been coupled with the results of a dispersion model and with population data to estimate PWEs by LGA. In this way, the concentration values are referred to the population, which is the target of the HIA. We have considered a variety of possible outcomes, encompassing both mortality (natural mortality, cause-specific mortality) and several morbidity outcomes. We have addressed not only $PM_{2.5}$ but also the complementary contributions of daily levels of PM_{10}, mainly attributable to Sahara desert dust, and the lead contamination in Ikorodu. Children are the segment of the population most affected by air pollution as they suffer from extraordinarily high infant mortality, experience frequent episodes of pneumonia and other respiratory disorders, and have to cope with a large limitation of their intellectual capability. It amounts to irreversible damage to the next generation. Finally, we have considered several methodological aspects in our assessment (exposure estimation, choice of the ERFs, alternative demographic assumptions) to overcome the main limitations described further below.

The HIA for Lagos refers to the most recent period of ambient air pollution monitoring—August 2020 to July 2021. This is the period with the most accurate measurement of air pollution. On the other hand, the other data for the HIA refer to a preceding period (that is, 2018 population data and available health statistics for 2017 and 2018). We believe that the error induced by this choice is minimal because the recent mortality rate has trended lower over the past decade, although at the same time population growth has been observed. The net effect is that our estimates are on the conservative side. In addition, it should be noted that the measurement period occurred during the COVID-19 pandemic, which has affected Africa and Nigeria as well, with a decrease in economic activity as reflected by the change in the internal gross product, a 3.5 percent drop in 2020 at the national level compared to the previous year when there was no COVID-19. This aspect makes our assessment for 2020–2021 somewhat conservative in comparison to the air pollution data probably experienced in past years.

The most relevant uncertainty regarding our work is due to the difficulty in the estimation of the population at risk. Two different sources have been considered in this work because they provide potential extremes of the population size estimate. Assumptions about age distribution across different LGAs, often driven by operational choices, are another source of uncertainty. The difficulties in such estimations stem from the large size of slum settlements that have become a prominent feature of the urban landscape of Sub-Saharan Africa, and from the dynamic nature of this population (Amegah 2021; Thomson et al. 2021). We are confident that our sensitivity choices, though imperfect and leading to a broad spread in the estimates, are the best approach to characterizing the potential size range of the Lagos population.

Another concern about the estimates is related to the absence of reliable baseline health data for the entire population. The value of good-quality mortality data for public health is widely acknowledged. While effective civil registration systems remain the "gold standard" source for continuous mortality measurement, in most African countries fewer than 25 percent of deaths are registered, and it appears to be no different in Lagos (Joubert et al. 2012). In addition, only a fraction of the hospital institutions (the public sector) register mortality and morbidity statistics, and a large fraction of health care providers do not release regular information. This difficulty is coupled with the traditional lack of medical certification for persons dying at home. We have used two sources of mortality information related to Nigeria (GBD and WHO) and have scaled down to Lagos, accounting for the differences between national and local age distributions. For hospitalizations, we have used the registrations of the events in the public sector with the strong assumption that the private sector has a proportionally similar load of patients. Finally, it is clear that a source-specific HIA was not performed as a clear partition of $PM_{2.5}$ exposure data was not available.

Before comparing the present HIA with other evaluations conducted worldwide and in Africa, it is worth noting the strengths and limitations of the present work. There are only a few examples of HIAs in Africa. Wheida et al. (2018) notably conducted an HIA to quantify the mortality attributable to long-term exposure to $PM_{2.5}$, NO_2, and O_3 in Greater Cairo (Egypt). As in Lagos, $PM_{2.5}$ concentrations vary from 50 to over 100 μg/m^3 in the different sectors of the Egyptian megacity, with an average concentration of 75 μg/m^3. In the population older than 30 years, 11 percent of the natural mortality could be attributed to $PM_{2.5}$. No assessment of infant mortality and childhood morbidity was conducted. In Ethiopia, Kumie et al. (2021) performed real-time monitoring of $PM_{2.5}$ concentrations and assessed the health impact in Addis Ababa. After a continuous measurement of 3 years, the annual average $PM_{2.5}$ concentration was found to be 42.4 μg/m^3. The $PM_{2.5}$ related mortality was estimated at 2,043 premature deaths, assuming a counterfactual equal to 10 μg/m^3. Finally, in Ghana, a series of studies are ongoing in Accra to address various sources of air pollution such as waste management (Kanhai et al. 2021) and transportation (Garcia et al. 2021).

These studies, however, rely on effect estimates from other parts of the world because data from the African continent are largely deficient due to low access to good-quality health care, the high prevalence of infectious diseases, and different sources of air pollutants. As a

TABLE A1.15. COMPARISON OF CURRENT ESTIMATES OF $PM_{2.5}$ MORTALITY RATES IN LAGOS STATE TO ESTIMATES FROM PREVIOUS WORK BY CROITORU, CHANG AND KELLY (2020)

Risk model	Croitoru, Chang, and Akpokodje (2020)	This study
IER functions for deaths due to cardiovascular and respiratory plus lung cancer and diabetes		$PM_{2.5}$ concentration: 47 μg/m^3 based on 1-year, 2020–21, measuring campaign 2019 IER functions (GBD 2020) **Base case** population: 13.3 million Mortality rate (per 10^5): **38.5** **Sensitivity** population: 25.6 million Mortality rate (per 10^5): **37.0**
IER functions for deaths due to cardiovascular and respiratory plus lung cancer and diabetes	$PM_{2.5}$ concentration: 68 μg/m^3 Population size: 24.4 million GBD 2018 IER function Mortality rate (per 10^5): **45.9**	$PM_{2.5}$ concentration: 68 μg/m^3, same as Croitoru, Chang, and Akpokodje (2020) 2019 IER functions (GBD 2020) **Base case** population: 13.3 million Mortality rate (per 10^5): **47.0** Sensitivity population: 25.6 million Mortality rate (per 10^5): **45.5**
GEMM for NCD and=d lower respiratory illnesses plus Heft-Neal et al. (2018) for infant mortality		$PM_{2.5}$ concentration: 47 μg/m^3 based on 1-year, 2020–21, measuring campaign **Base case** population: 13.3 million Mortality rate (per 10^5): **119.2** **Sensitivity** population: 25.6 million Mortality rate (per 10^5): **118.6**

result, the health effects in Africa are likely underestimated (Abera et al. 2021). The paper by Heft-Neal et al. (2018), for example, found that in the African context, a 10 μg/m^3 increase in $PM_{2.5}$ concentration was associated with a 9.2 percent rise in infant mortality. $PM_{2.5}$ concentrations were responsible for 22 percent of infant deaths in the 30 countries of Africa considered in the study. This was equivalent to 449,000 additional infant deaths in 2015, an estimate that was more than three times higher than previous estimates (Heft-Neal et al. 2018). Finally, the recent work by Fisher et al. (2021) should be noted because they conducted an HIA for air pollution for the entire continent of Africa and indicated that ambient air pollution is increasing across the continent. In the absence of a deliberate intervention, it will likely increase morbidity and mortality, which will diminish economic productivity, impair human capital formation, and undercut development.

In 2020, Croitoru, Chang and Kelly published the first HIA of the burden of fine particulate matter in Lagos State. According to this study, in 2018, 11,200 premature deaths (45.9 deaths per 100,000 population) were attributed to exposure to $PM_{2.5}$ air pollution. The mortality was quantified using the 2017 version of the cause-specific IER functions (GBD 2018). In Table A1.15, we compare our mortality figures with the estimates calculated by Croitoru, Chang and Kelly (2020) using the 2019 IER functions (GBD 2020) for cardiovascular and respiratory mortality, lung cancer, and diabetes deaths. We also provide results based on the relationships of Heft-Neal et al. (2018) for infant mortality, and GEMM (Burnett et al. 2018) for deaths in the broader category of NCDs plus lower respiratory illnesses, for various Lagos State population choices (base case versus sensitivity), with different values of the annual $PM_{2.5}$ exposure—47 μg/m^3 used in this study based on the 1-year measuring campaign 2020–2021 and 68 μg/m^3 used in Croitoru, Chang and Kelly (2020). The baseline mortality was estimated using the WHO GHE hazard rates. Our mortality rates are consistent with the results of Croitoru, Chang and Kelly (2020) when assuming the same $PM_{2.5}$ exposure (68 μg/m^3) and using the same impact risk model (GBD IER), but our mortality estimates increase by a factor of 2.5 when switching from the IER model to the GEMM and Heft-Neal et al. relationships. This difference is due in part to the size of the baseline mortality used by the different models (Table A1.9), but, more importantly, the difference is related to the shape of the ERFs (Figure A1.7). For instance, the rate of decrease in the health risk at higher exposures using the GEMM relationship is much less than predicted by the IER model.

In conclusion, the work illustrates a dramatic situation in Lagos that highlights the large burden of PM air pollution on public health. A future analysis would benefit from greater knowledge about exposure assessment, possibly source-specific, and systematic collection of demographic and health data. Further, it would be useful in follow-up analyses to undertake regional and/or local epidemiologic studies in Lagos so that ERFs would better reflect local conditions. Short of that, it would be ideal to develop disease-specific mortality risk estimates for Lagos that could be utilized to enhance the accuracy of the burden assessment from $PM_{2.5}$ exposure.

REFERENCES

Abera, A., J. Friberg, C. Isaxon, M. Jerrett, E. Malmqvist, C. Sjöström, T. Taj, and A. M. Vargas. 2021. "Air Quality in Africa: Public Health Implications." *Annu Rev Public Health* 42:193–210. Doi:10.1146/annurev-publhealth-100119-113802.

Amegah, A. K. 2021. "Slum Decay in Sub-Saharan Africa: Context, Environmental Pollution Challenges, and Impact on Dweller's Health." *Environ Epidemiol* 5 (3): e158. doi:10.1097/EE9.0000000000000158.

Brown, L., M. Lynch, A. Belova, R. Klein, and A. Chiger. 2020. "Developing a Health Impact Model for Adult Lead Exposure and Cardiovascular Disease Mortality." *Environ Health Perspect* 128 (9): 97005. doi:10.1289/EHP6552.

Burnett R., H. Chen, M. Szyszkowicz, N. Fann, B. Hubbell, C. A. Pope 3rd, J. S. Apte, et al. 2018. "Global Estimates of Mortality Associated with Long-Term Exposure to Outdoor Fine Particulate Matter." *Proc Natl Acad Sci U S A* 115 (38): 9592–97. doi:10.1073/pnas.1803222115.

Burnett, R., and A. Cohen. 2020. "Relative Risk Functions for Estimating Excess Mortality Attributable to Outdoor $PM_{2.5}$ Air Pollution: Evolution and State-of-the-Art." *Atmosphere* 11: 589. https://doi.org/10.3390/atmos11060589.

Burnett, R. T., C. A. Pope, M. Ezzati, C. Olives, S. S. Lim, S. Mehta, H. H. Shin, et al. 2014. "An Integrated Risk Function for Estimating the Global Burden of Disease Attributable to Ambient Fine Particulate Matter Exposure." *Environ Health Perspect* 122 (4): 397–403.

Chen, J., and G. Hoek. 2020. "Long-Term Exposure to PM and All-Cause and Cause-Specific Mortality: A Systematic Review and Meta-Analysis." *Environ Int* 143: 105974. doi:10.1016/j.envint.2020.105974.

Cohen A. J., H. R. Anderson, B. Ostro B, K. D. Pandey, M. Krzyzanowski, N. Künzli, K. Gutschmidt, et al. 2004. Chapter 17. "Urban air pollution." In Ezzati M, Lopez A. D., Rodgers A., Murray C.J.L. (eds): *Comparative quantification of health risks: global and regional burden of disease due to selected major risk factors*. Volume 1. Geneva, Switzerland: World Health Organization.

Croitoru, L., J. C. Chang, and J. Akpokodje. 2020. "The Health Cost of Ambient Air Pollution in Lagos." *Journal of Environmental Protection* 11:753–765. https://doi.org/10.4236/jep.2020.119046.

De Longueville, F., Y. C. Hountondji, S. Henry, and P. Ozer. 2010. "What Do We Know About Effects of Desert Dust on Air Quality and Human Health in West Africa Compared to Other Regions?" *Sci Total Environ* 409 (1): 1–8. doi:10.1016/j.scitotenv.2010.09.025.

Etyang, A. and J. Scott. 2013. "Medical Causes of Admissions to Hospital among Adults in Africa: A Systematic Review." *Global Health Action* 6:19090. http://dx.doi.org/10.3402/gha.v6i0.19090.

Fisher, S., D. C. Bellinger, M. L. Cropper, P. Kumar, A. Binagwaho, J. B. Koudenoukpo, Y. Park, G. Taghian, and P. J. Landrigan. 2021. "Air Pollution and Development in Africa: Impacts on Health, the Economy, and Human Capital." *Lancet Planet Health*. 5 (10): e681–e688. doi:10.1016/S2542-5196(21)00201-1. PMID: 34627472.

Garcia, L., R. Johnson, A. Johnson, A. Abbas, R. Goel, L. Tatah, J. Damsere-Derry, et al. 2021. "Health Impacts of Changes in Travel Patterns in Greater Accra Metropolitan Area, Ghana." *Environ Int* 155:106680. doi:10.1016/j.envint.2021.106680.

GBD 2017 Risk Factor Collaborators. 2018. "Global, Regional, and National Comparative Risk Assessment of 84 Behavioural, Environmental and Occupational, and Metabolic Risks or Clusters of Risks for 195 Countries and Territories, 1990–2017: A Systematic Analysis for the Global Burden of Disease Study." *Lancet* 392:1923–1994.

GBD 2019 Risk Factors Collaborators. 2020. "Global Burden of 87 Risk Factors in 204 Countries and Territories, 1990–2019: A Systematic Analysis for the Global Burden of Disease Study 2019." *Lancet* 396 (10258): 1223–49. doi:10.1016/s0140-6736(20)30752-2.

Heft-Neal, S., J. Burney, E. Bendavid, and M. Burke. 2018. "Robust Relationship between Air Quality and Infant Mortality in Africa." *Nature* 559 (7713): 254–258. doi: 10.1038/s41586-018-0263-3.

Hoek, G., M. K. Krishnan, R. Beelen, A. Peters, B. Ostro, and J. Kaufman. 2013. "Long-Term Air Pollution Exposure and Cardio-Respiratory Mortality." *Environmental Health* 12:43.

Huangfu, P., and R. Atkinson. 2020. "Long-term Exposure to NO2 and O3 and All-Cause and Respiratory Mortality: A Systematic Review and Meta-Analysis." *Environ Int.* 144:105998. doi: 10.1016/j.envint.2020.105998.

IHME. 2021. Global Health Data Exchange (GHDx, IHME). http://ghdx.healthdata.org/gbd-results-tool.

Joubert, J., C. Rao, D. Bradshaw, R. E. Dorrington, T. Vos, and A. D. Lopez. 2012. "Characteristics, Availability and Uses of Vital Registration and Other Mortality Data Sources in Post-Democracy South Africa." *Glob Health Action* 5:1–19. doi:10.3402/gha.v5i0.19263.

Kanhai, G., J. N. Fobil, B. A. Nartey, J. V. Spadaro, and P. Mudu. 2021. "Urban Municipal Solid Waste Management: Modeling Air Pollution Scenarios and Health Impacts in the Case of Accra, Ghana." *Waste Manag* 123:15–22. doi:10.1016/j.wasman.2021.01.005.

Kumie, A., A. Worku, Z. Tazu, W. Tefera, A. Asfaw, G. Boja, M. Mekashu, et al. 2021. "Fine Particulate Pollution Concentration in Addis Ababa Exceeds the WHO Guideline Value: Results of 3 Years of Continuous Monitoring and Health Impact Assessment." *Environ Epidemiol* 5 (3): e155. doi:10.1097/EE9.0000000000000155.

Kunzli, N., R. Kaiser, S. Medina, M. Studnicka, O. Chanel, P. Filliger, M. Herry, et al. 2000. "Public-Health Impact of Outdoor and Traffic-Related Air Pollution: A European Assessment." *Lancet* 356:795–801.

Lanphear, B. P., R. Hornung, J. Khoury, K. Yolton, P. Baghurst, D. C. Bellinger, R. L. Canfield, et al. 2005. "Low-Level Environmental Lead Exposure and Children's Intellectual Function: An International Pooled Analysis." *Environ Health Perspect* 113 (7): 894–899. doi:10.1289/ehp.7688.

McAllister, D., L. Liu, T. Shi, Y. Chu, C. Reed, J. Burrows, D. Adeloye, et al. 2019. "Global, Regional, and National Estimates of Pneumonia Morbidity and Mortality in Children Younger than 5 Years between 2000 and 2015: A Systematic Analysis." *Lancet Global Health* 7:e47–57. http://dx.doi.org/10.1016/S2214-109X(18)30408-X.

McDuffie, E. E., R. V. Martin, J. V. Spadaro, R. Burnett, S. J. Smith, P. O'Rourke, M. S. Hammer, et al. 2021. "Source Sector and Fuel Contributions to Ambient PM(2.5) and Attributable Mortality Across Multiple Spatial Scales." *Nat Commun* 12 (1): 3594. doi:10.1038/s41467-021-23853-y.

Orellano, P., J. Reynoso, N. Quaranta, Bardach, A., and A. Ciapponi. 2020. "Short-Term Exposure to Particulate Matter (PM(10) and PM(2.5)), Nitrogen Dioxide (NO(2)), and Ozone (O(3)) and All-Cause and Cause-Specific Mortality: Systematic Review and Meta-Analysis." *Environ Int* 142:105876. doi:10.1016/j.envint.2020.105876.

Ostro, B., and L. Chestnut. 1998. "Assessing the Health Benefits of Reducing Particulate Matter Air Pollution in the United States." *Environ Res* 76:94–106.

Pew Charitable Trusts. 2017. "Health Impacts Project. Policies to Prevent and Respond to Childhood Lead Exposure An Assessment of the Risks Communities Face and Key Federal, State, and Local Solutions." https://www.pewtrusts.org/-/media/assets/2017/08/hip_childhood_lead_poisoning_report.pdf.

Pope, C. A., 3rd, R. T. Burnett, D. Krewski, M. Jarrett, Y. Shi, E. E. Calle, and M. J. Thun. 2009. "Cardiovascular Mortality and Exposure to Airborne Fine Particulate Matter and Cigarette Smoke: Shape of the Exposure-Response Relationship." *Circulation* 120 (11): 941–8.

Pope, C. A., 3rd, R. T. Burnett, M. C. Turner, A. Cohen, D. Krewski, M. Jerrett, S. M. Gapstur, and M. J. Thun. 2011. "Lung Cancer and Cardiovascular Disease Mortality Associated with Ambient Air Pollution and Cigarette Smoke: Shape of the Exposure-Response Relationships." *Environ Health Perspect* 119 (11): 1616–21.

Pope, C. A, 3rd, M. J. Thun, E. E. Calle, D. Krewski, K. Ito, and G. D. Thurston. 2002. "Lung Cancer, Cardiopulmonary Mortality, and Long-Term Exposure to Fine Particulate Air Pollution." *JAMA* 287:1132–1141.

Querol, X., A. Tobías, N. Pérez, A. Karanasiou, F. Amato, M. Stafoggia, C. Pérez García-Pando, et al. 2019. "Monitoring the Impact of Desert Dust Outbreaks for Air Quality for Health Studies." *Environ Int* 130:104867. doi: 10.1016/j.envint.2019.05.061.

Ruckart, P. Z., R. L. Jones, J. G. Courtney, T. T. LeBlanc, W. Jackson, M. P. Karwowski, P. Cheng, P. Allwood, E. R. Swendsen, and P. N. Breysse. 2021. "Update of the Blood Lead Reference Value — United States, 2021." *MMWR Morb Mortal Wkly Rep* 70:1509–1512. doi:http://dx.doi.org/10.15585/mmwr.mm7043a4external icon.

Thomson, D. R., A. E. Gaughan, F. R. Stevens, G. Yetman, P. Elias, and R. Chen, 2021. "Evaluating the Accuracy of Gridded Population Estimates in Slums: A Case Study in Nigeria and Kenya." *Urban Sci* 5:48. https://doi.org/10.3390/urbansci5020048.

Thurston, G. D., H. Kipen, I. Annesi-Maesano, J. Balmes, R. D. Brook, K. Cromar, S. De Matteis, et al. 2017. "A Joint ERS/ATS Policy Statement: What Constitutes an Adverse Health Effect of Air Pollution? An Analytical Framework." *Eur Respir J* 49 (1): 1600419. doi:10.1183/13993003.00419-2016.

US EPA. 1999. "Implementer's Guide to Phasing Out Lead in Gasoline."

US EPA. 2019. "Integrated Science Assessment for Particulate Matter." EPA/600/R-19/188. U.S. Environment Protection Agency, Research Triangle Park 2019.

Vohra, K., A. Vodonos, J. Schwartz, E. A. Marais, M. P. Sulprizo, and L. J. Mickley. 2021. "Global Mortality from Outdoor Fine Particle Pollution Generated by Fossil Fuel Combustion: Results from GEOS-Chem." *Environ Res* 195:110754. doi:10.1016/j.envres.2021.110754.

Wheida, A., A. Nasser, M. El Nazer, A. Borbon, G. A. Abo El Ata, M. Abdel Wahab, and S. C. Alfaro. 2018. "Tackling the Mortality from Long-Term Exposure to Outdoor Air Pollution in Megacities: Lessons from the Greater Cairo Case Study." *Environ Res* 160: 223–231. doi:10.1016/j.envres.2017.09.028.

WHO. 2000. *Evaluation and Use of Epidemiological Evidence for Environmental Health Risk Assessment.* Copenhagen: WHO Regional Office for Europe, EUR/00/5020369 (E68940).

WHO. 2001. *Quantification of Health Effects of Exposure to Air Pollution*. Report on a WHO Working Group. Bilthoven, Netherlands, November 20–22, 2000. WHO Regional Office for Europe, EUR/01/5026342 (E74256).

WHO. 2013a. *Review of Evidence on Health Aspects of Air Pollution – REVIHAAP Project: Technical Report*. Copenhagen: WHO Regional Office for Europe. http://www.euro.who.int/__data/assets/pdf_file/0004/193108/REVIHAAP-Final-technical-report.pdf.

WHO. 2013b. *Health Risks of Air Pollution in Europe — HRAPIE Project. Recommendations for Concentration–Response Functions for Cost–Benefit Analysis of Particulate Matter, Ozone and Nitrogen Dioxide*. Copenhagen, Denmark: WHO.

WHO. 2021. *WHO Global Air Quality Guidelines. Particulate Matter (PM2.5 and PM10), Ozone, Nitrogen Dioxide, Sulfur Dioxide and Carbon Monoxide*. https://apps.who.int/iris/handle/10665/345329.

WHO Regional Office for Europe. 2016. *Health Risk Assessment of Air Pollution – General Principles*. Copenhagen: WHO Regional Office for Europe.

World Bank. 2020. *The Cost of Coastal Zone Degradation in Nigeria: Cross River, Delta and Lagos States*.

ANNEX 2
SUPPLEMENTARY MATERIAL

Annex S1: Estimating the Health and Mortality Effects of Air Pollution in Lagos

A2.1. MORTALITY AND MORBIDITY DATA AT THE LOCAL LEVEL

Summary statistics for inpatient and outpatient data reported for 2017 in Lagos have been collected. The data relevant for the HIA are synthesized in the tables below.

TABLE A2.1. INPATIENT HOSPITAL ADMISSIONS, 2017

Disease	ICD-10	Cases	Deaths	Comment
Ischemic heart disease (IHD)	120-25	5	0	Ages 15+: four cases
Stroke		842	171	Listed as code 170
Chronic obstructive pulmonary disease (COPD)	J40-44	12	0	Asthma (J45): 159 cases (no deaths)
Lung cancer	C30-39	31	1	Ages 15+: 28 cases; 1 infant death
Diabetes	E10-14	556	35	Ages 15+: 541 cases & 35 deaths
Pneumonia	J12-18	1,412	46	Under 5:1,221 cases & 41 deaths
Other Acute lower respiratory infections (ALRI)	J20-22	276	8	Under 5: 227 cases & 3 deaths

TABLE A2.2. SHARE OF TOTAL INPATIENT HOSPITAL ADMISSIONS BY DISEASE

Disease	Incidences	Deaths
Circulatory	**27.0%**	**65.5%**
IHD	0.2%	–
Stroke	26.9%	65.5%
Respiratory	**55.2%**	**21.1%**
COPD	0.4%	–
Lung cancer	1%	0.4%
ALRI	53.9%	20.7%
Diabetes	**17.7%**	**13.4%**

TABLE A2.3. OUTPATIENT HOSPITAL ADMISSIONS, 2017

Disease	ICD-10	Cases	Deaths	Comment
Ischemic heart disease (IHD)	120-25	729	0	Ages 15+: 729 cases
Stroke		2,758	128	Listed as code 170
Chronic obstructive pulmonary disease (COPD)	J40-44	293	0	Asthma (J45): 4,413 cases (2 deaths)
Lung cancer	C30-39	3	1	Ages 50+: 3 cases (1 death)
Diabetes	E10-14	8,203	24	Ages 15+: 8,202 cases & 24 deaths
Pneumonia	J12-18	6,338	37	Under 5: 3,964 cases & 30 deaths
Other Acute lower respiratory infections (ALRI)	J20-22	3,860	6	Under 5: 1,902 cases & 4 deaths

TABLE A2.4. SHARE OF OUTPATIENT HOSPITAL ADMISSIONS BY DISEASE

Disease	Incidences	Deaths
Circulatory	**15.7%**	**65.3%**
IHD	3.3%	–
Stroke	12.4%	65.3%
Respiratory	**47.3%**	**22.4%**
COPD	1.3%	–
Lung cancer	0.01%	0.5%
ALRI	46.0%	21.9%
Diabetes	**37.0%**	**12.2%**

As a comparison to the Lagos data, the relative distribution of deaths for six GBD causes of death at the national level in 2019 (IHME 2021) is reported in the table below.

IHD+Stroke	LRI	COPD	LC	DM	6-COD Total
38.1%	49.5%	4.0%	1.8%	6.5%	349,146

Note: The mortality ratio CVM (cardiovascular mortality) to LRI (lower respiratory infections) is about 3:1 in Lagos versus 0.77 at the national level.

A2.2. SENSITIVITY CALCULATIONS USING AN ALTERNATIVE ASSESSMENT OF THE PWE

In the following tables and figures, results of a sensitivity assessment of the exposures are presented: for non-monitored LGA, $PM_{2.5}$ concentration estimates have been assigned based on the LGA's proximity to the nearest monitoring station.

TABLE A2.5. ANNUAL PM PWE BY LGA FOR THE SENSITIVITY ANALYSIS

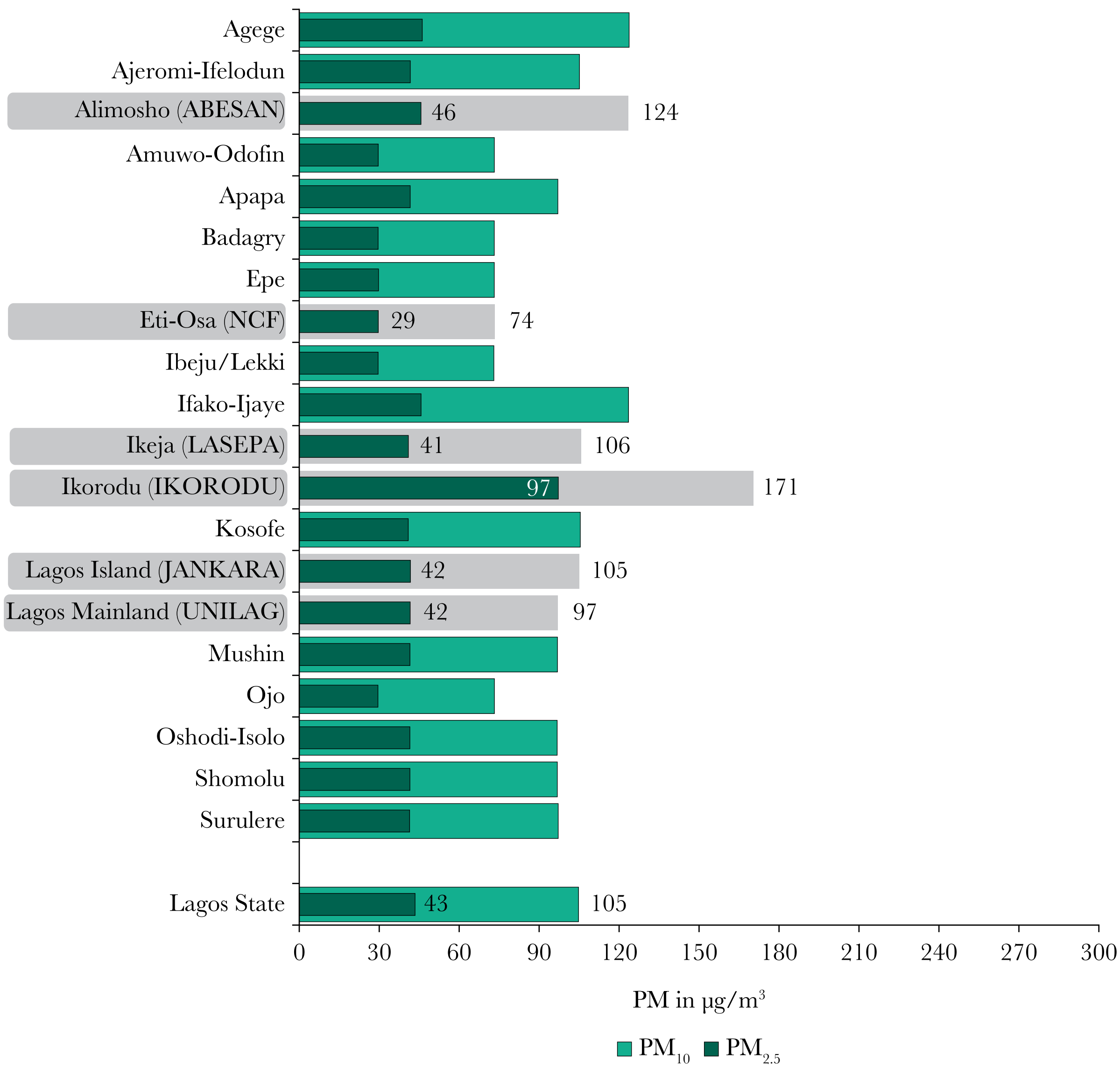
Local Government Area (LGA)	Longitude (deg)	Latitude (deg)	Land Area (km^2)	Population (all ages)		PWE, mg/m^3	
				Base Case	Sensitivity	$PM_{2.5}$	PM_{10}
Agege	3.316	6.623	17.0	673,840	1,507,591	46	124
Ajeromi-Ifelodun	3.337	6.456	13.9	1,003,027	2,094,583	42	105
Alimosho*	3.255	6.576	137.8	1,925,702	2,987,306	46	124
Amuwo Odofin	3.279	6.439	179.1	480,086	766,111	29	74
Apapa	3.371	6.435	38.5	325,412	762,336	42	97
Badagry	2.914	6.442	443.0	346,930	555,162	29	74
Epe	3.973	6.553	965.0	265,212	472,292	29	74
Eti-Osa*	3.536	6.452	299.1	414,147	1,435,282	29	74
Ibeju-Lekki	3.911	6.454	653.0	171,900	145,263	29	74
Ifako-Ijaye	3.309	6.665	43.0	624,214	1,086,220	46	124
Ikeja*	3.350	6.604	49.9	463,507	946,703	41	106
Ikorodu*	3.566	6.612	345.0	770,410	1,005,551	97	171
Kosofe	3.399	6.600	84.4	996,396	1,363,919	41	106
Lagos Island*	3.392	6.454	9.3	310,402	1,254,812	42	105
Lagos Mainland*	3.383	6.499	19.6	476,766	918,609	42	97
Mushin	3.347	6.530	14.1	922,094	1,928,542	42	97
Ojo	3.153	6.454	182.0	888,990	1,374,002	29	74
Oshodi	3.314	6.542	42.0	918,014	1,655,691	42	97

TABLE A2.5. *(Continued)*

Local Government Area (LGA)	Longitude (deg)	Latitude (deg)	Land Area (km^2)	Population (all ages)		PWE, mg/m^3	
				Base Case	Sensitivity	$PM_{2.5}$	PM_{10}
Shomolu	3.383	6.538	14.6	588,944	1,496,003	42	97
Sunilere	3.345	6.492	27.1	733,851	1,859,727	42	97
Lagos State (Base Case population)			**3,577**	**13,299,845**		**43**	**105**
Lagos State (Sensitivity population)			**3,577**		**25,615,703**	**42**	**103**

Source: Author's own elaboration.

FIGURE A2.1. AMBIENT AIR QUALITY IN LAGOS STATE AND LGAS FOR PWE SENSITIVITY ANALYSIS



Source: Author's own elaboration.

Note: The six LGAs where daily ambient concentrations were monitored during the monitoring campaign between August 2020 and July 2021 are highlighted by the gray boxes along the y-axis on the left.

TABLE A2.6. $PM_{2.5}$ ATTRIBUTABLE HEALTH BURDENS FOR PWE SENSITIVITY ANALYSIS, BASE CASE POPULATION

Local Government Area (LGA)	Infant Mortality	Total Mortality* (all ages)		Lower Respiratory Infections Children under 5-years		Onset Chronic Bronchitis Adults over 27-years		Restricted Activity Days All ages (in thousands)		Hospital Admissions All ages, cardiovascular and respiratory	
	Deaths	**Deaths**	**95%CI**	**Cases**	**95%CI**	**Cases**	**95%CI**	**Cases**	**95%CI**	**Cases**	**95%CI**
Agege	**400**	**820**	520–1,060	**9,350**	2,870–16.410	**810**	410–970	**2,300**	2,080–2,560		2–145
Ajeromi-Ifelodun	**550**	**1,140**	720–1,480	**12,910**	3,910–23,160	**1,110**	540–1,360	**3,140**	2,840–3,490	**100**	3–198
Alimosho	**1,130**	**2,320**	1,470–3,020	**26,730**	8,220–46.890	**2,320**	1,180–2,760	**6,580**	5,950–7,310	**211**	6–415
Amuwo Odofin	**190**	**410**	260–550	**4,550**	1,310–8,760	**420**	190–550	**1,060**	960–1,190	**33**	1–67
Apapa	**180**	**370**	230–480	**4,200**	1,270–7.530	**340**	160–430	**1,020**	920–1,140	**33**	1–64
Badagrv	**140**	**300**	190–400	**3,280**	950–6,330	**300**	140–400	**770**	690–860	**24**	1–48
Epe	**100**	**220**	140–300	**2,510**	730–4,840	**230**	100–300	**590**	530–660	**18**	1–37
Eti-Osa	**160**	**350**	220–470	**3,920**	1,130–7,560	**360**	160–470	**920**	830–1,030	**29**	1–57
Ibeju-Lekki	**70**	**150**	90–200	**1,630**	470–3,140	**150**	70–200	**380**	340–430	**12**	0–24
Ifako-Ijaye	**370**	**760**	480–980	**8,660**	2,660–15,200	**750**	380–900	**2,130**	1,930–2,370	**68**	2–134
Ikeja	**250**	**520**	330–670	**5,860**	1,770–10,570	**510**	250–630	**1,420**	1,290–1,580	**45**	1–89
Ikorodu	**810**	**1,510**	1,000–1,860	**18,210**	6,710–25,370	**1,060**	610–1,190	**5,170**	4,730–5,670	**177**	6–334
Kosofe	**530**	**1,100**	700–1,450	**12,600**	3,800–22,710	**1,100**	530–1,350	**3,060**	2,760–3,400	**97**	3–192
Lagos Island	**170**	**350**	220–460	**4,000**	1,210–7,170	**340**	170–420	**970**	880–1,080	**31**	1–61
Lagos Mainland	**260**	**540**	340–700	**6,160**	1,870–11,030	**500**	240–630	**1,500**	1,350–1,670	**48**	1–94
Mushin	**500**	**1,040**	660–1,360	**11,900**	3,610–21,330	**970**	460–1,210	**2,900**	2,620–3,220	**92**	3–182
Ojo	**350**	**760**	480–1,010	**8,420**	2,430–16,230	**780**	350–1,020	**1,970**	1,780–2,200	**62**	2–123
Oshodi	**500**	**1,040**	660–1,350	**11,850**	3,590–21,240	**970**	460–1,200	**2,880**	2,610–3,210	**92**	3–182
Shomolu	**320**	**660**	420–870	**7,600**	2,300–13,630	**620**	290–770	**1,850**	1,670–2,060	**59**	2–116
Surulere	**400**	**830**	520–1,080	**9,470**	2,870–16,980	**770**	370–960	**2,310**	2,080–2,560	**73**	2–145
Lagos State	**7,380**	**15,180**	9,650–19,740	**173,800**	53,700–306,100	**14,430**	7,050–17,720	**42,920**	38,900–47,700	**1,380**	42–2,710

Note: *Baseline rates obtained from the WHO GHE database for 2018.

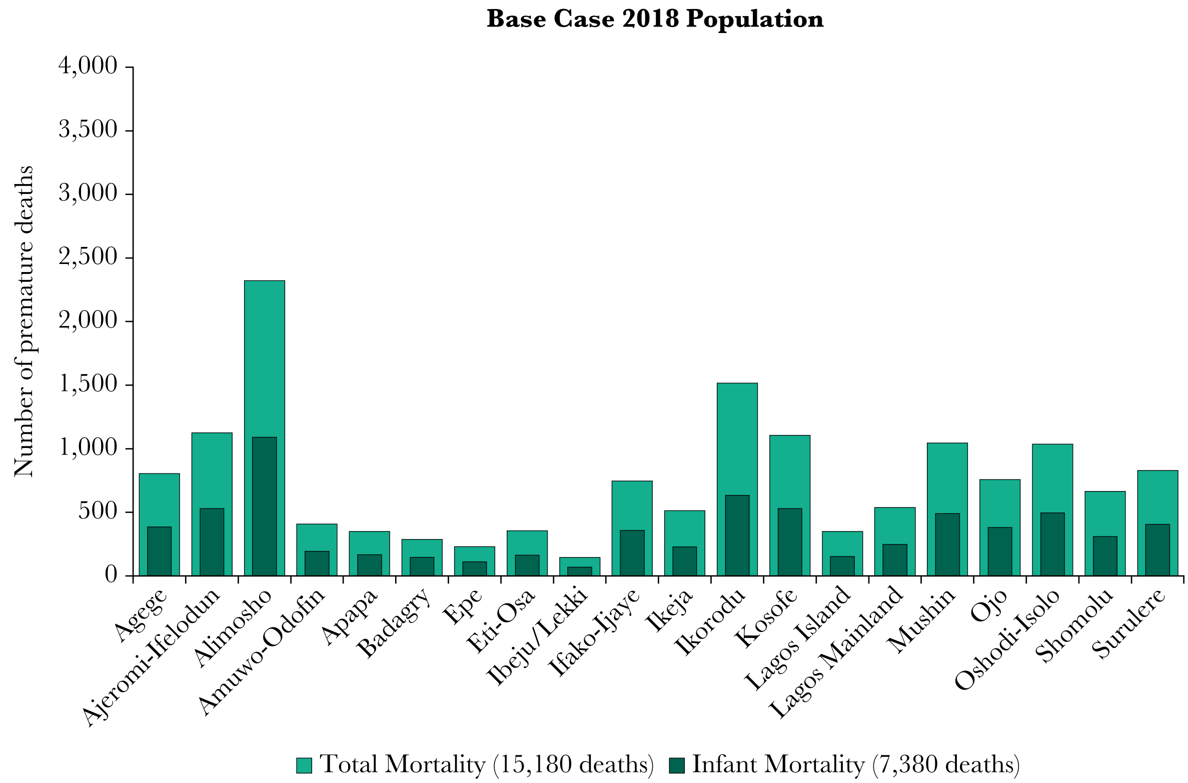
TABLE A2.7. $PM_{2.5}$ ATTRIBUTABLE HEALTH BURDENS FOR PWE SENSITIVITY ANALYSIS, SENSITIVITY POPULATION

Local Government Area (LGA)	Infant Mortality	Total Mortality* (all ages)		Lower Respiratory Infections Children under 5-years		Onset Chronic Bronchitis Adults over 27-years		Restricted Activity Days All ages (in thousands)		Hospital Admissions All ages, cardiovascular and respiratory	
	Deaths	**Deaths**	**95%CI**	**Cases**	**95%CI**	**Cases**	**95%CI**	**Cases**	**95%CI**	**Cases**	**95%CI**
Agege	**890**	**1,820**	1,150–2,360	**20,930**	6,430–36,710	**1,810**	920–2,160	**5,150**	4,660–5,720	**165**	5–325
Ajeromi-Ifelodun	**1,140**	**2,360**	1,500–3,090	**26,960**	8,170–48,360	**2,310**	1,120–2,840	**6,560**	5,930–7,290	**209**	6–413
Alimosho	**1,760**	**3,610**	2,290–4,680	**41,470**	12,750–72,750	**3,590**	1,830–4,280	**10,200**	9,230–11,340	**327**	10–644
Amuwo Odofin	**300**	**650**	410–870	**7,250**	2,100–13,990	**670**	300–880	**1,700**	1,530–1,900	**53**	2–106
Apapa	**420**	**870**	540–1,120	**9,840**	2,980–17,640	**800**	380–1,000	**2,400**	2,170–2,660	**76**	2–151
Badagry	**220**	**480**	300–630	**5,260**	1,520–10,140	**490**	220–640	**1,230**	1,110–1,370	**39**	1–77
Epe	**190**	**410**	250–540	**4,470**	1,290–8,620	**410**	180–540	**1,050**	940–1,170	**33**	1–66
Eti-Osa	**570**	**1,230**	770–1,630	**13,590**	3,930–26,200	**1,260**	560–1,640	**3,180**	2,870–3,550	**100**	3–199
Ibeju-Lekki	**60**	**130**	80–170	**1,380**	400–2,650	**130**	60–170	**320**	290–360	**10**	0–20
Ifako-Ijaye	**640**	**1,310**	830–1,700	**15,080**	4,630–26,450	**1,310**	670–1,560	**3,710**	3,360–4,120	**119**	4–234
Ikeja	**510**	**1,050**	660–1,370	**11,970**	3,610–21,580	**1,050**	510–1,280	**2,900**	2,630–3,230	**92**	3–183
Ikorodu	**1,060**	**1,980**	1,310–2,420	**23,770**	8,760–33,120	**1,390**	790–1,560	**6,740**	6,170–7,400	**231**	7–435
Kosofe	**730**	**1,520**	960–1,980	**17,250**	5,210–31,090	**1,510**	730–1,850	**4,180**	3,780–4,660	**133**	4–263
Lagos Island	**680**	**1,410**	900–1,850	**16,150**	4,890–28,970	**1,380**	670–1,700	**3,930**	3,550–4,370	**125**	4–247
Lagos Mainland	**500**	**1,040**	660–1,360	**11,860**	3,590–21,260	**970**	460–1,200	**2,890**	2,610–3,210	**92**	3–182
Mushin	**1,050**	**2,180**	1,380–2,850	**24,900**	7,550–44,630	**2,030**	960–2,530	**6,060**	5,480–6,740	**193**	6–381
Ojo	**540**	**1,180**	740–1,570	**13,010**	3,760–25,080	**1,200**	530–1,570	**3,050**	2,750–3,400	**95**	3–191
Oshodi	**900**	**1,870**	1,180–2,440	**21,380**	6,480–38,310	**1,740**	830–2,170	**5,200**	4,700–5,790	**166**	5–327
Shomolu	**820**	**1,690**	1,070–2,210	**19,320**	5,850–34,620	**1,570**	750–1,960	**4,700**	4,250–5,230	**150**	5–296
Surulere	**1,010**	**2,100**	1,330–2,740	**24,010**	7,280–43,030	**1,960**	930–2,440	**5,840**	5,280–6,500	**186**	6–368
Lagos State	**13,970**	**28,860**	18,320–37,590	**329,900**	101,200–585,200	**27,580**	13,400–33,970	**81,000**	73,290–90,010	**2,590**	79–5,110

Source: Author's own elaboration.

Note: *Baseline rates obtained from the WHO GHE database for 2018. Numbers may not add up due to rounding off errors.

FIGURE A2.2. $PM_{2.5}$ ATTRIBUTABLE MORTALITY BY LGA AND MORBIDITY FOR LAGOS STATE, PWE SENSITIVITY ANALYSIS



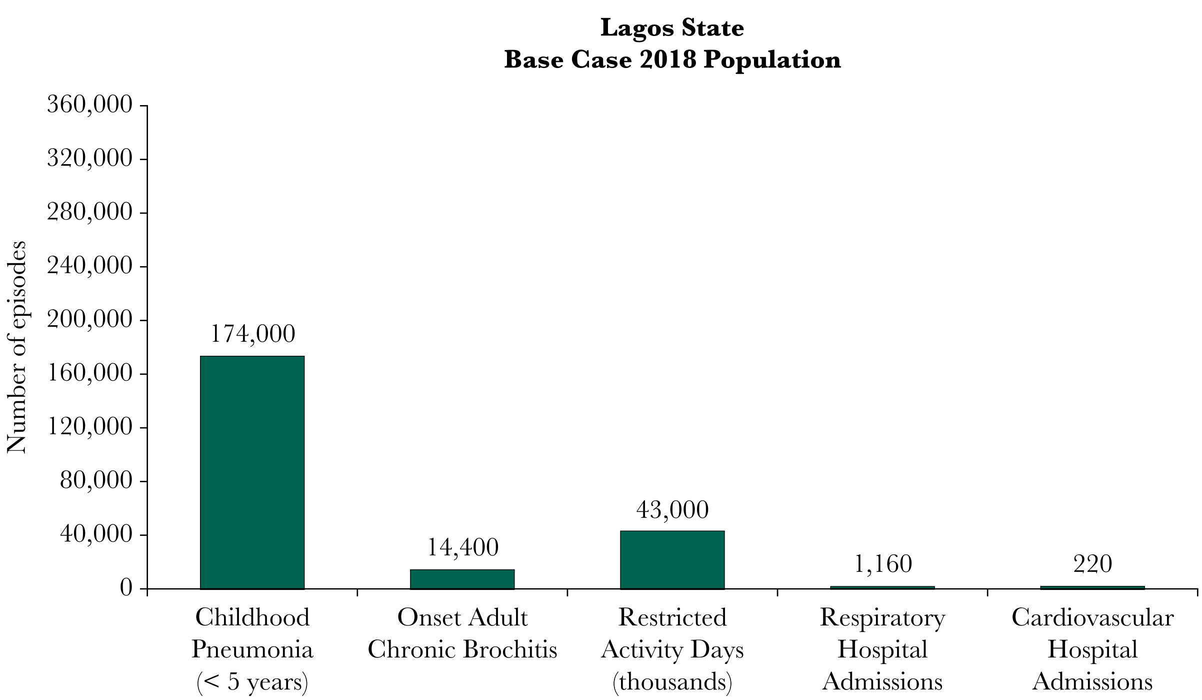
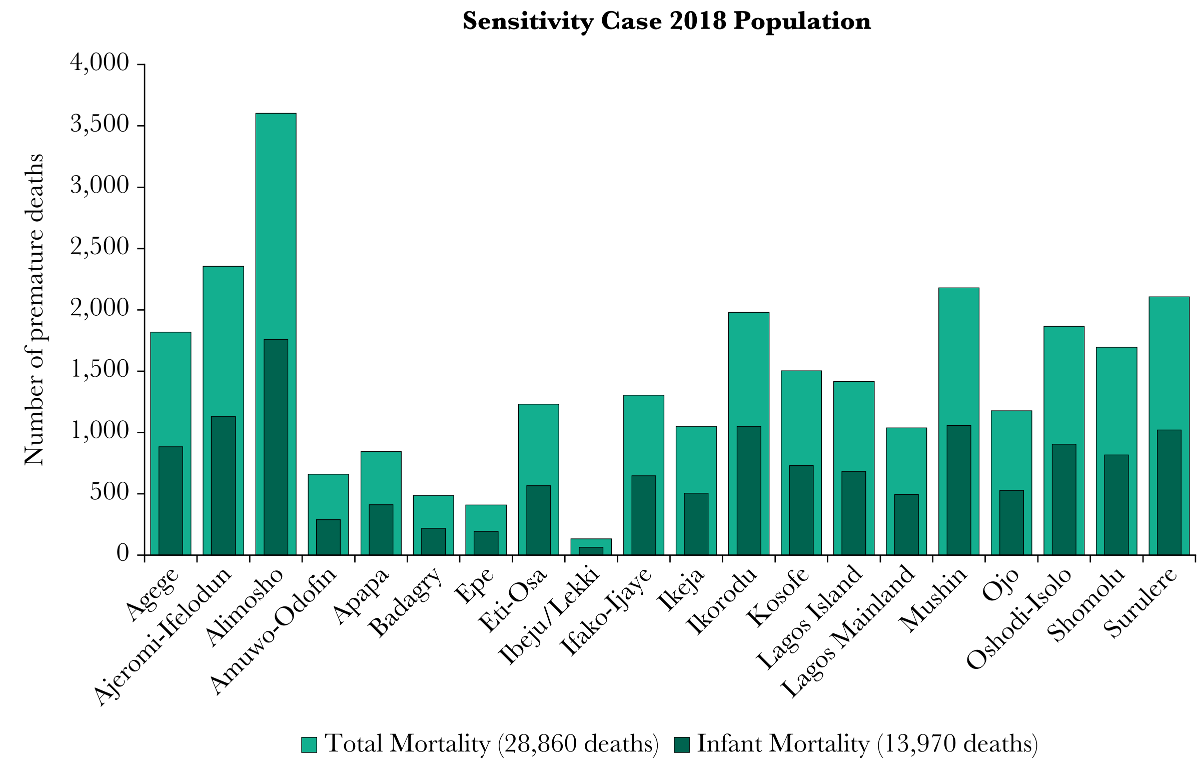
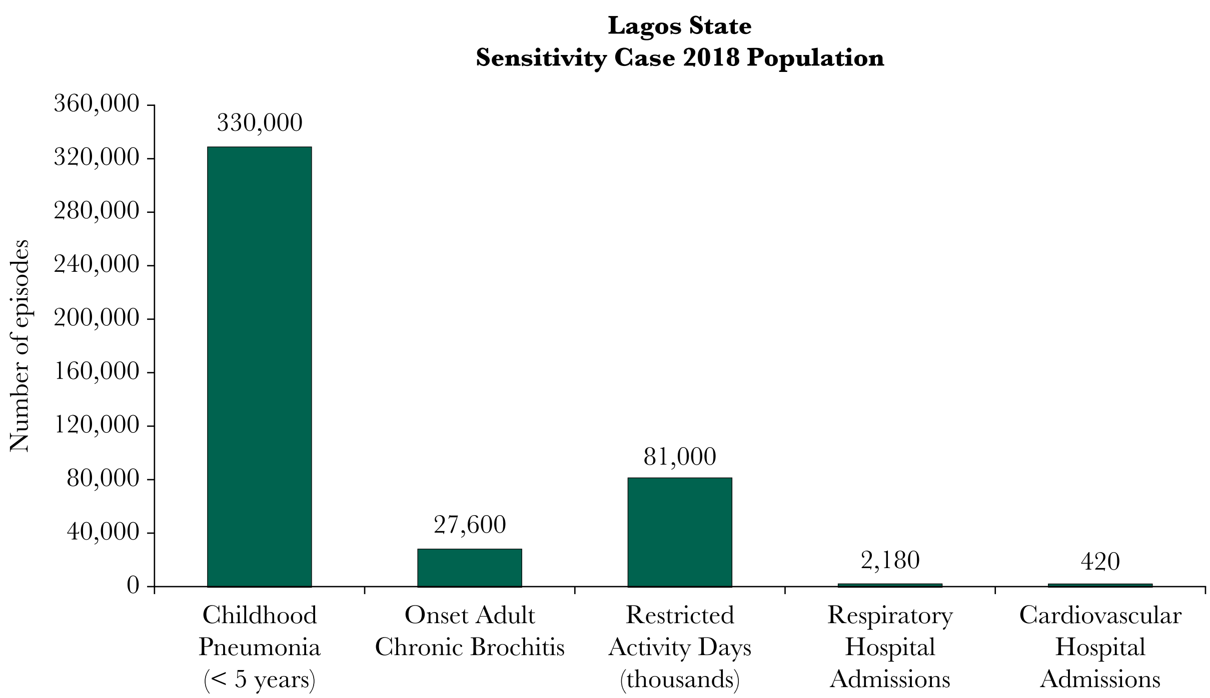


FIGURE A2.2. *(Continued)*





Source: Author's own elaboration.

Note: Adult mortality quantified using GEMM and infant mortality using Heft-Neal et al. (2018). Baseline rates obtained from the WHO GHE database for 2018.

ANNEX 3
ECONOMIC AND FINANCIAL ASSESSMENT: POLICY, INVESTMENT, AND COST ASSUMPTIONS

The use of "economic" or social cost is a useful concept for assessing activities that have environmental externalities, such as air pollution, because it includes health and other kinds of damage that are not typically reflected in the market. Because consumer decisions typically rely on market prices, it is also important for policy makers to ensure that financial costs (reflected in "market prices") are at appropriate levels to reduce air pollution, for example, by taxing air pollution or subsidizing clean fuels.

Cost-effectiveness analysis allows different control measures to be compared based on their cost to reduce air pollution (Naira/US dollar per ton of $PM_{2.5}$ reduced). The costs for implementing different interventions have been estimated using data from projects in Lagos and elsewhere. Where possible, the proposed interventions have been selected from projects already undertaken in Lagos or in Nigeria.

Many potential air quality interventions, such as public transport or the power grid, require **public investments** while others, such as emissions testing for vehicles or enforcing emissions standards for industry, require **regulatory costs.** To comply with emissions standards, such as emissions control equipment or clean fuels, there needs to be **private costs.** These expenditures will be referred to as **compliance costs.** For some air quality interventions, such as electricity tariffs from additional power sold by the grid or fare revenue from public bus or rail service, there may be additional revenue from improved service.

The main **benefits** of controlling air pollution are the expected reductions in health impacts. Premature mortality attributable to air pollution in Lagos has been estimated in this study at between 15,000 and 30,000 deaths per year, with infants under 1 year accounting for over half of the deaths. The value of premature mortality has been calculated between 1.9 and 3.6 percent of Lagos' GDP based on lost productivity, and between 3.7 and 7.2 percent using the VSL. By comparing the costs and benefits of reducing $PM_{2.5}$ for each intervention, it is possible to (a) estimate how much it would cost to reduce emissions and (b) estimate and compare the cost-effectiveness of different air pollution control measures.

For the economic and financial analysis, the share of air pollution from the key sectors has relied on the estimates from the emissions inventory and source apportionment work from the study.[42]

A3.1. AQM CONTROL STRATEGIES BY SECTOR

SOLID WASTE

Based on the air pollution monitoring and emissions inventory conducted for the study, the burning of MSW, both collected and uncollected, emerges as a major contributor to $PM_{2.5}$ air pollution in Lagos. Because such a large share of air pollution in Lagos originates from the open burning of solid waste, a critical policy for Lagos (and LAWMA) is to increase the amount of solid waste that is collected and eliminate the open burning of solid wastes at landfills.

Government policies for waste management can help minimize the amount of waste that is generated by ensuring that markets for recyclables and organic material are developed. Collection fees for solid waste could help cover the costs of collecting and disposing of solid waste. Regardless of collection fees, to reduce air pollution from solid waste, it is essential that the municipality collect as much solid waste as possible and ensure that the MSW collected is not burned.

Based on estimates of per capita solid waste, the total amount of MSW generated in Lagos is more than 15,000 tons per day, or more than 5 million tons per year. The majority of the share of Lagos' MSW that is collected goes to one of four active dumpsites, where waste pickers scavenge for usable items, mainly metal and plastics. The remainder of the waste, much of it organic, is left to decompose. Modern sanitary landfills are built to avoid contaminating groundwater and surface water and to capture the CH_4 produced from decomposing organic matter. CH_4 captured can be used to generate electricity or supplied to other energy users in the form of natural gas. Because CH_4 is a powerful GHG,[43] landfills that capture it can earn carbon credits through mitigating the release of CH_4.

The per capita generation of MSW in Lagos has been estimated at 0.75 kg per day, which translates to 15,000–18,000 tons of MSW per day for a city of 20–25 million people. Open burning is used as a way for households and enterprises to dispose of uncollected MSW, and open burning occurs at landfills through intentional burning and the spontaneous combustion of waste. It is assumed that through additional investment in collection vehicles and landfills phased in over several years, waste collection could progressively increase from the current rate estimated at 54 percent (PwC 2021) to around 80 percent of total MSW generated. Because available land for landfills is not limitless and the value of land in Lagos is continues to rise as the city grows, it is important to reduce the overall amount of MSW that goes into landfills. Investments in recycling, composting, and incineration would reduce the amount of waste needed to be deposited in landfills. The analysis assumes that the organic fraction of MSW is 50 percent, the combustible fraction is 75 percent (organic 50 percent + paper 15 percent + plastic 10 percent) and that 25 percent of the collected and recyclable MSW (paper and plastic) is recycled.

In addition to special handling procedures for hazardous wastes, it is important to encourage the separation of solid waste to facilitate recycling and composting. Organic waste, for instance, needs to be separated so that it does not contaminate recyclables such as paper and cardboard. Neighborhood collection sites that allow plastics, metals, and glass to be separated could enhance the feasibility of recycling by reducing the cost of collection and ensuring a higher-quality recycled product.

TRANSPORT

The transport sector is one of several large contributors to $PM_{2.5}$ air pollution in Lagos. Given its importance to the economy—moving people and goods—and the fact that it will undoubtedly grow, it is essential that air quality policy measures for the transport sector comprise a major part of Lagos' AQM plan. Among the important measures to reduce $PM_{2.5}$ emissions from the transport sector are (a) continued expansion and improvement of public transport; (b) improvement in emissions control among vehicle fleets such as trucks, buses, passenger cars, and motorcycles; and (c) the increased supply and guarantee of clean transport fuels in conjunction with stricter emissions standards for vehicle fleets.

INSPECTION AND MAINTENANCE

I&M programs are a prerequisite for implementing vehicle improvement programs. The establishment of LACVIS[44] in 2016 was an important development in the capability to monitor and enforce vehicle emission regulations, including the identification of gross polluters, mandatory maintenance, vehicle retirement, and retrofit programs. Currently, the program requires vehicles to be inspected and that they display their emissions certificates on the vehicle or face a fine.

Based on experience elsewhere, a large share of vehicle air pollution has been found to come from a small fraction of vehicles, so-called "gross polluters." In practice, this means that regulation and enforcement of vehicle emissions will be effective if it can control the worst polluters (Krzyzanowski et al. 2005),[45] which can be identified through I&M or roadside inspection.

IMPROVING VEHICLE TECHNOLOGY

Improving vehicle technology in line with cleaner fuel is the way many countries and cities have reduced vehicle emissions. While improved vehicle standards cannot immediately replace Lagos' old and high-polluting fleet, requiring that new vehicles meet stricter standards is an important start, including by providing incentives and penalties. The fixed number of legal ports of entry, and the fact that most secondhand vehicles originate from countries with well-established emission control regimes, imply that targeted efforts to verify and improve the emissions performance of secondhand vehicles are feasible.

Although detailed information on the emissions standards of the vehicle fleet in Lagos is not available, limited survey data suggest that most of the fleet is older than 15 years. Although Nigeria agreed in 2018 to establish Euro 4 standards for new vehicle registrations along with 50 ppm fuel sulfur standards, this has not yet occurred. A new vehicle inspection program was established in Lagos in 2016,[46] which is an important step to ensure that vehicles are safe and that emissions control equipment is maintained. Because high vehicle emissions often tend to be concentrated in a small percentage of vehicles, vehicle inspection is important for removing "gross polluters" from the road for repair or scrappage. I&M, combined with improving emission standards for new vehicles, is important for reducing emissions from the vehicle fleet.

MINIBUSES/*DANFOS*

Upgrading the vintage of vehicle fleet could significantly reduce $PM_{2.5}$ emissions. For example, if a Euro 1 vehicle can be replaced by a Euro 4 vehicle,[47] $PM_{2.5}$ emissions could be reduced ninefold (see Table A3.1). Requiring that *danfos* be less than 16 years old—Euro 4 equivalent vehicles were introduced in Europe and the US in 2005—would ensure that the emissions control equipment for new and most used vehicles in Nigeria would be at least Euro 4-spec. To achieve the lower emissions from newer vehicles, it is necessary to improve fuel quality. Without lower sulfur fuels, the emissions control equipment (both catalysts and filters) on newer vehicles could be permanently destroyed.

TABLE A3.1. ALTERNATIVE VEHICLE TECHNOLOGIES FOR LARGE BUSES

Technology	Purchase cost (US$)	$PM_{2.5}$ emissions ($gPM_{2.5}$/km)
Baseline[a]	200,000	0.14
Clean diesel	400,000	0.025
CNG	450,000	0.009
Hybrid (diesel-electric)	500,000	0.012
Electric	750,000	0.003

Note: [a] Baseline assumes Euro 1 diesel buses (properly tuned). https://www.catf.us/wp-content/uploads/2019/02/CATF_Pub_Diesel_VS_CNG.pdf.

BUSES

Many countries and municipalities have attempted to reduce air pollution by converting vehicle fleets to cleaner technologies such as "clean diesel," natural gas (CNG/LNG), diesel-electric hybrids, or fully electric. The costs of establishing dedicated alternative fuel systems for vehicles include new fuel or motor systems as well as refueling stations. Because of the difficulties of guaranteeing clean diesel fuel free from adulteration, some cities have used this as a reason for moving to alternative fuels such as CNG or electric. Focusing on fleet vehicles such as taxis, buses, or delivery trucks has been a proven approach for alternative fuel vehicles, since this requires the establishment and maintenance of fewer refueling facilities, and conversion and maintenance can be handled by dedicated service personnel. It also allows the refueling facilities to maintain their own fuel quality, such as the ultra-low sulfur diesel that is required for advanced catalysts and particulate filters. Given the global trend and falling costs of hybrid and electric vehicles, an evaluation of the costs of such vehicles should be undertaken sooner rather than later, particularly for fleet vehicles such as buses, taxis, and delivery trucks (Mufson and Kaplan 2021).[48]

PUBLIC TRANSPORT

The expansion of public transport should be considered an important way of improving the efficiency of transport in Lagos and of reducing both air pollution and GHG emissions. With support from international donors, Lagos has invested in both infrastructure and institutions to improve public transport, including BRT, light rail, and ferries. The upgrading and expansion of public transport in Lagos could have a large positive impact on air quality. Public transport investments are large and multi-year and must be justified largely on their transportation benefits rather than on their contribution to improving air quality. Although the air quality benefits of public transport can be large, public transport investments need to be evaluated on their long-term contribution to air quality rather than on their capacity to make an immediate positive impact on air quality.

FREIGHT TRANSPORT

Investments in alternatives to road transport for freight are under way in Lagos and should help relieve road traffic congestion and reduce air pollution. Major rail infrastructure such as the Lagos-Ibadan portion of the larger Lagos-Kano rail project will connect Apapa seaport and thus reduce the amount of truck traffic in central Lagos. As with BRT and light-rail projects, large investments in rail freight must be justified by their transportation benefits, such as reductions in shipping costs and delivery times. Nonetheless, investment in rail freight from the busy Apapa and Tin Can ports can reduce truck traffic and the air pollution they generate.

In addition to rail freight, measures to reduce emissions from freight trucks must be part of the solution to air pollution in Lagos. In parallel with measures to upgrade light-duty vehicles and buses, there needs to be an expanded program combining vehicle inspections, emissions certificates, fines for noncompliance, and a guaranteed supply of clean diesel for heavy-duty trucks. This will likely require investments in newer heavy-duty trucks, or the retrofitting of existing trucks with pollution controls such as catalysts and diesel particulate filters. Either option will likely be costly for truck owners, but the gains are also likely to be large, given the high share of $PM_{2.5}$ that comes from diesel combustion.

FUEL QUALITY

Improved fuel quality can lower $PM_{2.5}$ emissions through the introduction of more sophisticated emissions control systems on vehicles, such as catalysts and particulate filters that require the use of cleaner fuels. Many of the catalysts and particulate traps that are installed in vehicles that are imported, either new or used, into Nigeria and other countries would quickly become ineffective with Nigeria's current fuel quality (assumed to be 1,424 ppm sulfur for gasoline and 2,389 ppm sulfur for diesel). Yet establishing stricter standards for transport fuels—gasoline, diesel, and marine fuel oil—has been hampered in Nigeria by fuel smuggling, including from illegal refineries in the Niger delta, and by the delay in the construction of the Dangote refinery. At 650,000 bpd, the Dangote refinery would be the largest in Nigeria and would meet the country's refined petroleum product needs of around 600,000 bpd. Nigeria currently produces over 2.5 billion bpd of crude oil. In terms of fuel quality, the Dangote refinery is slated to produce Euro 6 standard fuels, meaning ultra-low sulfur diesel and gasoline (10 ppm sulfur). New fuel standards—150 ppm for gasoline and 50 ppm for diesel—were set to be introduced in Nigeria in 2017 but have not yet been implemented.

The current fuel quality in Nigeria does not allow the effective operation of vehicle catalysts beyond Euro 1, a standard that was implemented in Europe in the early 1990s. Properly functioning Euro 5 vehicles can lower emissions of $PM_{2.5}$ by a factor of 28 compared to Euro 1 vehicles. Reducing the sulfur content of petroleum fuels—gasoline, diesel, and fuel oil (marine)—can lower the production of secondary aerosols such as SOx, which have been estimated at 10 percent of $PM_{2.5}$ emissions from the transport sector. To guard against fuel adulteration and protect the emissions control equipment in vehicles, it is necessary to ensure that fuel quality at fueling stations is maintained (Table A3.3). Requiring that petroleum products in Lagos meet higher-quality standards will reduce emissions not only from transport but also from other users of diesel fuel such as industry and the backup electricity generators used throughout Lagos State.

INDUSTRY

Industry is known to be a major contributor to air pollution in Lagos. Several high-polluting industries have moved away from central Lagos in recent years, and the government has sometimes assisted in their relocation. The government's main role, however, is the monitoring and enforcement of air pollution standards, which may require automatic pollution monitoring equipment at major industrial plants. At the same time, helping industries convert to cleaner technologies or fuels, through training and technical assistance, can be an important way for them to remain competitive and improve their productivity and profitability. "Cleaner production" emerged in the 1980s and 1990s as a strategy for both reducing industrial pollution and facilitating the development of many high-tech and high value-added industries such as information and technology and food processing (World Bank 1998).

ELECTRICITY GENERATION

Nigeria's power sector is characterized by high technical and financial losses, and the current system cannot provide adequate electricity to the economy. As such, Nigeria has among the highest share of electricity provided by backup generators ("gensets") in the world. These generators are expensive to operate, noisy, and highly polluting. Gensets in Lagos may account for as much as 40 percent of electricity generation (1,940 GWh) and as much as 90 percent of air pollution from power generation (chapter 2). Long-term investment in power grid expansion and reliability would eventually reduce genset usage. Improvements to Nigeria's power sector are critical for the sustainability of the system and the economy. By increasing the supply of electricity, economic losses would be reduced while tariff revenues would increase, generating considerable income to pay for the reforms.

Gensets represent one of the least regulated sources of air pollution in Lagos. As noted earlier, improving the quality of diesel and gasoline suppled to Lagos would help reduce emissions from gensets. Currently, there are no emissions standards for electricity gensets in Nigeria. As in other countries, the emissions from such generators should be regulated, requiring (a) emission standards for electricity gensets, (b) improvements in fuel, and (c) the installation of pollution control equipment.

OTHER

There are many options for reducing emissions from other pollution sources. Policies to minimize the amount of resuspended roads, such as paving, could reduce a large fraction of dust emissions. Lower-cost options such as watering or reducing speed limits on unpaved roads can also be effective in the short term and during the dry season. Likewise, policies to reduce crop residue burning, including bans, could be especially effective during the dry season when emissions are at their peak. Subsidizing the use of LPG among low-income households could reduce the use of solid fuels for residential cooking. While a detailed assessment of the costs of reducing emissions from other sectors has not yet been carried out, it is reasonable to assume that selective policies and investments could be effective in reducing the share of $PM_{2.5}$ emissions by a few percent.

A3.2. FINANCING AQM

Among the potential sources of financing for air quality in Lagos are private financing, multilateral resources, and climate funds.

PRIVATE FINANCING

Access Bank. Access is a publicly listed commercial bank headquartered in Lagos. It has not only issued a green bond but equally invested in two green bonds issued by the Federal Government. (It may also have invested in the North South Power green bond in 2021.) Access Bank is well-positioned to take part in a subnational green bond, given its experience in the issuance and reporting obligations of its own green bond.

Capital Assets. A privately held issuing house based in Lagos, Capital Assets acted as the financial adviser to the Federal Government in the issuance of the first and second green bonds in Nigeria, both of which were oversubscribed. Issuing houses are a key part of the process for issuance of capital market instruments. Capital Assets has a ready pool of institutional and other investors interested in green bonds.

Nigerian Stock Exchange (NSE). The NSE is the premium exchange for trading of public instruments in Nigeria, with a capitalization of N83 trillion (US$202 billion). The NSE was a key player in the issuance of a green bond by the Federal Government and currently lists four green bonds on its platform. NSE is concerned with the additional reporting obligations associated with green bonds but believes that local capacity can be developed to support issuers in meeting their reporting obligations.

MULTILATERAL RESOURCES

Resources available through the multilaterals provide an avenue to mobilize additional funds—Figure A3.1 lists commitments by MDBs to climate finance. The MDBs most relevant to the LASG are the African Development Bank (AfDB), the European Investment Bank (EIB), the World Bank Group (WBG), and the Islamic Development Bank (ISDB). Others that are likely to have commitments not listed in figure A3.1 are Africa Finance Corporation (AFC) and International Finance Corporation (IFC). These institutions typically have accreditation with climate funds such as the Global Environment Facility (GEF) and the Green Climate Fund (GCF) and have internal programs designed to provide technical support in developing interventions to address climate issues.

Figure A3.2 illustrates contributions to climate financing as of 2019 and shows an increase since the signing of the Paris Agreement in 2015.

Leveraging existing platforms for technical assistance—such as the Africa Climate Resilient Infrastructure (ACRIF)—it is likely that the LASG can access funding for technical support to design relevant interventions or to create a blended approach to funding projects that can address air pollution. Table A3.1 provides an overview of potential funding from the World Bank Group that could be available to Lagos to address climate concerns, many of which would also improve air quality.

The ACBP has several focal areas that overlap with the priorities of Lagos State that could address air pollution.

FIGURE A3.1. CLIMATE FINANCE COMMITMENTS BY MDBS

CLIMATE FINANCE COMMITMENTS BY MDB

African Development Bank
Total **US$ 3,600 million**
For low- and middle-income economies **US$ 3,600 million**

African Development Bank
Total **US$ 7,073 million**
For low- and middle-income economies **US$ 7,068 million**

EUROPEAN Bank for Reconstruction and Development
Total **US$ 5,002 million**
For low- and middle-income economies **US$ 3,923 million**

EUROPEAN Investment Bank
Total **US$ 21,658 million**
For low- and middle-income economies **US$ 3,558 million**

Inter-American Development Bank Group
Total **US$ 4,958 million**
For low- and middle-income economies **US$ 4,417 million**

Islamic Development Bank
Total **US$ 466 million**
For low- and middle-income economies **US$ 464 million**

World Bank Group
Total **US$ 18,806 million**
For low- and middle-income economies **US$ 18,437 million**

FIGURE A3.2. FUNDING SOURCES FOR CLIMATE FINANCING (INCLUDING PRIVATE SECTOR)

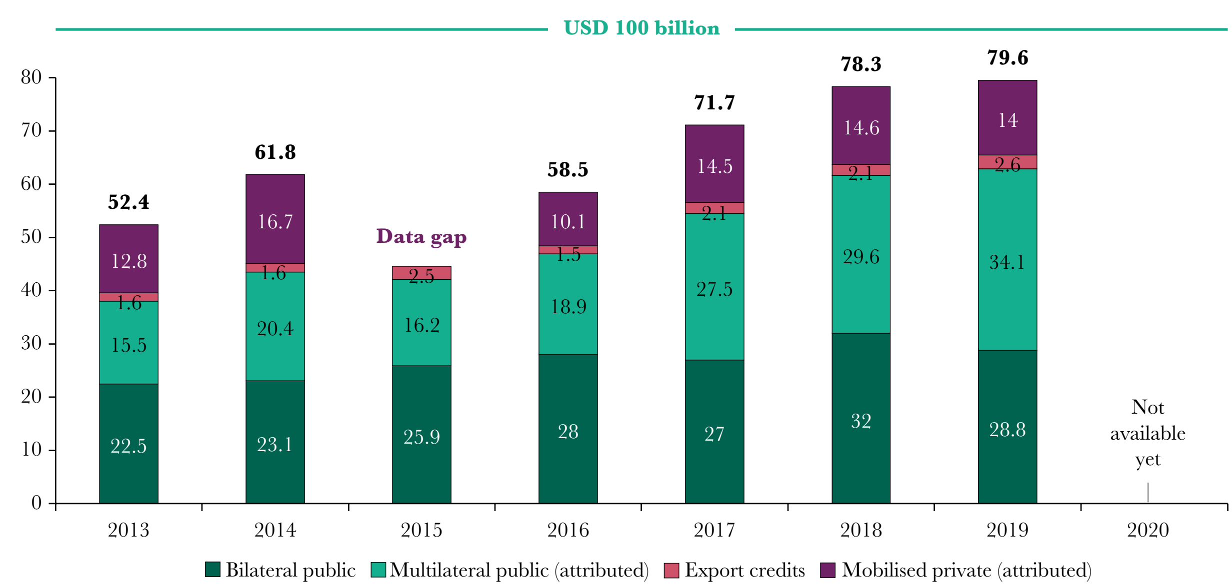


TABLE A3.2. WORLD BANK AFRICA CLIMATE BUSINESS PLAN (ACBP) FUNDING WINDOWS

IDA/IBRD	Indicator/commitment	Time period	Relevance to Africa
IDA19	IDA'S climate co-benefits share of total commitments will increase to at least 30 percent on average over FY21–23, with half supporting adaptation action.	FY21–23	Africa share of US$53 billion, pro-rated, would mean US$5.3 billion per year from portfolio (or total of US$15.9 billion)
WBG	The WBG is stepping up its climate support for Africa With continued strong support for IDA, our fund for the world's poorest countries,[a] this will provideUS$22.5 billion for Africafor climate adaptation and mitigation for the five years from 2021–25.	FY21–25	Africa-focused; would be a summation of co-benefits from IDA and IBRD portfolio
WBG	[...] in line with these new climate financing commitments and future direction of our Africa Business Plan[b] more than half of the US$22.5 billion financing will be devoted to supporting adaptation and resilience in Africa. This will amount to about US$12 billion to US$12.5 billion over five years from 2021–25.	FY21–25	Africa focused; would be a summation of adaptation co-benefits from IDA and IBRD portfolio
IBRD	Increasing the climate co-benefit target of 28 percent by FY20 to an average of at least 30 percent over FY20–23, with this ambition maintained or increasing to FY30.[c]	FY20–23, and through 2030	Bankwide target, no formal Africa target

Technical assistance or blended finance from the ACBP could help the LASG scale up its green bond program. In the energy sector, the ACBP has a focus on renewable energy generation and capacity as well battery storage. In transport, the plan has an objective to support five new BRT corridors in the region, which aligns with the LASG 2021 budget.

Alignment with the ACBP. Lagos stands to benefit from support from the ACBP's city interventions. Sectors such as energy and transport also provide a rationale for Lagos State to sieve its various plans to identify interventions that are consistent with the pollution solution and that could be funded through the commitments in the ACBP. The planned issuance of a green bond could benefit from technical support in the structuring or the provision of a blended financing approach to make the terms of issuance more sustainable.

A3.3. CONTROL COST ASSUMPTIONS

The first step in estimating the cost-effectiveness of each sectoral intervention was to apportion total $PM_{2.5}$ emissions across the sectors. A second simplifying assumption was that $PM_{2.5}$ emissions are directly proportional to ambient concentrations. Using the average of $PM_{2.5}$ source apportionment monitoring data of six sites (figure 10) and the baseline emissions inventory (Table A3.4), the following table apportions $PM_{2.5}$ emissions (column 2) and ambient concentrations (column 3) to the five sectors (solid waste, industry, transport, power, and other). It is assumed that the cost of policies and actions are perfectly divisible to achieve a given level of air pollution reduction.

TABLE A3.3. ACTION AREAS IN THE ACBP

Action area to support IDA-19 and Corporate climate actions and targets45		
Business element	**World Bank instruments for delivery on climate action**	**Timing**
Delivery of IDA and Corporate commitments	▶ **Resilient Cities and Green Mobility** ▷ Cities ▶ Integrated planning: multisectoral climate-smart urban and transport plans prepared with up-to-date data for at least five African cities ▶ 30 cities with integrated, city-based resilience approach ▶ Target of US$2 billion in investment financing for urban resilience-building activities ▷ Green mobility ▶ Support 5 new BRTs in fast-growing African cities (making at least 50% of jobs accessible within an hour of commute) ▶ Secure maintenance to make 100,000 km of climate-resilient African roads	FY21–23; FY24–26
	Special Areas of Emphasis	
	▶ **Macroeconomic planning and policy** ▷ Increase engagement with ministries of finance and planning and other stakeholders on NDCs ▷ Promote concrete and systematic policy actions (IDA19) ▷ Analytics to inform policy action and design of prior actions in DPFs	FY21–23; FY24–26
	▶ **Green and Resilient Infrastructure** Supports targets of Strategic Directions above, including ▷ **Energy** ▶ renewable energy. ▶ battery storage. ▶ renewable energy generation capacity ▷ **Urban** ▶ low carbon and compact urban planning ▶ integrated, city-based resilience approach	FY21–23; FY24–26

PUBLIC REGULATION VERSUS PRIVATE COMPLIANCE COSTS

Two sets of costs for reducing air pollution have been evaluated. **Public costs** include the building of public infrastructure such as landfills and roads, as well as public administrative costs such as pollution monitoring, regulation, and licensing. The costs of reducing emissions from vehicles, factories, or electric generators to comply with emission standards lie with the owners and are referred to as **private compliance costs.** Where possible, the net cost (investment minus revenue) of public investments, regulatory costs, and compliance costs have been estimated for each air quality measure. A notable exception is the cost required by industrial enterprises to reduce their air pollution. Aside from the lack of information from industrial enterprises in Lagos, there is a wide range of industrial processes that produce air pollution, making

TABLE A3.4. APPORTIONMENT OF $PM_{2.5}$ EMISSIONS AND AMBIENT CONCENTRATIONS BY SECTOR

Sectors	Share of $PM_{2.5}$ emissions (t/yr) - %	Contribution to ambient $PM_{2.5}$ levels (ug/m^3)	Air pollution reduction scenarios			
			35 ug/m^3	25 ug/m^3	15 ug/m^3	10 ug/m^3
Solid Waste	26	11.7	−2.5	−4.9	−7.5	−9.0
Industry	20	9.0	−1.2	−4.0	−6.5	−8.0
Transport	20	9.0	−3.7	−5.0	−6.3	−7.6
Power	8	3.6	−1.6	−3.2	−3.2	−3.2
Other	26	11.7	−1.0	−2.8	−6.5	−7.2
Total	100	45	−10.0	−20.0	−30.0	−35.0

Source: Author's own elaboration based on PM source apportionment.

a cost assessment of private compliance costs for industry prohibitive. It is also assumed that at least part of the public regulation cost (such as vehicle emissions testing or solid waste collection) can be paid through licensing or user fees.

SOLID WASTE

Collection and disposal costs for MSW are calculated from waste collection fees charged by private concessionaires. The cost of household waste collection services in Lagos was estimated at US$5.87 per ton in 2014. Assuming this figure has increased to US$10 per ton today, the cost of collecting and disposing of 18,750,000 tons per day (0.75 kg/cap/day times 25 million) is US$73 million per year (Aliu et al. 2014). Composting assumes that the organic fraction (50 percent) collected is composted, with costs based on the EarthCare program in Lagos and the Terra Firma experience in Bangalore India (World Bank 2016b). The assumed cost of building a new sanitary Olusosun-size (100 acres) landfill, at US$500,000 per acre, is US$50 million. If recycling and composting are implemented, less landfill space (and the associated cost) is needed. MSW that is not recycled or composted is assumed to be landfilled or incinerated. For both composting and recycling investments and operating expenses, it is assumed that 80 percent of the costs can be offset through income from the sale of products, such as fertilizer from composting, and paper and plastics from recycling.

INDUSTRY

The public costs associated with the control of industrial emissions are assumed to be the monitoring and enforcement costs for the regulator, while the private sector will need to invest in pollution control measures to meet the standard. The main regulatory expense is assumed to be the monitoring and enforcement of industrial emission standards, including through the installation of automatic emissions monitoring systems on large industrial sources. Monitoring costs of US$100,000 are assumed for 1,000 enterprises, totaling US$100 million. Compliance costs have not been estimated but would include pollution control equipment, cleaner fuels, or energy efficiency measures. Cleaner production—covering emissions control equipment and cleaner fuels—would likely have a net benefit for industries such as food and beverages, information and technology, and electronics. The payback for energy efficiency measures is typically short for many industrial investments (pumps, motors, boilers, fans) and would lead to reductions in emissions in proportion to reductions in fuel consumption.

TRANSPORT

Euro 3 and Euro 4 vehicle standards are assumed to be achieved through testing, compliance, and enforcement, phased in over time. More than half of light-passenger vehicles are less than 16 years old and likely therefore to have Euro 4 equipment already installed, both for new and used vehicles. Modest costs are assumed for these vehicles to meet Euro 3 standards—for example, addition of new catalytic converters—but many other vehicles would need to either be retired or retrofitted to comply. Most used vehicles in Nigeria come from Europe, the US, and Japan, all of which have established emissions control standards of Euro 4 or higher. Regulation costs are assumed to include emissions testing for all vehicles, ranging from US$4 (motorcycles) to heavy trucks (US$30), and it is expected that the emissions testing will be done by the current testing service (LCVIS). Compliance costs are assumed to be the expenditures vehicle owners need to make in order to meet Euro 3 and 4 emissions standards. Compliance costs will be greatest for heavy trucks, which are assumed to be among the oldest fleets in Lagos. For passenger vehicles, minivans (including *danfos*), and motorcycles, private compliance costs are assumed to be the costs of catalytic converters, installation costs, plus the costs of clean fuel. The incremental cost of clean fuels (on average US$0.02–0.03 per liter) would be paid by vehicle owners in the form of higher diesel and gasoline prices.

CLEAN FUEL

Clean fuel is not assumed to be an independent reduction action but is required for engines to achieve lower emission levels under Euro vehicle standards. Low-sulfur diesel and gasoline (Euro 3 and 4 compliant) are assumed to be available (with guaranteed fuel quality) throughout Lagos State. Until domestic refineries can produce such fuels in sufficient quantity, it is assumed that fuel is imported. The incremental cost for low-sulfur fuels is calculated at US$76 million per year (Miller et al. 2017) with the costs borne by consumers at around 5 percent increase in the cost, or US$0.02–0.03 per liter. Given that all petroleum products are currently imported, the real challenge in obtaining clean fuel in Lagos (and Nigeria in general) is to prevent fuel adulteration. Additional regulatory costs are assumed to ensure that fuel quality is guaranteed, including fines and potential cancellation of retail licenses for violations of fuel quality standards. A program to guarantee fuel quality, as has been implemented in other countries, can help ensure the quality of fuel in the face of numerous incentives to adulterate it (Gwilliam Kojima, and Johnson 2004).

ELECTRICITY

It is assumed that the majority of emissions from the power sector are from gensets in the residential, commercial, and industrial sectors rather than from the natural, gas-fired power plants on the electric grid. The cost of power sector reform in Lagos has been calculated at around US$100 million, based on World Bank project costs for increasing power supply in the amount currently provided by gensets. Several efforts are under way to improve the efficiency of Nigeria's power sector, including investment in transmission, distribution, and metering (World Bank 2020).[49] Such projects provide an estimate of the costs of improving the supply and reliability of the grid, measured as additional kWh that are available to consumers, and thus generating additional revenues from electricity sales. The increase in tariff revenue from increased power generation associated with the reforms is calculated at over US$200 million per year, meaning that the reforms would pay for themselves in less than 2 years.

Alternatively, emissions from gensets could be regulated and emission controls enforced, requiring gensets to install pollution control equipment. Although backup generators are not regulated in Nigeria, other jurisdictions around the world provide experience and

TABLE A3.5. COST-EFFECTIVENESS OF SELECTED AIR QUALITY MEASURES

	Public "regulation" cost (US$, millions)	Private "compliance" cost (US$, millions)	$PM_{2.5}$ reduction potential (t/year)	Cost-effectiveness (US$/t $PM_{2.5}$ reduced)
Solid waste				
Enhanced MSW collection and new landfills	83	—	3,328	24,947
Enhanced MSW collection with recycling and composting	47	—	3,328	14,130
Industry				
Emissions monitoring and standard enforcement	95	??	3,000	31,605
Transport				
Vehicle regulation (Euro 3)[a]	12	149	1,200	133,725
Vehicle regulation (Euro 4)[a]	12	223	2,800	69,933
Power				
Power sector reform	110	—	1,152	95,833
Genset regulation and emissions control	5	246	1,152	218,229

Source: Author's own elaboration.

Note: [a] Requires fuel quality improvements.

information on the costs of controlling genset emissions. The cost to reduce emissions from backup generators is estimated at one-quarter of the total capital costs of gensets in Lagos (based on genset emissions control costs from the US) or US$280 million.[50] While power sector reform would result in additional revenue from electricity sales that would offset the costs of reform measures, the genset emissions control expenditures would be a net cost to genset owners.

COST-EFFECTIVENESS

Based on the costs of different measures to reduce $PM_{2.5}$ emissions, it is possible to estimate the cost-effectiveness of different interventions. As seen in Table A3.5, the measures to reduce solid waste burning are among the lowest cost for air pollution control in Lagos.

A3.4. CO-BENEFITS OF CLIMATE CHANGE MITIGATION

Given the large costs of air pollution in Lagos, it is important that policies to address climate change also look for solutions to reduce ambient air pollution. Fortunately, the sectors targeted in Lagos' Climate Action Plan— waste, transport, industry, and energy—are precisely those contributing the most to $PM_{2.5}$ emissions. That said, within each of these priority sectors, different measures to reduce GHG emissions will have varying degrees of success in reducing air pollution. Several measures can reduce both air pollution and GHG emissions (Table A3.6). It is also possible to compare the costs of air pollution to the costs of climate change (Box A3.1).

TABLE A3.6. CLIMATE CO-BENEFITS OF SELECTED AIR QUALITY MEASURES

	Avoided CO_2	Avoided CH_4	Avoided black carbon
Transport			
Public transport	✓	No	✓
Clean fuel	No	No	✓
Euro 3/4 vehicles	No	No	✓
Alternative vehicles (CNG, hybrid, electric)	✓	No	✓
Solid waste			
Enhanced collection	✓	✓	✓
Composting	✓	✓	✓
Industry			
Energy efficiency	✓	No	✓
Pollution controls	No	No	✓
Power			
Sector reform	✓	No	✓
Genset emissions control	No	No	✓
Other			
LPG for cooking	✓	No	✓
Paving roads	No	No	✓

BOX A3.1. AIR POLLUTION VERSUS CLIMATE CHANGE COSTS

How do the costs of air pollution compare to the costs of climate change? The PMEH study has estimated the health costs of ambient air pollution based primarily on premature deaths attributable to high levels of ambient $PM_{2.5}$ pollution. While it is difficult to measure the costs of climate change, a notional measure known as the "social cost of carbon" has been devised to reflect the costs of climate impacts such as droughts, floods, and sea level rise. The social cost of carbon (SCC) has been used by policy makers worldwide to attempt to internalize the negative externalities of climate change. In the US, a wide range of SCC values have been used, reflecting assumptions about the extent of climate change damage and the discount rate.[52] Lagos CO_2-equivalent emissions have been estimated at 2.64 million tons.[51] If a mid-range global value of US$50/t$CO_2$e is used for the SCC, the cost of climate change for Lagos amounts to US$1.3 billion. The health impact of $PM_{2.5}$ emissions in Lagos has been estimated at US$2.6–5.0 billion, or more than twice the value of CO_2 emissions.

ANNEX 4
METHODOLOGY FOR DEVELOPING AN AQI

A4.1. WHAT IS AN AQI?

Air pollution can be measured and presented in many forms. It includes all the aerosols and gaseous components, each with its own way of affecting human health to various degrees depending on exposure rate. Some pollutants like CO and O_3 can lead to an immediate response and require standard metrics presented on a shorter time scale (for example, 8 hourly) than other pollutants (24 hourly). Their presentation also varies—for example, aerosols are reported as mass fractions, and gases as volumetric fractions of air.

An Air Quality Index (AQI) unifies the complicated science of pollution composition, exposure rates-based health severity, ambient standards, measurement, and standard protocols and breaks it down into simple, color-coded bins that give people an instant visual grasp of pollution levels in their surroundings, enabling them to develop the necessary alertness.

FIGURE A4.1. SCHEMATIC DIAGRAM OF AN AIR QUALITY INDEX

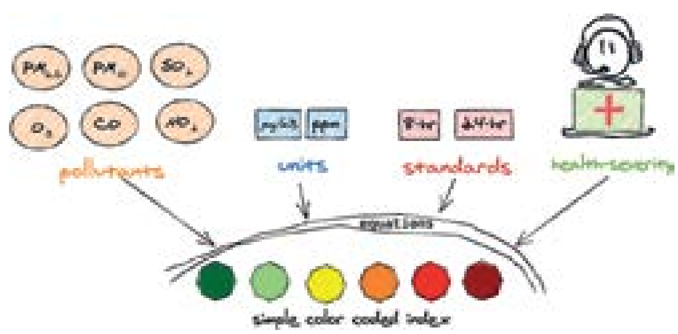
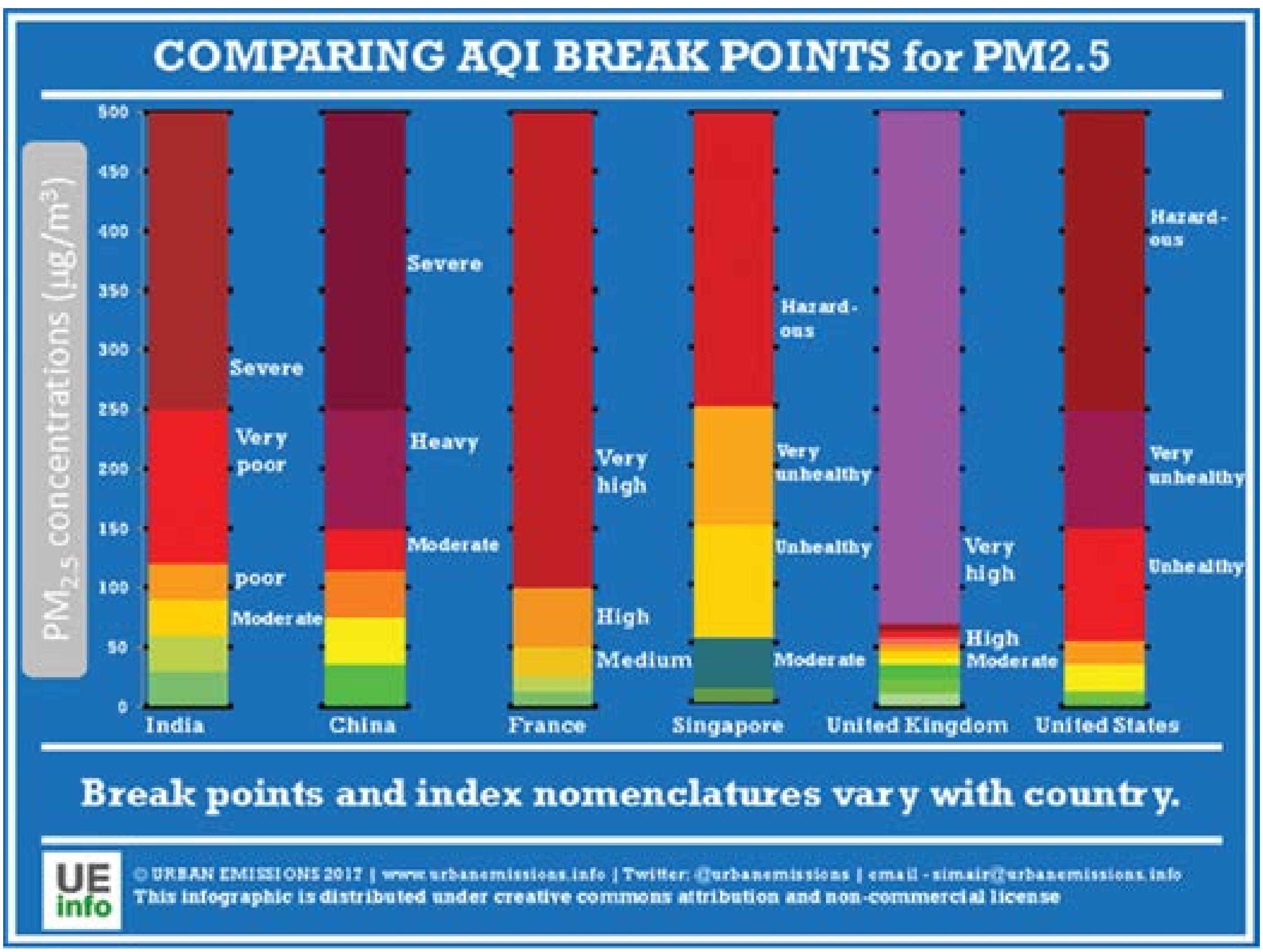


FIGURE A4.2. COLOUR CODING OF AIR QUALITY

A4.2. HOW IS AQI CALCULATED?

While the methods to monitor air pollution and estimate its health impacts are becoming standardized across the globe, this is not the case for methods used for calculating an AQI. These methods, and the degree of alertness disseminated by health alert systems, vary depending on different countries' interpretation of thresholds for regulatory purposes and background conditions. This step is primarily driven by predetermined local standards and the feasibility of reaching the lowest possible pollution levels. For example, in a region where dust is naturally present and ubiquitous, it is not possible to reach WHO guidelines for PM_{10} and $PM_{2.5}$. The same principle also holds for the formulation of an AQI by individual countries, which notionally mirrors that country's standards. For example, for $PM_{2.5}$ presented in the following figure, a concentration of 50 µg/m³ is considered borderline "unhealthy" in the US but "satisfactory" in India.

FIGURE A4.3. AQI BREAKPOINTS AND NOMENCLATURE FOR DIFFERENT COUNTRIES



Mathematically, an AQI is calculated using the following equation:

$$AQI = \frac{AQI_{hi} - AQI_{low}}{BP_{hi} - BP_{low}} * (CONC - BP_{lo}) + AQI_{low}$$

where

- » CONC = concentration of the pollutant
- » AQI = air quality index for the pollutant
- » BP_{hi} = breakpoint that is greater than or equal to CONC
- » BP_{lo} = breakpoint that is less than or equal to CONC
- » AQI_{hi} = AQI value corresponding to BPhi
- » AQI_{lo} = AQI value corresponding to BPlo

Every pollutant has a predefined breakpoint and AQI ranges for each of the color codes. An example for India is presented below.

The numbers in the first column represent the AQI bins (high and low values to be used in the calculator). The number ranges that are under each of the pollutants represent the breakpoints. In this table, all the breakpoints are in µg/m^3, except for CO which is listed in mg/m^3.

The top of the AQI scale is 500, which means there will be point in the calculation when the AQI value itself will not change between absolute value of 1,000 and 2,000 µg/m^3 of $PM_{2.5}$ or PM_{10}. Once the color code reaches the severe category, there is no change in the AQI value or the alert message.

This report reviewed seven methodologies from the US, the EU, the UK, India, China, the Republic of Korea, and Singapore. A summary of parameters used to calculate an AQI by each of these countries is presented below. Like the breakpoint variation in calculating AQI between countries, there is also a significant variation in the use of parameters and time scales. In the case of $PM_{2.5}$ and PM_{10}, all the countries use 24-hour average concentrations to calculate the AQI. For SO_2 and NO_2, the most-used time frame is the 24-hour average; and for CO and O_3, the most-used time frame is the 8-hour average. In the case of O_3, when 8-hour averages reach a certain threshold, the calculators switch to using 1-hour

FIGURE A4.4. POLLUTANT PREDEFINED BREAKPOINT AND AQI RANGES FOR INDIA

AQI Category (Range)	PM_{10} 24-hr	$PM_{2.5}$ 24-hr	NO_2 24-hr	O_3 8-hr	CO 8-hr (mg/m^3)	SO_2 24-hr	NH_3 24-hr	Pb 24-hr
Good (0–50)	0–50	0–30	0–40	0–50	0–1.0	0–40	0–200	0–0.5
Satisfactory (51–100)	51–100	31–60	41–80	51–100	1.1–2.0	41–80	201–400	0.6–1.0
Moderate (101–200)	101–250	61–90	81–180	101–168	2.1–10	81–380	401–800	1.1– 2.0
Poor (201–300)	251–350	91–120	181–280	169–208	10.1–17	381–800	801–1200	2.1–3.0
Very poor (301–400)	351–430	121–250	281–400	209–748*	17.1–34	801–1600	1201–1800	3.1–3.5
Severe (401–500)	430+	250+	400+	748+*	34+	1600+	1800+	3.5+

**One hourly monitoring (for mathematical calculation only)* averages—this happens in the methodologies employed by the US, EU, China, and Singapore.

A summary of all the breakpoints and nomenclature for these seven countries is presented below. All the concentrations are presented in μg/m^3.

An Excel-based AQI calculator is included with this report that will allow for exploring the methodologies and their interpretations.

The three steps in using the calculator are: (a) enter concentrations, preferably in μg/m^3, but could be in other units; (b) from the seven countries, select a methodology to use; and (c) click to calculate the AQI. Another variation of the calculator is available in the resource material. That version can utilize larger datasets for multiple pollutants and build AQI trends.

FIGURE A4.5. SUMMARY OF PARAMETERS FOR ESTIMATING AN AQI FOR COUNTRIES UNDER REVIEW

		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
		$PM_{2.5}$			**PM_{10}**			**SO_2**			**NO_2**			**CO**			**Ozone**		
		24hr	8hr	1hr	24hr	8hr	1hr	24hr	8hr	1hr	24hr	8hr	1hr	24hr	8hr	1hr	24hr	8hr	1hr
1	USA	x			x			x			x				x			x	x
2	EU	x			x					x			x						x
3	UK	x			x					x			x					x	
4	India	x			x			x			x				x			x	
5	China	x			x			x			x			x				x	x
6	S.Korea				x			x			x				x			x	
7	Singapore	x			x			x					x		x			x	x
8																			
9																			
10																			

FIGURE A4.6. SUMMARY OF BREAKPOINTS AND NOMENCLATURE FOR SEVEN COUNTRIES UNDER REVIEW

United States

Number of bins: **6**

Number of polls: **18**

	AQI Low	AQI High	col.code	Break Points 1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
				$PM_{2.5}$	$PM_{2.5}$	$PM_{2.5}$	PM_{10}	PM_{10}	PM_{10}	SO_2	SO_2	SO_2	NO_2	NO_2	NO_2	CO	CO	CO	Ozone	Ozone	Ozone
				24hr	8hr	1hr	24hr	8hr	1hr	24hr	8hr	1hr	24hr	8hr	1hr	24hr	8hr	1hr	24hr	8hr	1hr
				ug/m^3	ug/m^3	ug/m^3	ug/m^3	ug/m^3	ug/m^3	ug/m^3	ug/m^3	ug/m^3	ug/m^3	ug/m^3	ug/m^3	ug/m^3	ug/m^3	ug/m^3	ug/m^3	ug/m^3	ug/m^3
				0			0			0			0				0			0	0
1 Good	0	50	43	12			54			95			85				5210			110	0
2 Moderate	50	100	27	35			154			203			161				11131			142	254
3 Unhealthy for sensitive groups	100	150	45	55			254			501			579				14684			173	333
4 Unhealthy	150	200	3	150			354			823			1043				18237			213	414
5 Very Unhealthy	200	300	13	250			424			1635			2007				35999			406	820
6 Hazardous	300	500	9	500			604			2718			3293				59683			0	1226

European union

Number of bins: **6**

Number of polls: **18**

	AQI Low	AQI High	col.code	Break Points 1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
				$PM_{2.5}$	$PM_{2.5}$	$PM_{2.5}$	PM_{10}	PM_{10}	PM_{10}	SO_2	SO_2	SO_2	NO_2	NO_2	NO_2	CO	CO	CO	Ozone	Ozone	Ozone
				24hr	8hr	1hr	24hr	8hr	1hr	24hr	8hr	1hr	24hr	8hr	1hr	24hr	8hr	1hr	24hr	8hr	1hr
				ug/m^3	ug/m^3	ug/m^3	ug/m^3	ug/m^3	ug/m^3	ug/m^3	ug/m^3	ug/m^3	ug/m^3	ug/m^3	ug/m^3	ug/m^3	ug/m^3	ug/m^3	ug/m^3	ug/m^3	ug/m^3
				0			0					0			0						0
1 Very Good	0	50	10	10			20					100			40						50
2 Good	50	100	43	20			40					200			90						100
3 Medium	100	200	27	25			50					350			120						130
4 Poor	200	300	45	50			100					500			230						240
5 Very Poor	300	400	46	75			150					750			340						380
6 Extremely Poor	400	500	3	800			1200					1250			1000						800

United Kingdom

Number of bins: **10**

Number of polls: **18**

	AQI Low	AQI High	col.code	Break Points 1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
				$PM_{2.5}$	$PM_{2.5}$	$PM_{2.5}$	PM_{10}	PM_{10}	PM_{10}	SO_2	SO_2	SO_2	NO_2	NO_2	NO_2	CO	CO	CO	Ozone	Ozone	Ozone
				24hr	8hr	1hr	24hr	8hr	1hr	24hr	8hr	1hr	24hr	8hr	1hr	24hr	8hr	1hr	24hr	8hr	1hr
				ug/m^3	ug/m^3	ug/m^3	ug/m^3	ug/m^3	ug/m^3	ug/m^3	ug/m^3	ug/m^3	ug/m^3	ug/m^3	ug/m^3	ug/m^3	ug/m^3	ug/m^3	ug/m^3	ug/m^3	ug/m^3
				0			0					0			0					0	
1 Low	0	1	43	11			16					88			67					33	
2 Low	1	2	43	23			33					177			134					66	
3 Low	2	3	43	35			50					266			200					100	
4 Moderate	3	4	27	41			58					354			267					120	
5 Moderate	4	5	44	47			66					443			334					140	
6 Moderate	5	6	45	53			75					532			400					160	
7 High	6	7	46	58			83					710			467					187	
8 High	7	8	3	64			91					887			534					213	
9 High	8	9	53	70			100					1064			600					240	
10 Very High	9	10	13	100			150					1500			1000					300	

India

Number of bins: **6**

Number of polls: **18**

	AQI Low	AQI High	col.code	Break Points 1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
				$PM_{2.5}$	$PM_{2.5}$	$PM_{2.5}$	PM_{10}	PM_{10}	PM_{10}	SO_2	SO_2	SO_2	NO_2	NO_2	NO_2	CO	CO	CO	Ozone	Ozone	Ozone
				24hr	8hr	1hr	24hr	8hr	1hr	24hr	8hr	1hr	24hr	8hr	1hr	24hr	8hr	1hr	24hr	8hr	1hr
				ug/m^3	ug/m^3	ug/m^3	ug/m^3	ug/m^3	ug/m^3	ug/m^3	ug/m^3	ug/m^3	ug/m^3	ug/m^3	ug/m^3	ug/m^3	ug/m^3	ug/m^3	ug/m^3	ug/m^3	ug/m^3
				0			0			0			0				0			0	
1 Good	0	50	10	30			50			40			40				1000			50	
2 Satisfactory	50	100	43	60			100			80			80				2000			100	
3 Moderate	100	200	6	90			250			380			180				10000			168	
4 Poor	200	300	45	120			350			800			280				17000			208	
5 Very Poor	300	400	3	250			430			1600			400				34000			748	
6 Severe	400	500	9	500			750			2500			800				50000			1000	

FIGURE A4.6. *(Continued)*

China

Number of bins: **6**

Number of polls: **18**

	AQI			Break Points																	
				1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
				$PM_{2.5}$	$PM_{2.5}$	$PM_{2.5}$	PM_{10}	PM_{10}	PM_{10}	SO_2	SO_2	SO_2	NO_2	NO_2	NO_2	CO	CO	CO	Ozone	Ozone	Ozone
				24hr	8hr	1hr	24hr	8hr	1hr	24hr	8hr	1hr	24hr	8hr	1hr	24hr	8hr	1hr	24hr	8hr	1hr
				ug/m^3	ug/m^3	ug/m^3	ug/m^3	ug/m^3	ug/m^3	ug/m^3	ug/m^3	ug/m^3	ug/m^3	ug/m^3	ug/m^3	ug/m^3	ug/m^3	ug/m^3	ug/m^3	ug/m^3	ug/m^3
	Low	High	col.code	0			0			0			0			0				0	0
1 Optimal	0	50	4	35			50			50			40			2000				100	0
2 Good	50	100	6	75			150			150			80			4000				160	0
3 Light Pollution	100	200	22	115			350			800			280			24000				265	0
4 Moderate Pollution	200	300	3	150			420			1600			565			36000				800	800
5 High Pollution	300	400	21	250			500			2100			750			48000				0	1000
6 Severe Pollution	400	500	30	500			600			2620			940			60000				0	1200

Korea

Number of bins: **6**

Number of polls: **18**

	AQI			Break Points																	
				1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
				$PM_{2.5}$	$PM_{2.5}$	$PM_{2.5}$	PM_{10}	PM_{10}	PM_{10}	SO_2	SO_2	SO_2	NO_2	NO_2	NO_2	CO	CO	CO	Ozone	Ozone	Ozone
				24hr	8hr	1hr	24hr	8hr	1hr	24hr	8hr	1hr	24hr	8hr	1hr	24hr	8hr	1hr	24hr	8hr	1hr
				ug/m^3	ug/m^3	ug/m^3	ug/m^3	ug/m^3	ug/m^3	ug/m^3	ug/m^3	ug/m^3	ug/m^3	ug/m^3	ug/m^3	ug/m^3	ug/m^3	ug/m^3	ug/m^3	ug/m^3	ug/m^3
	Low	High	col.code				0			0			0				0			0	
1 Good	0	50	43				30			54			48				2368			81	
2 Moderate	50	100	27				80			135			96				10658			162	
3 Unhealthy for sensitive groups	100	150	45				120			271			241				14210			244	
4 Unhealthy	150	250	3				200			406			321				17763			609	
5 Very Unhealthy	250	350	13				300			1083			964				35526			1015	
6 Hazardous	350	500	9				600			2707			3214				59210			1218	

Singapore

Number of bins: **6**

Number of polls: **18**

	AQI			Break Points																	
				1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
				$PM_{2.5}$	$PM_{2.5}$	$PM_{2.5}$	PM_{10}	PM_{10}	PM_{10}	SO_2	SO_2	SO_2	NO_2	NO_2	NO_2	CO	CO	CO	Ozone	Ozone	Ozone
				24hr	8hr	1hr	24hr	8hr	1hr	24hr	8hr	1hr	24hr	8hr	1hr	24hr	8hr	1hr	24hr	8hr	1hr
				ug/m^3	ug/m^3	ug/m^3	ug/m^3	ug/m^3	ug/m^3	ug/m^3	ug/m^3	ug/m^3	ug/m^3	ug/m^3	ug/m^3	ug/m^3	ug/m^3	ug/m^3	ug/m^3	ug/m^3	ug/m^3
	Low	High	col.code	0			0			0					0		0			0	0
1 Good	0	50	43	12			50			80					0		5000			118	0
2 Moderate	50	100	27	55			150			365					0		10000			157	0
3 Unhealthy	100	200	45	150			350			800					1130		17000			235	0
4 Very Unhealthy	200	300	3	250			420			1600					2260		34000			785	785
5 Hazardous	300	400	13	350			500			2100					3000		46000			0	980
6 Hazardous	400	500	9	500			600			2620					3750		57500			0	1180

FIGURE A4.7. STEPS FOR CALCULATING AQI

2

Select a nation for required formate	India	and click calculate AQI

3

	Reqd time. avg	Conc	Unit	AQI	Remarks
$PM_{2.5}$	24hr	120.0	Micro-g/m^3	300	Poor
	8hr		Micro-g/m^3	NA	
	1hr		Micro-g/m^3	NA	
PM_{10}	24hr	130.0	Micro-g/m^3	120	Moderate
	8hr		Micro-g/m^3	NA	
	1hr		Micro-g/m^3	NA	
SO_2	24hr	54.0	Micro-g/m^3	68	Satifactory
	8hr		Micro-g/m^3	NA	
	1hr		Micro-g/m^3	NA	
NO_2	24hr	34.0	Micro-g/m^3	43	Good
	8hr		Micro-g/m^3	NA	
	1hr	80.0	Micro-g/m^3	NA	
CO	24hr		Micro-g/m^3	NA	
	8hr	2000.0	Micro-g/m^3	100	Satifactory
	1hr	10000.0	Micro-g/m^3	NA	
Ozone	24hr		Micro-g/m^3	NA	
	8hr	80.0	Micro-g/m^3	80	Satifactory
	1hr	200.0	Micro-g/m^3	NA	

Conditional Pollutant	$PM_{2.5}$ - 24 hr	300	Poor
Average of worst two		210	Poor
Average of all		118	Moderate

1

END NOTES

1. uMoya-NILU, Who We Are, http://www.umoya-nilu.co.za.
2. 6-hour mean at each sampling location.
3. World Health Organization.
4. "Criteria pollutants" are those for which an ambient air quality standard has been established.
5. According to the GBD's latest assessment, the PM attributable mortality is 6.455 million (plus 365,000 for O_3). This figure includes 373,000 neonatal disorders (including preterm birth and low-birth weight).
6. The study used a VSL value similar to that in Croitoru, Chang and Kelly (2020), which in turn used a benefits transfer methodology and a base value from a meta-analysis conducted in OECD countries (World Bank 2016).
7. CH_4 has a 100-year global warming potential 28 times that of CO_2.
8. The investment by West Africa ENRG would amount to US$125–150 million for a 25 MW waste-to-energy facility that would process 2.5 tons of MSW per day.
9. Many of the catalysts and particulate traps that are installed in vehicles that are imported either new or used into Nigeria and other countries would quickly be made ineffective with the current fuel quality (assumed to be 1,424 ppm sulfur for gasoline and 2,389 ppm sulfur for diesel).
10. At 650,000 barrels per day (bpd), the Dangote Refinery would be the largest in Nigeria and meet the country's refined petroleum product needs of around 600,000 bpd. Nigeria currently produces over 2.5 billion bpd of crude oil. In terms of fuel quality, the refinery is slated to produce Euro 6 standard fuels, meaning ultra-low sulfur diesel and gasoline (10 ppm sulfur).
11. ECOWAS directives C/Dir.2/09/20 and C/Dir.1/09/20, respectively.
12. For example, in California, fewer than 15 percent of vehicles are responsible for as much as half of total vehicle emissions. Similarly, in Europe, 3 percent of the fleet have been found to account for 27 percent of emissions.
13. It may also be possible to lease alternative-fuel vehicles as is being done with fleet vehicles in the US and Europe. Several jurisdictions are currently procuring electric vehicle fleets through leasing and service contracts with vehicle manufacturers and third-party contractors. For example, a county in Maryland, US recently signed an agreement to convert its school bus fleet to electric vehicles over the next 15 years.
14. National Poverty Eradication Program.
15. In Bangkok, two-stroke motorcycles and diesel engines accounted for over 95 percent of motor vehicle particulate matter in the early 2000s.
16. Railway Technology, "Lagos Rail Mass Transit System," March 13, 2020, https://www.railway-technology.com/projects/lagosrailmasstransit.
17. http://www.urbanrail.net/af/lagos/lagos.htm
18. Power – 208 Mt CO_2e; AFOLU – 136 Mt CO_2e; Transport – 52 Mt CO_2e; Oil and gas – 40 Mt CO_2e.
19. Estimates from the emissions inventory suggest that gensets may account for more than 95 percent of power sector emissions of $PM_{2.5}$. ARIA.
20. A recent study based on satellite measurements of $PM_{2.5}$ shows that agricultural field burning is a significant source of $PM_{2.5}$ in Sub-Saharan Africa, including Nigeria, during the field burning season from November to February. Preliminary data from air quality monitoring from six monitoring stations in Lagos show a dramatic increase in $PM_{2.5}$ levels during December 2020. To the extent that this increase is associated with seasonal field burning, measures to address biomass burning should be investigated.

21 In Ikeja, studies of household fuel used for cooking show that kerosene (48.6 percent) and LPG (36.3 percent) are the most common, with charcoal (7.1 percent), fuelwood (5.7 percent), and electricity (2.4 percent) providing a minor share.
22 https:/www.nesrea.gov.ng/publications-downloads/laws-regulations/.
23 https://ngfcp.dpr.gov.ng/media/1070/petroleum-act.pdf.
24 The DPR is currently transiting into the Nigerian Upstream Petroleum Regulatory Commission (NUPRC) as passed by the Nigerian Petroleum Industry Act of 2021.
25 The Vienna Convention addresses the loss of the O_3 layer as a global issue and establishes that all parties should take appropriate measures to avoid impacts on human health and the environment with the modification of the O_3 layer.
26 The Montreal Protocol, established in 1987, refers to the substances that deplete the O_3 layer and seeks measures for their control for atmospheric protection. The protocol was amended in 1990 (London), 1992 (Copenhagen), 1995 (Vienna), 1997 (Montreal), and 1999 (Beijing).
27 The Stockholm Convention, which entered in force in 2004, aims to protect human health and the environment from the effects of POPs.
28 PCEH claimed that the Climate Change Department's mandate was limited to inventorization and management of the impacts of GHGs and does not permit them to formulate policies for other air pollutants such as CO, NO_x, VOCs, and SO_2. Climate Change claims that such mandate does indeed lie with them.
29 According to the 2021 Appropriations Act, the FMEnv had allocations for N46.17 billion, while the total budget was N13.59 trillion.
30 The 2021 Appropriations Act identified three projects for air quality under the FMEnv's budget allocation. These were related to the introduction of smart air quality monitoring, the procurement of analyzers for air monitoring stations, and the implementation of pollution studies for cement.
31 NOSDRA Act 2006 is available at http://extwprlegs1.fao.org/docs/pdf/nig124170.pdf.
32 https://placng.org/i/wp-content/uploads/2019/12/Report-of-the-Senate-Committee-on-Environment-on-National-Oil-Spill-Detection-and-Response-Agency-Act-Amendment-Bill-2017.pdf.
33 https://www.lasepa.gov.ng/wp-content/uploads/2020/01/Environmental-Management-Protection-Law-2017-1.pdf.
34 The five strategic goals of AQM are (a) develop nationwide ambient air quality standards; (b) develop capacities to assess and determine national, state, or city emissions reduction requirements; (c) establish strategies to achieve the desired emissions reduction; (d) develop strategies to implement and enforce ambient air quality standard; and (e) develop capacity to track and evaluate emissions reduction results.
35 See endnote 25.
36 See endnote 26.
37 See endnote 27.
38 See endnote 5.
39 Natural cause mortality refers to deaths from all causes except accidents, violence, and suicides.
40 Exposure-response function is the mathematical relationship linking the size of a particular health effect to an exposure level of concern.
41 A relative risk is the ratio of health effects (incidence, mortality) between two groups of people exposed to different levels of air pollution.
42 The sectoral shares of $PM_{2.5}$ emissions and ambient concentrations that have been used for the economic and financial analysis are waste (26 percent), industry (20 percent), transport (20 percent), power (8 percent), and other (26 percent). As more detailed data and additional source assessment modeling work are completed, the share of pollution from different sources and sectors can be adjusted.
43 See endnote 7.
44 LACVIS currently has 20 inspection centers with an intention to build a total of 50 centers throughout Lagos by 2024. See Lagos Computerized Vehicle Inspection Service (LACVIS) http://lacvis.com.ng/about-us.
45 See endnote 12.

46 The Lagos Computerized Vehicle Inspection Service (LACVIS). https://lacvis.com.ng.

47 Currently the majority of *danfos* are gasoline-powered, though a shift to diesel is likely to increase as gasoline subsidies are reduced.

48 See endnote 13.

49 Based on costs from the recent PSRO project in Nigeria, the investment cost to increase the amount of electricity from the current grid in Nigeria is around US$50,000 per GWh.

50 Calculated as gensets producing 1,940 GWh per year in Lagos, an installed capacity of 2,790 MVA, and a total cost of US$1,116 million (US$400/kVA).

51 For example, policy makers in the US have calculated the SCC between US$2 and $100 per ton of CO_2, reflecting whether only American or total global damages are considered, and whether high versus low discount rates are used. Resources for the Future, https://www.rff.org/publications/explainers/social-cost-carbon-101/.

52 Lagos Climate Action Plan, p. ix.

BIBLIOGRAPHY

Adenaike, F. A., and A. J. Omotosho. 2020. "An Overview of Solid Waste Resource Recovery Efforts in Lagos." *International Journal of Waste Resources* 10:384.

Adeniran, J. A., R. O. Yusuf, M. O. Amole, L. Jimoda, and J. Sonibare. 2017. "Air Quality Impact of Diesel Back-up Generators (BUGs) in Nigeria's Mobile Telecommunication Base Transceiver Stations (BTS)." *Management of Environmental Quality: An International Journal* 28 (5): 723–44. http://www.emeraldinsight.com/doi/10.1108/MEQ-09-2015-0168.

ALG. 2013. "Consultancy Services for the Extension of the Strategic Transport Master Plan and Traffic Demand Model to Cover the Mega Region."

Aliu, I. R., O. E. Adeyemi, and A. Adebayo. 2014. "Municipal Household Solid Waste Collection Strategies in an African Megacity: Analysis of Public Private Partnership Performance in Lagos." *Waste Management and Research* 32 (9_suppl): 67–78. doi:10.1177/0734242X14544354.

Apte, Joshua S., Julian D. Marshall, Aaron J. Cohen, and Michael Brauer. 2015. "Addressing Global Mortality from Ambient PM2.5." *Environmental Science and Technology* 49 (13): 8057–66.

Ayodele, T. R., M. A. Alao, and A. S. O. Ogunjuyigbe. 2018. "Recyclable Resources from Municipal Solid Waste: Assessment of Its Energy, Economic and Environmental Benefits in Nigeria." *Resources, Conservation and Recycling* 134:165–73. https://www.sciencedirect.com/science/article/pii/S0921344918301149.

Carbon Credit Capital. 2021. "Value of Carbon Market Update 2021." https://carboncreditcapital.com/value-of-carbon-market-update-2021-2/.

Cervigni, Raffaello, John Allen Rogers, and Irina Dvorak. 2013. *Assessing Low-Carbon Development in Nigeria: An Analysis of Four Sectors*. Washington, DC: World Bank. https://openknowledge.worldbank.org/handle/10986/15797.

Croitoru, L., J. C. Chang, and A. Kelly. 2020. "The Cost of Air Pollution in Lagos." Washington, DC: World Bank. https://openknowledge.worldbank.org/handle/10986/33038.

Eliasson, I., P. Jonsson, and B. Holmer. 2008. "Diurnal and Intra-Urban Particle Concentrations in Relation to Windspeed and Stability during the Dry Season in Three African Cities." *Environmental Monitoring and Assessment* 154 (1): 309. https:// doi.org/10.1007/s10661-008-0399-y.

Emagbetere, E., J. Odia, and B. U. Oreko. 2016. "Assessment of Household Energy Utilized for Cooking in Ikeja, Lagos State, Nigeria." *Nigerian Journal of Technology* 35 (4): 796–804.

Fakinle, B. S., E. L. Odekanle, A. P. Olalekan, H. E. Ije, D. O. Oke, and J. A. Sonibare. 2020. "Air Pollutant Emissions by Anthropogenic Combustion Processes in Lagos, Nigeria." *Civil and Environmental Engineering* 7 (1): 2–16. https://doi.org/10.1080/23311916.2020.1808285.

Fenton, Paul. 2017. "The Role of Port Cities and Transnational Municipal Networks in Efforts to Reduce Greenhouse Gas Emissions on Land and at Sea from Shipping—An Assessment of the World Ports Climate Initiative." *Marine Policy* 75: 271–77. https://www.sciencedirect.com/science/article/pii/S0308597X15003826.

Gorham, R., B. Eijbergen, and A. Kumar. 2017. "Urban transport: Lagos shows Africa the way forward (again)." Transport for Development, World Bank Blogs. https://blogs.worldbank.org/transport/urban-transport-lagos-shows-africa-way-forward-again.

The Guardian. "Lagos Revamps Water Transport with High-Capacity Boats." July 9, 2021. https://guardian.ng/features/travel/lagos-revamps-water-transport-with-high-capacity-boats/.

Gwilliam Ken, Masami Kojimaa, and Todd Johnson. 2004. *Reducing Air Pollution from Urban Transport*. ESMAP /World Bank. https://esmap.org/node/1145.

Heft-Neal, S., J. Burney, E. Bendavid, and M. Burke. 2018. "Robust Relationship between Air Quality and Infant Mortality in Africa." *Nature* 559:254–258.

Hickman, Jonathan E., Niels Andela, Kostas Tsigaridis, Corinne Galy-Lacaux, Money Ossohou, and Susanne E. Bauer. 2021. "Reductions in NO_2 Burden Over North Equatorial Africa from Decline in Biomass Burning in Spite of Growing Fossil Fuel Use, 2005 to 2017." *Proceedings from the National Academy of Sciences (PNAS)* 118 (7): e2002579118. https://doi.org/10.1073/pnas.2002579118.

IEA (International Energy Agency). 2021. "Nigeria Energy Outlook." https://www.iea.org/articles/nigeria-energy-outlook.

Jambeck, J., Hardesty, B. D., Brooks, A. L., Friend, T., Telecki, K., Fabres, J., Beaudoin, Y., Bamba, A., Francis, J., Ribbink, A. J., Baleta, T., Bouwman, H., Knox, J. and C. Wilcox. 2018. "Challenges and Emerging Solutions to the Land-Based Plastic Waste Issue in Africa." *Marine Policy* 96: 256–63. https://www.sciencedirect.com/science/article/pii/S0308597X17305286.

Johnson, T. M., J. Li, Z. Jiang, and R. P. Taylor. 1996. "China: Issues and Options in Greenhouse Gas Emissions Control." Discussion Papers 330, Washington, DC: World Bank.

Kelly, Frank J., and Tong Zhu. 2016. "Transport Solutions for Cleaner Air." *Science* 352 (6288): 934 LP–936. http://science.sciencemag.org/content/352/6288/934.

Kemper, K., and S. Chaudhuri. 2020. "Air Pollution: A Silent Killer in Lagos." *World Bank Blogs*. https://blogs.worldbank.org/africacan/air-pollution-silent-killer-lagos.

Krzyzanowski, K.-D., Birgit Kuna-Dibbert, and Jürgen Schneider. 2005. *Health Effects of Transport-Related Air Pollution*. World Health Organization (WHO). https://www.euro.who.int/__data/assets/pdf_file/0006/74715/E86650.pdf.

Lagos State Waterways Authority. 2017. "Lagos Transport Statistics."

LAMATA. 2008. "Lagos Vehicular Emission (Air Quality) Monitoring Study."

Lagos State Government. 2020. "Lagos Climate Action Plan, Second Five Year Plan 2020-2025." Ministry of Environment and Water Resources.

LASEPA. 2014. "Air Pollution and Particulate Matter. Study Results."

Madziga, M., A. Rahil, and R. Mansor. 2018. "Comparison between Three Off-Grid Hybrid Systems (Solar Photovoltaic, Diesel Generator and Battery Storage System) for Electrification for Gwakwani Village, South Africa." *Environments* 5 (5): 57. http://www.mdpi. com/2076-3298/5/5/57.

Miller, Joshua, Ray Minjares, Tim Dallmann, and Lingzhi Jin. 2017. "Financing the Transition to Soot-Free Urban Bus Fleets in 20 Megacities." International Council on Clean Transportation (ICCT). https://theicct.org/sites/default/files/publications/Soot-Free-Bus-Financing_ICCT-Report_11102017_vF.pdf.

Miller, Paul. 2018. "New World-Scale Dangote Refinery in Nigeria Will Boast Advanced Technology for Feedstock and Product Flexibility and Environmentally Responsible Operations." ARC Advisory Group. https://www.arcweb.com/blog/.

Mufson, S., and S. Kaplan. 2021. "A Lesson in Electric School Buses." *Washington Post*, February 24, 2021. https://www.washingtonpost.com/climate-solutions/2021/02/24/climate-solutions-electric-schoolbuses.

Narain, Urvashi, and Chris Sall. 2016. *World Bank Group Methodology for Valuing the Health Impacts of Air Pollution: Discussion of Challenges and Proposed Solutions*. Washington, DC: International Bank for Reconstruction and Development/World Bank. https://openknowledge.worldbank.org/handle/10986/24440.

Olawuni, P. O., O. P. Daramola, and M. Soumah. 2017. "Environmental Implications of Abattoir Waste Generation and Management in Developing Countries: The Case of Lagos State Abattoir in Agege, Nigeria." *Greener Journal of Social Sciences* 7 (2): 007–014.

Omorogbe, Paul. 2021. "Waste-To-Energy Facility: British High Commission, Lagos State Environment Officials on Site Visit." *Nigerian Tribune*, February 14, 2021. https://tribuneonlineng.com/waste-to-energy-facility-british-high-commission-lagos-state-environment-officials-on-site-visit/.

Ozoh, O. B., T. J. Okwor, O. Adetona, A. O. Akinkugbe, C. E. Amadi, C. Esezobor, O. O. Adeyeye, O. Ojo, V. N. Nwude, and K. Mortimer. 2018. "Cooking Fuels in Lagos, Nigeria: Factors Associated with Household Choice of Kerosene or Liquefied Petroleum Gas (LPG)." *Int. J. Environ. Res. Public Health* 15:641. https://doi.org/10.3390/ijerph15040641.

PPPRA. 2021. "Petroleum Products Stock and Days Sufficiency Data." February 1.

Pricewaterhouse Coopers, 2021. Nigeria Solid Wastes and Plastics Management Institutional Analysis. World Bank Group, 2021.

Rennert, K., and C. Kingdon. "Social Cost of Carbon 101." Resources for the Future https://www.rff.org/publications/explainers/social-cost-carbon-101/.

Salau, O., L. Sen, S. Osho, and O. Adejonwo. 2016. "Empirical Investigation of Formal and Informal Sectors in Waste Recycling of the Municipal Waste Management System of Developing Countries: The Case Study of Lagos State." *Journal of Environment and Ecology* 7 (2): 21. https://www.macrothink.org/journal/index.php/jee/article/view/10007.

Schipper, L., J. Guy, M. Balam, N. Kete, J. Mooney, B. Bertelsen, D. Noriega, and C. Weaver. 2006. "Cleaner Buses for Mexico City, Mexico: From Talk to Reality." *Transportation Research Record* 1987 (1): 62–72. doi:10.1177/0361198106198700107.

Shah, Jitu, ed. 2003. *Thailand: Reducing Emissions from Motorcycles in Bangkok*. ESMAP/World Bank. https://documents1.worldbank.org/curated/en/908081468782070640/pdf/ESM2750Thailan1ng0Emissions1Bangkok.pdf.

Sofiev, M., J. Winebrake, L. Johansson, E. Carr, M. Prank, J. Soares, J. Vira, R. Kouznetsov, K.-P. Jalkanen, and J. Corbett. 2018. "Cleaner Fuels for Ships Provide Public Health Benefits with Climate Tradeoffs." *Nature Communications* 9 (1): 406. https://doi.org/10.1038/ s41467-017-02774-9.

Thurston, G., Y. Awe, B. Osto, and E. Sanchez-Triana. 2021. "Are All Air Pollution Particles Equal? How Constituents and Sources of Fine Air Pollution Particles (PM2.5) Affect Health." PMEH, Washington, DC: World Bank Group.

UNEP (United Nations Environment Programme). 2020. "West African Ministers Adopt Cleaner Fuels and Vehicle Standards." February 20. https://www.unep.org/news-and-stories/story/west-african-ministers-adopt-cleaner-fuels-and-vehicles-standards.

Winkel, R., U. Weddige, D. Johnsen, V. Hoen, and S. Papaefthimiou. 2016. "Shore Side Electricity in Europe: Potential and Environmental Benefits." *Energy Policy* 88:584–93. https://www.sciencedirect.com/science/ article/pii/S0301421515300240.

World Bank. 1998. *Pollution Prevention and Abatement Handbook: Toward Cleaner Production (PPAH)*. Washington, DC: World Bank. https://elibrary.worldbank.org/doi/abs/10.1596/0-8213-3638-X.

World Bank. 2002. *Lagos Urban Transport Project (LUTP).* Environmental Management Framework. Final Report.

World Bank. 2010. "EarthCare Solid Waste Composting Project (Carbon Finance)." Project Identification Document 2003. https://documents1.worldbank.org/curated/en/597581468298478449/pdf/533460ISDS0FAX10Box345607B01PUBLIC1.pdf.

World Bank. 2013. "Lagos Urban Transport Project (LUTP)." Independent Evaluation Group (IEG), Implementation Completion Review (ICR).

World Bank. 2014. *Diesel Power Generation: Inventories and Black Carbon Emissions in Nigeria*. Washington, DC: World Bank. https://openknowledge.worldbank.org/handle/10986/28419.

World Bank. 2015. *Second Pollution Abatement Project, Arab Republic of in Egypt*. Implementation Completion and Result Report.

World Bank. 2016a. "Innovative Financing for Air Pollution Control in Jing-Jin-Ji." https://projects.worldbank.org/en/projects-operations/project-detail/P154669.

World Bank. 2016b. "Sustainable Financing and Policy Models for Municipal Composting." Urban Development Series Knowledge Papers. https://documents1.worldbank.org/curated/en/529431489572977398/pdf/113487-WP-compostingnoweb-24-PUBLIC.pdf.

World Bank. 2019a. *Arab Republic of Egypt. Air and Water: An Economic Assessment*.

World Bank. 2019b. *Nothing Normal About Bad Air: Economic Growth and Air Pollution in India.* Washington, DC: World Bank.

World Bank. 2020. *Nigeria - Power Sector Recovery Operation (English)*. Washington, D.C: World Bank. http://documents.worldbank.org/curated/en/991581593223433078/Nigeria-Power-Sector-Recovery-Operation.

Zhou, Y., and S. D. Grosse. 2019. "Valuing the Benefits of Reducing Childhood Lead Exposure - Human Capital, Parental Preferences, or Both?" Centers for Disease Control and Prevention (CDC). Prepared for workshop at Harvard Center for Risk Analysis, September 26–27, 2019. https://cdn1.sph.harvard.edu/wp-content/uploads/sites/1273/2019/09/Zhou-Grosse-2019.pdf.

WORLD BANK GROUP

1818 H Street, NW
Washington, D.C. 20433 USA
Telephone: 202-473-1000
Internet: www.worldbank.org/environment