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A WORLD BANK STUDY

# Assessing Low-Carbon Development in Nigeria

## AN ANALYSIS OF FOUR SECTORS

Raffaello Cervigni, John Allen Rogers, and
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## *An Analysis of Four Sectors*

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*Cover image:* A member of a women's farming cooperative stands before solar panels that power her community's drip irrigation farms. Solar market gardens provide a cost-effective, labor-saving, and clean way of delivering much-needed irrigation water, particularly during the long, dry season. © Jennifer Burney, Center on Food Security and the Environment, Stanford University. Used with the permission of Jennifer Burney / Center on Food Security and the Environment, Stanford University. Further permission required for reuse.

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# Preface

The Federal Government of Nigeria has adopted an ambitious strategy, known as "Vision 20: 2020," to make Nigeria the world's 20th largest economy by the year 2020.

To evaluate how climate change considerations could be integrated into the implementation of Vision 20: 2020, the Federal Government of Nigeria and the World Bank have agreed to undertake a multiyear program of analytical work that has resulted in two books published in the World Bank's Directions in Development (DID) series. The first volume is *Toward Climate-Resilient Development in Nigeria*; the second is *Low-Carbon Development: Opportunities for Nigeria*. The present volume is a third book on the topic, being published in the World Bank Studies series.

This book is a collection of the technical reports on the four sectors of inquiry—agriculture and land use, oil and gas, power, and transport—that informed the preparation of the DID book on low-carbon development. By consolidating the results of the sector-specific analyses, the DID book on low-carbon development finds that, in the absence of policies to accompany economic growth in key carbon-emitting sectors with a reduced carbon footprint, emissions of greenhouse gases could more than double in the next two decades in Nigeria. At the same time, the research identified a number of opportunities for Nigeria to achieve the development objectives of Vision 20: 2020 and beyond, while stabilizing emissions at 2010 levels and providing domestic benefits on the order of 2 percent of GDP.

The present volume contains all the details on the working material (data, methodology, and assumptions) that were used to arrive at the final findings reported in the DID volume. It is therefore geared at a technical audience interested in the sector-specific aspects of low-carbon development.

The results presented here are based on data and information collected up to June 2012; changes in government policies or other developments that have occurred since then are not reflected in the book.

# About the Editors and Authors

## Editors

**Raffaello Cervigni** is a lead environmental economist with the Africa Region of the World Bank. He holds a master's degree in economics (MPhil) from Oxford University and a PhD in economics from University College London. He has more than 18 years of professional experience in programs, projects, and research financed by the World Bank, the Global Environment Facility, the European Union, and the Italian Government in many sectors. He is currently the World Bank's regional coordinator for climate change in the Africa Region, after having served for about three years in a similar role for the Middle East and North Africa Region. He is the author or coauthor of over 40 technical papers and publications, including books, book chapters, and articles in learned journals.

**John Allen Rogers** is an engineer specializing in low-carbon development modeling. As senior climate change specialist at the World Bank, he has developed EFFECT, a Visual Basic, Excel-based bottom-up model of climate-changing greenhouse gas emissions with associated costs and benefits, that can be applied to on-road transport as well as to the power sector, industry, nonresidential, and household electricity consumption. EFFECT is currently used by the World Bank, the Asian Development Bank, and others in approximately 18 countries. Before joining the World Bank, Rogers worked for over 20 years as an international consultant after a long career in engineering, quality control, and marketing with heavy-duty vehicle and diesel engine manufacturers.

**Irina Dvorak** is a climate change consultant with the Africa Region of the World Bank. She is specializing in environmental policies and international negotiations. She worked as a junior professional officer in the World Bank's coordination team for climate change for the Africa Region. Before joining the World Bank, she was a staff member of the German Technical Cooperation and had positions in both headquarters and field offices, including as a technical assistant for the Central Africa Forests Commission (COMIFAC) in Yaoundé, Cameroon. She studied in Germany and France and holds a master's degree in political science and sociology from the University of Freiburg, Germany.

## Lead Authors

**Louis Bockel (Part 1, Agriculture and Land Use Sector)** is an agricultural policy support officer with the Agricultural Development Economics Division at FAO. He is at the same time the team leader and the originator of EX-ACT, an analysis tool aimed at estimating the impact of agriculture and forestry development projects on greenhouse gas emissions and carbon sequestration. Louis carries out product development, technical supervision of applications, and dissemination activities, looking for new partnerships and collaboration to encourage a broader use of the tool in project and policy appraisals.

**H. Martyn Howells (Part 2, Oil and Gas Sector)** is a petroleum engineer, currently working as a consultant at the World Bank in the Global Gas Flaring Reduction Partnership (GGFR), a public-private partnership engaged in helping governments and companies reduce gas flaring in the oil and gas industry. Prior to joining the World Bank, he worked at Shell for 33 years exploring for and developing oil and gas fields in many parts of the world.

**Max Henrion (Part 3, Power Sector)** is the chief executive officer of Lumina Decision Systems in Los Gatos, California. He has 30 years of experience as a professor, decision consultant, software designer, and entrepreneur. He has led teams to develop decision and policy models for clients in government and industry in energy and environment, aerospace, analytics, and consumer choice. He is the originator of Lumina's flagship software product, Analytica. Before founding Lumina, he was an associate professor at Carnegie Mellon University and vice president of decision technology at the search engine company, Ask Jeeves. He has a BA in natural sciences from Cambridge University, a master of design from the Royal College of Art, and a PhD in operations research from Carnegie Mellon. He is the author or coauthor of three books, including *Uncertainty: A Guide to Dealing with Uncertainty in Policy and Risk Analysis* (Cambridge University Press, 1990), and more than 60 peer-reviewed articles.

**Robin Kaenzig (Part 4, Road Transport Sector)** is an associate transport economist/modeller, BSc (Hons), with Integrated Transport Planning Ltd. (ITP). He has played a key role in the planning and development of bus rapid transport systems in a number of major African cities, bus network rationalization studies in Lagos and Accra, and plans for cable car operations in Lagos. Kaenzig also plays a leading role in ITP's environmental studies. He has quantified the scale of impact of major transport schemes and policy measures on greenhouse gas emissions, using innovative microsimulation techniques to predict future emission levels on implementation of new bus rapid transit schemes.

# Acknowledgments

This book is the result of collaboration among several individuals and organizations that have provided many different inputs throughout the process of its preparation. The work was initiated and coordinated by a World Bank team led by Raffaello Cervigni and including (in alphabetical order by first name) Abimbola Adubi, Ademola Braimoh, Amos Abu, Anushika Karunaratne, Beula Selvadurai, Ella Omomene Iklaga, Erik Magnus Fernstrom, Francesca Fusaro, Govinda R Timilsin, Irina Dvorak, Jane Ebinger, John Allen Rogers, Joseph E. Akpokodje, Martyn Howells, Oluwafemi Faleye, Roger Gorham, Shobha Shetty, Stephen Danyo, Stephen Ling, and Venkata Ramana Putti. The World Bank peer reviewers for this book were Sameer Akbar, Christophe de Gouvello, and Todd Johnson.

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PART 1

# Agriculture and Land Use Sector

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# Abbreviations

| | |
|---|---|
| ADP | Agricultural Development Project |
| AFAN | All Farmers Association of Nigeria |
| AFOLU | agriculture, forestry, land use |
| AGB | above-ground biomass |
| ATA | Agricultural Transformation Agenda |
| CCA | Climate Change Assessment |
| CGIAR | Consultative Group on International Agricultural Research |
| CGIAR CSI | Consortium for Spatial Information |
| $CO_2e$ | $CO_2$ equivalent |
| CPS | World Bank Country Partnership Strategy |
| CSA | climate smart agriculture |
| DM | dry matter |
| EX-ACT | EX Ante Appraisal Carbon-balance Tool |
| FAO | Food and Agriculture Organization of the United Nations |
| FAOSTAT | FAO database |
| FGN | Federal Government of Nigeria |
| FMARD | Nigerian Federal Ministry of Agriculture and Rural Development |
| GAFSP | Global Agriculture and Food Security Program, FGN |
| GHG | greenhouse gases |
| IPCC | Intergovernmental Panel on Climate Change |
| LAC | low active clay |
| LC | low-carbon |
| LUC | land use change |
| LULUC | land use and land use change |
| MACC | Marginal Abatement Cost Curve |
| METI | Japan's Ministry of Economy, Trade and Industry |
| M ha | millions of hectares |
| NAIP | National Agriculture Investment Plan |
| NASA | National Aeronautics and Space Administration |

| | |
|---|---|
| NBS | National Bureau of Statistics (Nigeria) |
| NFLUC | Non-Forest Land Use Changes |
| NFSP | National Food Security Program (Nigeria) |
| NPV | net present value |
| NRDS | National Rice Development Strategy (Nigeria) |
| NTPF | non-timber forest product |
| NV | Nigeria Vision |
| SGM | sustainable grazing management |
| SLM | sustainable land management |
| SOC | soil organic content |
| SRI | sustainable rice intensification |

All currency values are in constant 2009 US$ unless otherwise specified.

# Executive Summary

In Vision 20: 2020 the Federal Government of Nigeria laid out ambitious targets for increasing the domestic agricultural production sixfold by 2020. Output growth would be achieved through reduction in postharvest losses, increased yields, and expansion of cropland. The present study analyzes the climate change mitigation potential of the agricultural sector within the constraint of meeting these growth targets. The EX Ante Appraisal Carbon-balance Tool (EX-ACT), developed by the Food and Agriculture Organization of the United Nations (FAO), was used for the analysis. The tool enables comparison of emissions between scenarios involving different land use and management choices. The analysis was conducted for a 25-year period, 2010–35, with a 15-year *implementation* period for land management changes and a 10-year *capitalization* period during which no further land management changes are considered but emissions effects deriving from the earlier changes are assessed.

The team constructed a *reference scenario* to provide a plausible pathway for achieving the Vision 20: 2020 growth targets in 2025, based on government policies and expert opinion. First, a growth model was established to estimate expected contributions of cropland expansion and yield increases to meet the overall sector output growth targets. Then more detailed land use and technology change projections were developed in line with the broad parameters set by the growth model. Net greenhouse gas (GHG) emissions were calculated from the detailed land use and technology models, which also incorporated a spatial analysis of land suitability and specific government policies (for example, on afforestation, expansion of irrigation and rural roads, and other land use changes).

The reference scenario produces emissions of about 2.7 billion t $CO_2$e for 2010–35, at an average of 1.2 t $CO_2$e/ha/yr. Annual emissions are 6 times lower by 2035, reaching 25 Mt $CO_2$e from an initial 161 Mt $CO_2$e in 2010. The difference is due mainly to reduction in emissions from land use change (LUC), as land use patterns stabilize and in particular deforestation slows down and is eventually halted, although 50 percent of secondary forest area is still lost by the end of the simulation period, leaving only 5 percent of the country being covered by secondary forest. By 2035, grassland (–16 percent compared to 2010), fallow (–67 percent), and other land classes (–30 percent) are also reduced to make room for cropland expansion (+45 percent). However, because croplands are better managed with less use of fire on perennial plantations, and with improved seeds and water management on irrigated surfaces, they provide a net sink of 44 Mt $CO_2$e per yearby 2035. The results show that by improving land management to meet the ambitious Vision 20: 2020 growth targets, significant reductions in GHG emissions are already achieved, but further improvements are possible. Roughly two-thirds of the emissions are due to LUCs, and one-third come from livestock; therefore these activities should be the focus for improvements under the low-carbon scenarios.

A revised growth model demonstrates that the same sector output targets can be met with reduced expansion of cropland if yield growth is accelerated by a realistic amount following the increased adoption of improved and conservation agriculture techniques. Based on the reduced rate of cropland expansion (1.2 percent on average, rather than 1.6 percent) built into the revised growth model, two low-carbon scenarios were explored. Both involve the introduction of a range of sustainable land management (SLM) technologies, which raise agricultural productivity, increase density of trees in the landscape, or both. Under the constraint of fixed maximum average land area (assumed at 800,000 hectare per year) that can be converted to SLM technologies, one scenario (A) selects SLM options so as to maximize the emissions reduction potential, while the alternative scenario (B) maximizes the net benefits accruing to farmers.

All SLM technology options are associated with positive costs for the government, which is assumed to provide technical support and some financial support for their implementation. The balance of costs to private farmers and landowners is very different and depends greatly on the specific type as well as form of production. Scenario A focuses on those options that maximize the emission reduction potential per ha of land, as most notably avoided deforestation and agroforestry. Scenario B, however, focuses on the options that provide the highest private return, particularly conservation agriculture, which increases crop yields for a relatively low investment. (Note that agroforestry also provides significant yield increases, but requires more intense up-front investment from farmers, particularly in labor, and is therefore only marginally profitable for them). Overall, scenario A results in a mitigation potential of 1.0 billion t $CO_2$e (compared to the reference scenario) entailing costs to the Government of US$ 3.2 billion (in NPV terms), while generating a net return of US$ 5.7 billion to farmers (also NPV). Scenario B generates roughly half the emission reductions, at slightly more than 0.6 billion t $CO_2$e, at a similarly reduced public cost of about US$ 2.2 billion, while private returns are roughly increased by one-third, reaching US$ 7.3 billion.

Finally, a revised model demonstrates that introduction of carbon payments to private farmers/landowners at a minimum price of $ 6.1 per t $CO_2$e would be sufficient to achieve the same overall private returns as in scenario B, even when adopting the same mix of SLM options as in scenario A. Nevertheless, even with such moderate payment schemes, some options, such as avoided deforestation, remain economically unattractive to farmers when assessed in isolation.

The results outline the broad potential for sector growth targets to be achieved with greatly reduced carbon emissions through the adoption of appropriate SLM technologies. Some combination of technologies or practices generates net benefits to farmers, while others are not so financially attractive but involve even greater emission reductions and other environmental benefits. Despite their benefits, however, the large-scale introduction of SLM technologies pose significant practical obstacles—mostly associated with convincing risk-averse farmers to adopt new practices and providing a supportive environment for making up-front investments that will pay off a few years after the initial investment. Chapter 4 reviews some of the steps that may be necessary for SLM to take off, including development of the required agricultural research and extension services, and providing a stable, conducive policy framework. Decentralization, reallocation of funding, and increased cooperation and interaction between diverse stakeholders are some of the institutional steps required.

CHAPTER 1

# Introduction

The Federal Government of Nigeria (FGN) and the World Bank have agreed to carry out a Climate Change Assessment (CCA) within the framework of the Bank's Country Partnership Strategy (CPS) for Nigeria (2010–13). The CCA includes an analysis of options for low-carbon development in selected sectors, including power, oil and gas, transport, and agriculture. The goal of the low-carbon analysis is to define likely trends in carbon emissions up to 2035, based on government sector development plans, and to identify opportunities for achieving equivalent development objectives with a reduced carbon footprint.

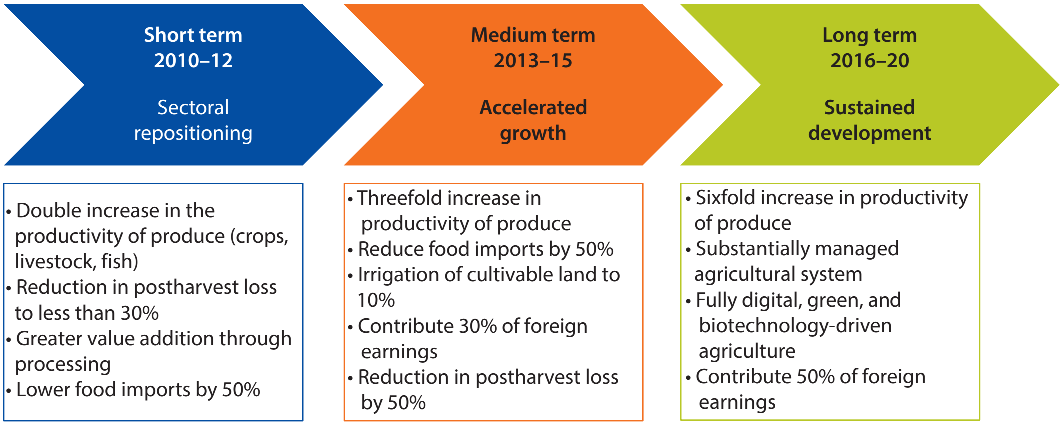
Agriculture and land use change are major contributors to Nigeria's total greenhouse gases (GHG) emissions. According to FAOSTAT (2013) estimates, agriculture alone, excluding land use change (LUC), accounted in 2010 for emissions of 48,154.36 gigagrams (Gg) $CO_2$e, while the average annual emissions from net forest conversions 2000–10 are estimated at 180,228 gigagrams $CO_2$e and recent estimations of emissions from drained cultivated organic soils are not available.[1] At the same time, agriculture also offers various mitigation options, essentially through enhanced carbon storage in soil and vegetation.

The agriculture sector currently contributes 33 percent of national income and almost 70 percent of employment (CBN 2002; World Bank 2007), and is likely to remain a major economic sector, even if current stagnant or declining sector output is not reversed.

Agriculture features prominently in Vision 20: 2020 (FGN 2010a), the overall growth strategy adopted by the Government in 2008, which aims for Nigeria to become one of the world's 20 leading economies by 2020. Vision 20: 2020 establishes targets for threefold and sixfold increases in domestic agricultural productivity by 2015 and 2020, respectively. These targets are to be achieved through (1) reduction of postharvest losses; (2) increasing yields (by expansion of irrigation and greater use of improved and disease-resistant crop varieties); and (3) expansion of cropland. Figure 1.1 illustrates the Vision 20: 2020 phased approach to achieve these objectives.

More recently, the FGN adopted the Agricultural Transformation Agenda (ATA) (FGN 2011) for transformation of the sector through processes including

**Figure 1.1 Implementation of the Vision 20: 2020 Roadmap**




*Source:* Design based on FGN 2009.

import substitution, export orientation, and value-addition through processing and backward integration linkages. Emphasizing the role of the private sector, the ATA focuses on a selected number of value-chains (including rice, cassava, sorghum, cocoa, and cotton), on complementary investments in infrastructure, and on providing improved access to credit and steps toward an enabling policy environment.

### *Scope and Limitations of the Analysis*

This section analyzes greenhouse emissions from agriculture, forestry, and land use (AFOLU). Emissions from agro-industries are not included. This part of the low-carbon study comprises the following components:

- Development of a reference scenario of GHG net emissions for the agriculture sector, consistent with Vision 20: 2020 and other government plans
- Identification of opportunities for reduced net emissions—reduced emissions and/or enhanced carbon sequestration—while achieving the same development objectives as in the reference scenario
- Economic assessment of low-carbon options in order to help the Nigerian government to prioritize policy options.

The analysis does *not* intend to evaluate the feasibility of government policy targets incorporated into the reference scenario, but rather to investigate whether—and at what cost to farmers and to the government—those targets could be achieved with lower net carbon emissions. The agriculture targets under Vision 20: 2020 are ambitious and will be affected by many uncertain variables. Hence the reference scenario is not necessarily the most likely to actually materialize, but does serve as a basis of comparison with the low-carbon alternative.

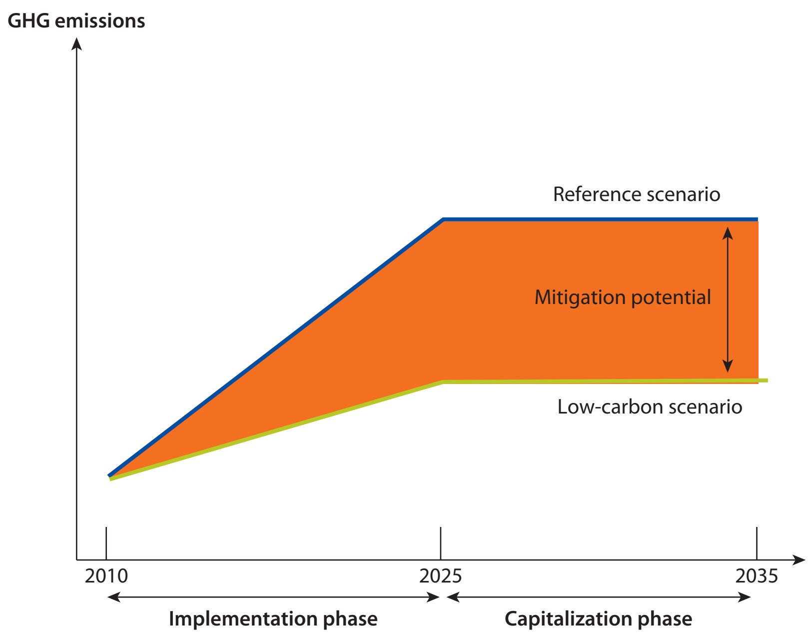
The study evaluates costs and benefits in a partial equilibrium setting, with no attempt to capture the indirect, general equilibrium effects of adopting low-carbon technologies or management practices. The results of this analysis (the first of its kind in Nigeria) should be considered as a first approximation of the potential for low-carbon development in the Nigerian agriculture sector. The study aims at providing policy makers with an order-of-magnitude estimate of mitigation potential, and an understanding of the value of dedicating further efforts (including through specific projects) at pursuing low-carbon development in agriculture, but is not meant to inform the design of specific, project-level interventions.

### *Methodology and Data Sources*

GHG emissions under the reference and low-carbon scenarios are estimated using EX-ACT (Ex Ante Appraisal Carbon-balance Tool), developed by the Food and Agriculture Organization (FAO) and aimed at providing ex ante estimates of the impact of agriculture and forestry projects or policies on net GHG emissions (Bernoux et al. 2010). The mitigation potential of the low-carbon scenario is calculated as the difference in emissions resulting from the two scenarios (figure 1.2).

In consultation with government officials and other experts on Nigeria, the research team agreed to adopt a conservative assumption that the Vision 20: 2020 targets—including a sixfold increase in agricultural productivity—would be met by 2025 rather than 2020. Both scenarios therefore start in the year 2010 and span a 15-year implementation phase in which aggressive investments are

**Figure 1.2 Mitigation Potential of Low-Carbon Practices on the Agriculture Sector**




*Source:* World Bank data.

made to achieve sector development targets, and a 10-year capitalization phase, in which benefits of those investments continue to accrue.

A simple growth model was used to estimate the magnitude of crop expansion, consistent with the Vision 20: 2020 targets.[2] More detailed land use and technology change models were then constructed within the overall growth parameter in order to calculate emissions. The detailed assumptions used in the modeling drew from discussions among experts from the government, FAO, and World Bank staff to determine distributions of secondary forests, grasslands, degraded lands, and other lands, taking into account a spatial analysis of soil quality, slope, and other suitability factors for cultivation. Expert opinion was also used to select the most plausible low-carbon options suited to the Nigerian context.

The data sources on agronomic practices and land use are listed in tables 1.1 and 1.2.

**Table 1.1 Sources for Nigerian Agronomic Practices**

| *Practices* | *Data sources* |
|---|---|
| Yield, irrigation | • Federal Government of Nigeria—National Implementation Plan (NIP) (FGN 2010a)<br>• Getting Agriculture Going in Nigeria (World Bank 2006)<br>• Nigerian Federal Ministry of Agriculture and Rural Development—National Agricultural Investment Plan (NAIP) (FGN 2010a)<br>• The Nigerian Federal Ministry of Agriculture and Rural Development—Global Agriculture and Food Security Program (GAFSP) (FGN 2010b) |
| Fertilizer use | • FAOSTAT (faostat.fao.org)<br>• National Bureau of Statistic of Nigeria (NBS) (NBS 2009) |
| Rice planning | • National Rice Development Strategy (NRDS) (NFRA—JICA 2009) |
| Livestock management, yield evolution, regional agriculture practices disparity | • New Nigerian Agricultural Policy (FGN 2010c) |
| SLM practices | • FADAMA study (Ike 2012)<br>• Benefit Cost Analysis of SLMW in Nigeria (World Bank 2010a)<br>• *NIGERIA Simulation of Sustainable Land Management Practices* (World Bank 2010b) |

*Source:* World Bank data.

**Table 1.2 Data Sources for Land Uses**

| *Practices* | *Data sources* |
|---|---|
| Rice | • National Rice Development Strategy (NRDS) (NFRA, JICA 2009) |
| Cropland and perennial crop | • FAOSTAT<br>• National Bureau of Statistic of Nigeria (NBS 2009) |
| Forest management | • Forest Resources Assessment for Nigeria 2010 (FAO 2010)<br>• UN Programme on Reducing Emissions from Deforestation and Forest Degradation (UN-REDD) (FGN and UNDP 2010; Odigha and Dahiru 2011) |
| Cropland, grassland, forest, soil quality | • Global Administrative Areas Database (GADM 2010)<br>• Global Land Cover Network (FAO 2009) |
| Climate and soil constraints for the cultivation of crops | • ASTER Global Digital Elevation Model (ASTER GDEM) (Japan Space Systems 2011)<br>• The CGIAR Consortium for Spatial Information (CGIAR-CSI 2008)<br>• IIASA Harmonized World Soil Database (IIASA 2008) |

*Source:* World Bank data.

**Table 1.3 Sources of Coefficients Used in the Analysis**

| *Type of vegetation* | *Type of coefficient* | *Tier 1 (IPCC 2006)* | *Tier 2 (data sources)* |
|---|---|---|---|
| Forests | Carbon content in above and below ground biomass for secondary forests | | Henry 2010 |
| | Emissions factors of forest biomass burning | × | |
| | Afforestation/reforestation: carbon pool content | × | |
| Annuals, perennials, grasslands, degraded lands, other | Nonforest land use changes (initial and final carbon pool in biomass and soil) | × | |
| Annuals | Carbon storage capacity of different agronomic practices | × | Chivenge et al. (2007); Leite et al. (2009) |
| Perennials | Above and below ground biomass growth rate | × | |
| | Emissions factors of biomass burning | × | |
| Rice | Methane emissions | × | |
| Grassland | Emissions factors of biomass burning | × | |
| Livestock | Methane emissions from enteric fermentation | × | |
| | Methane emissions from manure management | × | |
| | Nitrous oxide emissions from manure management | × | |
| | Mitigation potential of better feeding practices | × | |
| Inputs | Carbon dioxide emissions from urea application | × | |
| Other investments | $CO_2$ emissions of gasoil | × | |
| | $CO_2$ emissions of biodiesel | | Guo and Hanaki (2010) |
| | $CO_2$ emissions of the installation of irrigation system | × | |
| | $CO_2$ emissions from the construction of buildings and roads | × | |

*Source:* World Bank data.

Emissions factors and carbon storage coefficients are needed to convert land use changes and agronomic practices into GHG emissions. The EX-ACT tool includes default coefficients taken from the Intergovernmental Panel on Climate Change Guidelines 2006 (IPCC 2006), but where possible and appropriate, local data were used to drive values more suited to the Nigerian context. Table 1.3 summarizes the sources of the coefficients used in the analysis. More details are available in appendix A.

## Notes

1. Please refer to the first national communication of Nigeria to the UNFCCC for older but more comprehensive estimates (FGN 2003).
2. Note that it is assumed that the sixfold increase in the value of agricultural output envisioned under Vision 20: 2020 is only partly met through increases in physical output, with the rest accounted for in terms of an increases in price per value of output, at least partly due to increased value-added among other factors. Hence, the growth in physical output to 2025 used as the basis of the growth model is less than a sixfold increase.

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CHAPTER 2

# The Reference Scenario

## Agricultural Growth Model

A simplified growth model was constructed representing a feasible pathway to achieving the increase in total agricultural production envisaged by Vision 20: 2020. The model, based on literature, consultation with stakeholders, and expert judgment, accounts for overall economic growth in agriculture using the following three factors:

- **Cropland expansion**. The annual rate of cropland expansion is assumed to decline from 2.33 percent to 0.79 percent linearly, resulting in a compounded mean annual growth rate of 1.56 percent for 2010–25. Thereafter, the rate of expansion remains at 0.79 percent per year.

- **Yield growth.** Average crop yields (per unit area of cropland) are estimated to grow by 3 percent per year for the first two years and then by 5 percent for the next three through investments in improved agronomic practices, such as adoption of improved seeds and fertilization, based on national yield responses to similar investments in Asian countries (Evenson and Gollin 2003). Thereafter, a 4 percent[1] annual growth rate was assumed for the rest of the modeling period, since shorter fallow periods will decrease soil organic content, thus limiting yield growth.

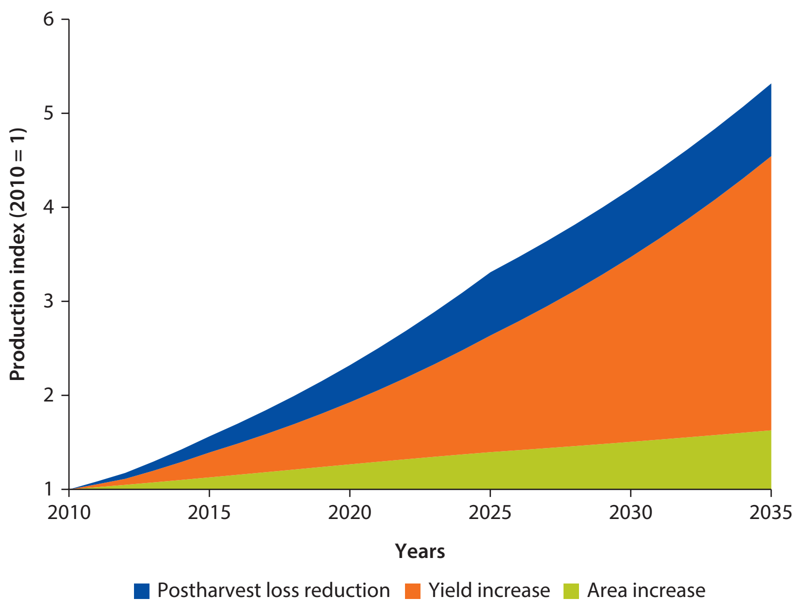
- **Annual growth due to the reduction of postharvest loss.** Postharvest loss is currently estimated at 33 percent of production. The Vision 20: 2020 strategy aims to reduce it by 50 percent by 2015 and 90 percent by 2020. The growth model assumes more conservatively that the 90 percent target will be reached by 2025 via a linear 6 percent decrease per year in the rate of postharvest loss. This is equivalent to an annualized compound growth rate of the volume of agricultural production reaching market of 2.48 percent during 2010–25. After 2025, reductions in postharvest losses are assumed to take place at a slower pace (less than 1 percent per year).

**Table 2.1 Agricultural Growth Model Predicted Growth**

| *Type of growth* | *Average % growth 2010–25* | *2026–35* |
|---|---|---|
| Annual cropland expansion | 1.56 | 0.79 |
| Annual yield growth | 4.07 | 4.00 |
| Annual growth due to postharvest loss reduction | 2.48 | 0.30 |

*Source:* Calculations based on sources in chapter 1 "Data Sources for the Agriculture and Land Use Sector" and tables 1.1–1.3.

**Figure 2.1 Agricultural Growth Model: Production Increase and Growth Sources**




*Source:* World Bank data.

The assumptions and results of the growth model are illustrated, respectively, in table 2.1 and figure 2.1.

## GHG Emissions Model

The growth model was then used as a basis for identifying a consistent set of land use and technological changes that could plausibly be expected to occur by 2025, and which would form the basis for estimating greenhouse gases (GHG) emissions from the agriculture sector and project an emissions model.

### *Land Use Changes*

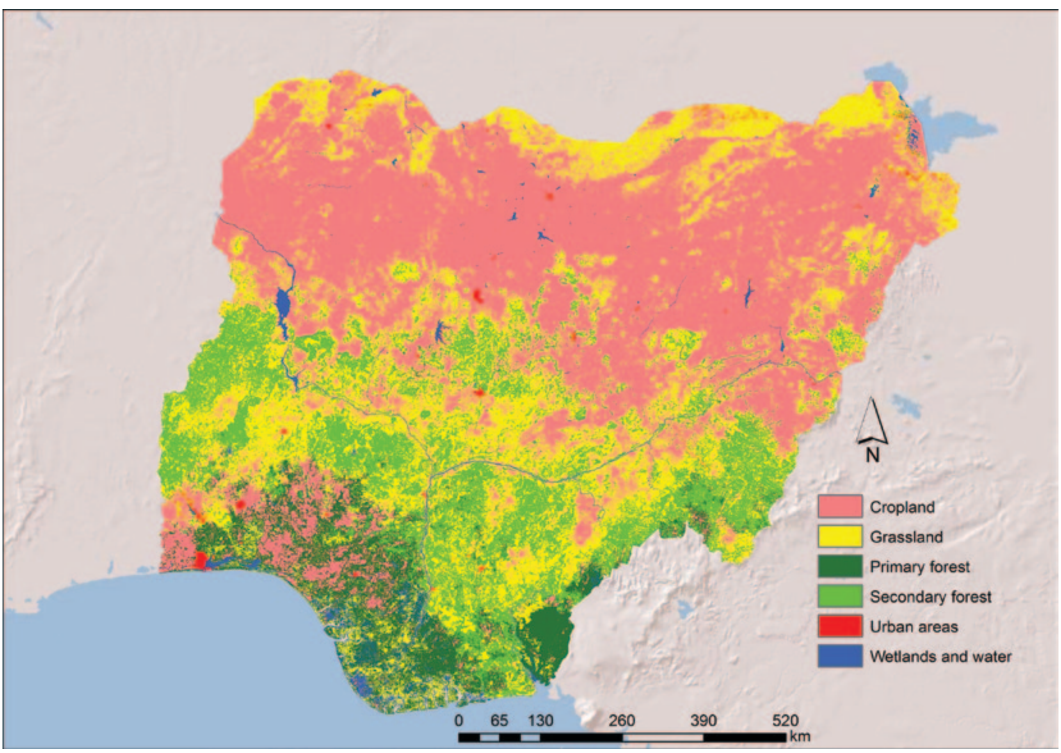
Land use changes are expected to contribute to greenhouse gas (GHG) emissions, albeit at a decreasing rate, particularly through conversion of forests, grassland (that is, pasturelands that also contribute to agriculture sector output), fallow acreage, and other lands to cropland. In accordance with government policies, land use changes are assumed to take place predominantly from 2010 to 2025. After 2025, land use patterns notionally follow the same trends as in the reference growth model, but only the land use changes until 2025 are counted in the calculation of emissions.

Conversion of forest to agricultural lands was assumed to affect only secondary forests. A GIS-based (geographic information services) evaluation of the suitability of secondary forests for agricultural conversion was undertaken based on current land use, slope, and soil quality (see map 2.1). Secondary forest areas were considered suitable for conversion if categorized as "partly with constraints" or as of "higher suitability." The results of the exercise are shown in map 2.2, which indicates that over 3 million hectares of existing secondary forest could be converted to agriculture under the two conditions given above.

The assumptions of the land use change model in the reference scenario, based on official policy, current trends, experts' opinion, and consistency with the growth model to 2025, are as follows:

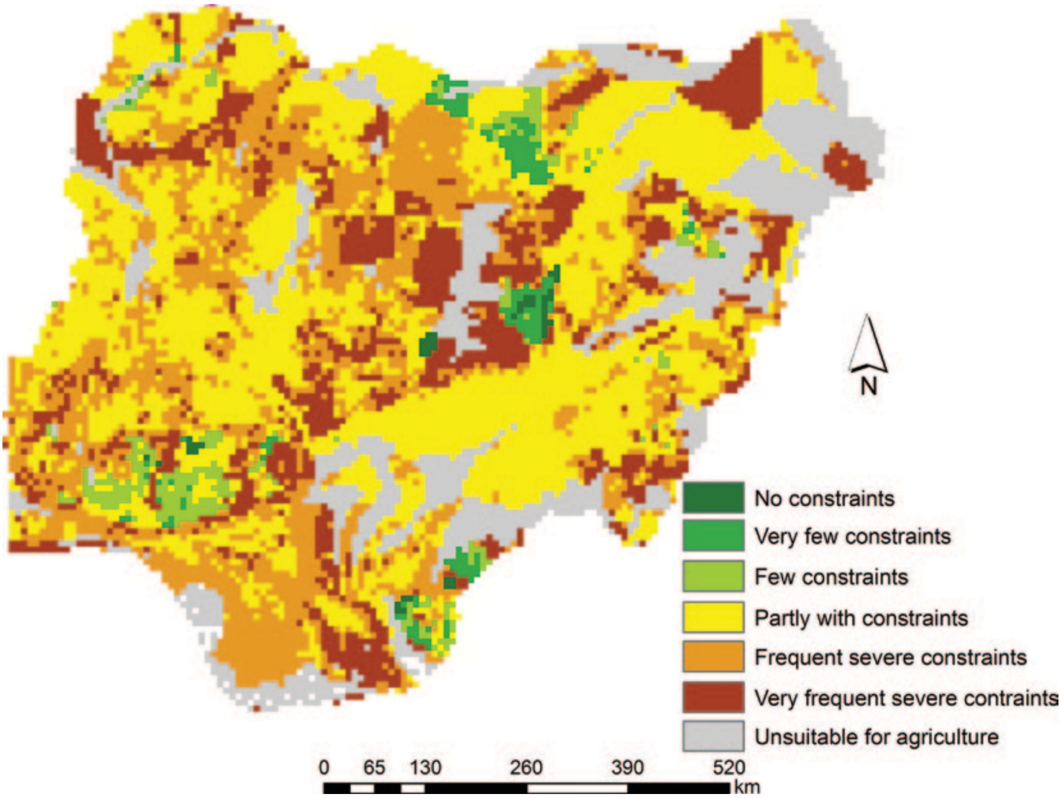
- Land conversions are based on linear processes, 2010–25.[2]
- The area of land under annual crops (cereals, tubers) increases by 1.56 percent/year, and the area under perennial crops (palm tree, rubber tree, cocoa) by 3.22 percent/year following the trend for 1990–2010.

**Map 2.1 Land Use Map, 2011**




*Source:* FAO GeoNetwork Database, World Bank Development Indicators 2011.

**Map 2.2 Land Suitable for Agricultural Use, 2011**




*Source:* FAO GeoNetwork Database, World Bank Development Indicators 2011.

- Ninety percent of secondary forest land suitable for agriculture is converted into annual crops, with the rest assigned to perennials and grasslands.
- Tropical secondary forest in the Southwest accounts for 75 percent of forest land converted to perennial crops, due to the wet preference of perennials. The remaining 25 percent of forest conversion to perennials takes place in moist secondary forest in the North.
- As the area of forest available for conversion is insufficient to meet the total increase in cropland, some grassland and fallow are also converted to cropland, since they offer a better soil quality for cultivation than degraded land or other land.
- The area of wet rice cultivation within annual cropland roughly doubles to 2.625 million ha by 2025, from 1.313 in 2010, meeting the Government's 2018 target from the National Rice Development Strategy (NFRA—JICA 2009).
- Based on consultation with the Department of Forestry, afforestation will take place over 600,000 hectares. Reforestation (dry and moist plantation forest) takes place on degraded land (50 percent), fallow (30 percent), and pasturelands (20 percent).

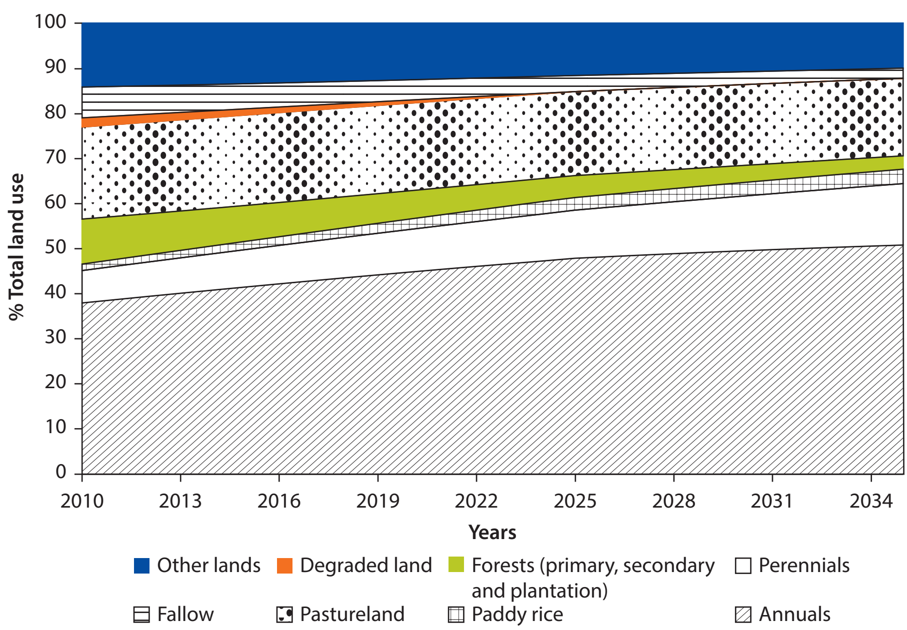
- Half of the degraded lands are restored into perennial plantation, while the rest is restored to pasturelands or forest.
- The conversion of other land uses (grassland, degraded land, fallow, other land[3]) is calculated in ways that ensure overall consistency of the land use matrix reported appendix B for 2025.

Figure 2.2 illustrates the change in land use over time. Overall, by 2025, forest land shrinks by more than 50 percent, and annuals and perennials increase by a factor of 1.3. Grassland and other lands remain stable or are slightly reduced. In 2010 crops (annual, perennial, rice) account for 46 percent of the total country area, forests for 10 percent, pasturelands for 20 percent, and the rest (degraded land, fallow, other) for 23 percent. In 2025 crops are projected to account for 61 percent of total land area. Forests have shrunk to 5 percent. Pasturelands remain stable at about 19 percent. After 2025, crop expansion slows down, and crops account in 2035 for 68 percent of the total country area, forest for 3 percent, pasturelands for 17 percent, and other lands for 12 percent. The land use change details can be found in appendix B; a concise overview is given in table 2.2.

### *Sector Investments and Technological Change*

The reference scenario assumes that the Vision 20: 2020 goal for improved crop cultivars and fish and livestock breeds to constitute 50 percent of stocks will be met by 2025, via linear growth. It further assumes that where applied, these improved varieties will be accompanied by better management, namely use of

**Figure 2.2 Land Use Evolution in the Reference Scenario**




*Source:* Calculations based on sources in chapter 1 "Data Sources for the Agriculture and Land Use Sector" and tables 1.1–1.3.

**Table 2.2 Land Use in 2010, 2025, and 2035 for the Reference Scenario**
*ha, thousands*

| *Land use* | *2010* | *2025* | *2035* |
|---|---|---|---|
| Annuals | 34,437 | 43,437 | 46,155 |
| Perennials | 6,552 | 9,712 | 12,419 |
| Paddy rice | 1,313 | 2,625 | 2,919 |
| Forest | 9,101 | 4,438 | 2,700 |
| Secondary forest | 8,805 | 3,542 | 1,804 |
| Plantation | 296 | 896 | 896 |
| Live fencing/agroforestry | 0 | 0 | 0 |
| Pastureland | 18,629 | 16,974 | 15,669 |
| Degraded land | 1,849 | 0 | 0 |
| Fallow | 6,234 | 3,257 | 2,076 |
| Other lands | 12,941 | 10,602 | 9,116 |
| Total | 91,054 | 91,054 | 91,054 |

*Source:* Calculations based on sources in chapter 1 "Data Sources for the Agriculture and Land Use Sector" and tables 1.1–1.3.

**Table 2.3 Projected Expansion of Infrastructure for Agriculture in 2025**

| | | *Surface, 1000 m²* | | |
|---|---|---|---|---|
| *Type of building* | *Quantity* | *Office* | *Concrete* | *Metal* |
| Livestock breeding and multiplication centers | 12 | 12 | 23.76 | 0 |
| Export conditioning centers | 12 | 12 | 23.76 | 0 |
| Agric seeds centers | 36 | 36 | 71.28 | 0 |
| Slaughterhouse | 36 | 36 | 71.28 | 0 |
| Large-scale rice processing | 181 | 36.20 | 0 | 325.80 |
| Cassava processing factories | 200, 000 | 0 | 0 | 2,000 |
| Storage capacity (3–44 Mt) | 41 | 2.05 | 40,795 | |

*Source:* Calculations based on sources in chapter 1 "Data Sources for the Agriculture and Land Use Sector" and tables 1.1–1.3.

suitable fertilizers and no residue burning for crops, and improved breeding and feeding practices for livestock. Livestock numbers increase continuously at the same rate as for 2000–10.

The government target to expand irrigation—from 1 percent of cultivated area in 2010 to 25 percent in 2020—is assumed to be reached only in 2035. Hence in 2025, 15.8 percent of the cropland will be irrigated. All the irrigated area will be managed with improved water efficiency. Degraded lands converted to pasturelands will be improved with organic and inorganic fertilizers and managed without fire, to allow recovery of soil fertility.

It is assumed that 6,000 kilometers of roads will be constructed to improve market access to remote areas. The proportion of tractor-ploughed arable land will rise from about 8.5 percent to 50 percent by 2025 (Oni 2004). Assumptions about the expansion of processing and storage infrastructure were derived from Vision 20: 2020 plans to strengthen agricultural export markets (summarized in table 2.3).

### *Climate and Soils*

Moist tropical climate and low-active clay (LAC) soil classifications were used for the analysis, as these were considered closest to the typical conditions in Nigeria. Although there is local variation in soil and climate conditions, a sensitivity analysis (see appendix E) was conducted which indicated that these factors would have little effect on the final results in terms of the comparative emissions between the reference and low-carbon scenarios.

## Emissions Baseline

GHG emissions were calculated from 2010 to 2035 for land use changes and other sector reforms that take place up to 2025—that is, the emissions consequences of agricultural development up to 2025 is being estimated—with allowance for a 10-year *capitalization* period thereafter, but further sectoral changes after 2025 are not represented in the calculation.

GHG emissions are expressed in $CO_2$e.[4] The different emissions sources have been grouped into four main categories:

- **Crops (including annuals, perennials, and paddy rice).** Crops provide a net carbon sink over time, due to an increase in soil carbon through the improved management practices introduced alongside new crop varieties in the reference model. Paddy cultivation, on the other hand, acts as a net source due to methane production from the flooded soil.
- **Land use changes.** These changes will emit or sequester $CO_2$ depending on whether the conversion is to a vegetation cover type with lower or higher carbon density. The greatest changes occur as a result of deforestation or afforestation. Land use change may result in GHG emissions/sequestration beyond the time at which it occurs, due to associated changes in soil carbon, which may some years to reach a new equilibrium.
- **Livestock and pasturelands.** Emissions from the livestock are essentially methane and nitrous oxide produced by the digestion processes of ruminants and from manure, while improved pastureland management can store carbon through an increase in the soil organic matter.
- **Agricultural inputs.** These involve GHG emissions associated with fertilizer consumption and production, infrastructure construction, and fuel consumption.

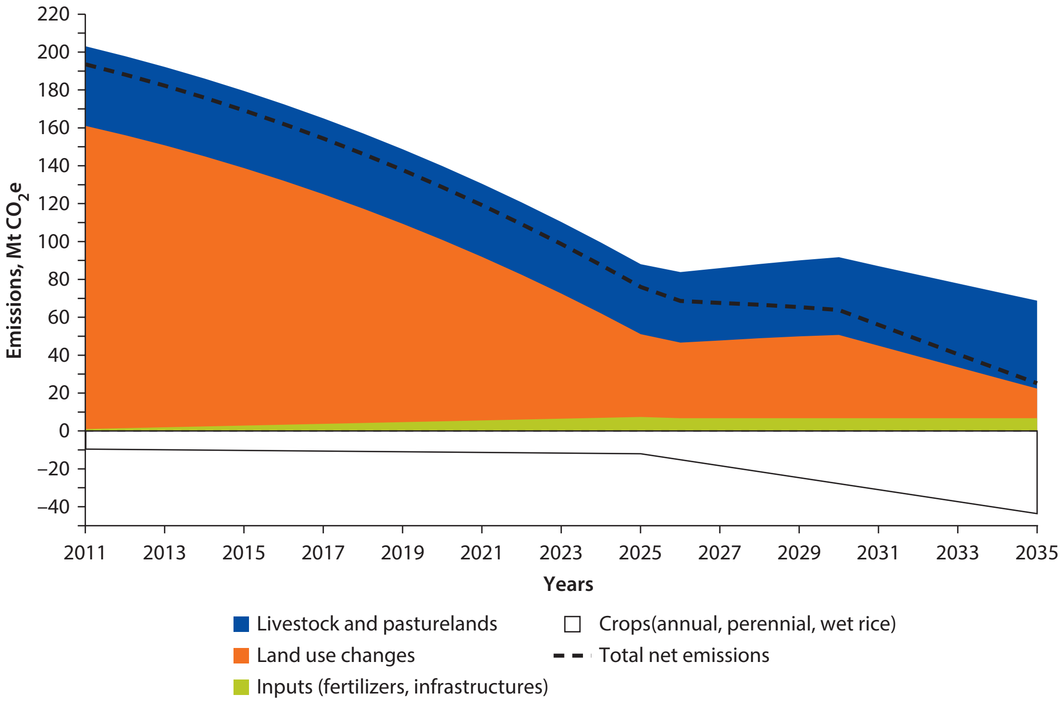
While emissions decrease over time, agriculture remains a net source of GHG in the reference scenario; it accounts for about 2.7 billion t $CO_2$e emissions during the whole period from 2010 to 2035 (that is, an average of 1.2 t $CO_2$e /ha/yr). Table 2.4 shows total annual emissions at the beginning (2010) and end (2035) of the simulation period. Figure 2.3 illustrates the evolution over time of the four main emissions categories, and the overall net emissions pathway.

**Table 2.4 Annual Emissions of 2010 and 2035 in the Reference Scenario**

| | *Emissions (Mt $CO_2$e/yr)* | | |
|---|---|---|---|
| *Land use* | *2010* | *2035* | *% Difference* |
| Land use changes | 127.1 | 15.6 | –88 |
| Crops | –9.4 | –43.6 | –364 |
| Livestock and grassland | 42,4 | 46.4 | +10 |
| Inputs | 0.6 | 6.7 | +1068 |
| Total | 160.6 | 25.2 | –84 |

*Source:* World Bank data.

**Figure 2.3 Annual Emissions by Land Use Activity, in the Reference Scenario, 2010–35**




*Source:* Calculations based on sources in chapter 1 "Data Sources for the Agriculture and Land Use Sector" and tables 1.1–1.3.

Annual emissions due to land use changes (representing 60 percent of cumulative emissions) decline by a factor of 8, as land use change (including net deforestation) is brought to a halt by 2025. Residual emissions from soil carbon changes related to land use change increase and then decrease after 2025 due to ongoing soil carbon loss from earlier occurring deforestation, with more gradual and increasing accumulation of soil carbon from afforestation.

Conversion of degraded land, fallow, and other lands into perennials accounts for 65 percent of gross sinks, followed by annual crops (22 percent) and afforestation (13 percent).

Emissions from livestock and grassland account for 30 percent of the cumulative total. They increase a little due to augmentation in the number of animals.

The net sink function of crops is enhanced over time as a result of both the increase in the area of perennials and improvements in agronomic practices for annual crops (for example, use of improved seeds and water management for the irrigated surfaces). Carbon storage increases after 2025 because residue burning in annual and perennial croplands is halted by that point. Wet rice remains a net GHG source, but its emissions are exceeded by the sink function of annuals and perennials.

Emissions from inputs and infrastructure increase, reflecting government plans to expand the use of fertilizers. However, they contribute to a limited part (4 percent) of total GHG emissions.

## Notes

1. As no scientific data were available, this figure was estimated thanks to consultations with FAO experts.
2. Forest loss is actually a decelerating process, rather than being strictly linear, but the effect is too minor to be evident in figure 1.4.
3. Other lands include gullies, dominantly grasses, discontinuous grassland; shrub/sedge/graminoid; freshwater marsh/swamp; natural waterbodies; sand dunes; montane grassland; reservoirs; rock outcrop; saltmarsh/tidal flat; alluvial; mining areas; and canals.
4. Which standardizes the contribution of each GHG, according to its Global Warming Power (GWP): 1 for carbon dioxide, 21 for methane, and 310 for nitrous oxide.

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CHAPTER 3

# The Low-Carbon Scenarios: Mitigation Options

The low-carbon scenarios pursue the same development goals as the reference scenario, that is, a roughly sixfold increase in the overall productivity of the agricultural sector by the end of the model period until 2035, but include additional investments aimed specifically at reducing the net greenhouse gases (GHG) emissions from the sector. These mitigation options are composed of available and proven sustainable land management (SLM) practices. According to TerrAfrica (World Bank 2011, 26), sustainable land management is the "adoption of land systems that, through appropriate management practices, enables land users to maximize the economic and social benefits from the land while maintaining or enhancing the ecological support functions of the land resources."

## Sustainable Land Management Options

SLM options occur in agricultural, livestock, and forestry land uses, and may be interlinked:

- **Conservation agriculture** aims at increasing yields environmental benefits through improved management of soil and water resources. The key agronomic practices included are crop rotation/intercropping, minimal turning of the soil (minimum or no tillage), and maintaining soil cover through cover cropping or mulching. However, the availability of mulch material (for example, crop residues, cut vegetation, manure, compost, and by-products of agro-industries) is typically lower in semi-arid regions (Kayombo and Lal 1993), which cover a significant part of Nigeria.

- **Avoiding deforestation** is another major mitigation benefit potentially achieved by conservation agriculture. Increased yields from well-established agricultural systems using conservation management practices can reduce the need to convert additional forest areas to cropland (for the same overall production targets[1]).

- **Agroforestry** refers to land use systems in which woody perennials are integrated with crops and/or animals on the same land management unit (Junge et al. 2008), including agro-silvicultural systems (intercropping, alley cropping), silvo-pastoral systems (fodder banks, live fences, trees and shrubs on pasture), and intermixtures. Agroforestry may also contribute to conservation agriculture by providing mulch.

- **Sustainable Rice Intensification (SRI)** practices can reduce methane emissions from rice paddies. SRI practices involve modifying the growing environment so that the rice plants can grow better with more economical use of inputs. For instance, instead of flooding the rice, the seedlings are planted in dry soils that are watered periodically. Seedlings are also spaced more widely, to allow for regular soil aeration and weeding as the plants develop.

- **Better feeding and breeding practices** help reduce livestock emissions from enteric fermentation and manure, which can even be offset by sequestering carbon in the biomass and soil of pasturelands. Improved rangeland management may involve rotational grazing, reduction of fire use, application of fertilizers or manure, irrigation, improved grass varieties, association with legumes, and other practices. Sustainable rangeland management should also result in lower stocking densities.

The public and private costs for the various SLM options vary. Public costs are incurred through provision of government support for each option; for example, provision of improved seed, fertilizers or feed, extension services, and administrative/management costs. Farmers or private landowners incur costs—for example, labor and producing/purchasing fertilizer, feed, and fuel—but also benefit from the incomes accruing from increased production.

Table 3.1 summarizes the different SLM technologies appropriate for Nigeria that have been used to formulate the low-carbon scenario, including information on public costs and private costs/benefits that will be used in the models. Appendix C, tables C.1 and C.2, present those technologies in more detail, and table C.3 provides information on the assumptions behind the calculation of costs for those SLM options.

## Adjusted Agricultural Growth Model

The agricultural growth model was adjusted to assess whether it was feasible for crop expansion to decrease to 0 percent by 2025, while still reaching the same sector production targets, given the higher yields expected from the introduction of SLM technologies. Reduction of postharvest loss remains the same as in the reference scenario, as indicated in table 3.2 and figure 3.1. Annual yield growth is expected to be a little higher than in the reference scenario, but numerous studies indicate that the increase in yield from SLM may take a little time to become noticeable. Therefore the increase in annual growth yield is estimated to

**Table 3.1 Mitigation Options Adopted in the Low-Carbon Scenario**

| *Description* | *Dynamic of adoption and year lag* | *Potential yield increase* | *Potential carbon benefits* | *Public costs $/ha/yr* | *Private costs and benefits $/ha/yr (negative = benefit)* | *Key constraints* |
|---|---|---|---|---|---|---|
| ***SLM practice: protection of existing forests—avoiding deforestation*** | | | | | | |
| The forest is preserved | Gradual adoption rate (geometric)<br>No year lag, because it is vital to take action immediately to preserve the remaining forest and biodiversity it shelters. | | Depends on the type of forest, its density, and the use after conversion.<br>From 0.75 to 4.25 t C/ha/yr for a Brazilian tropical forest | Year 1: 1481<br>Years 2–4: 600<br>Following years: 0<br>Cost to protect the forest (physical and policy/ management protection), plus an opportunity cost the first year (nonharvesting of timber) | During entire period: 588<br>Opportunity cost for nonconversion of the forest into a more profitable land use<br>Benefits: Non-Timber Forest Product (NTPF), i.e., fauna and flora | Often the sole option to preserve forested area is to intensify agricultural production on other land.<br>Need to find and provide more affordable fuel-efficient stoves or sustainable alternative fuels to decrease the pressure on wood resources.<br>Timber for some countries can be important export revenue that they might not want to loose.<br>Sustainable forest management is effective if designed on a participatory basis. |

*table continues next page*

**Table 3.1 Mitigation Options Adopted in the Low-Carbon Scenario** (*continued*)

| *Description* | *Dynamic of adoption and year lag* | *Potential yield increase* | *Potential carbon benefits* | *Public costs $/ha/yr* | *Private costs and benefits $/ha/yr (negative = benefit)* | *Key constraints* |
|---|---|---|---|---|---|---|
| ***SLM practice: conservation agriculture*** | | | | | | |
| Minimum or no-tillage<br>Mulching<br>Crop rotation integrating leguminous and crop association | Gradual adoption rate (geometric)<br>Conservation agriculture is one of the most important low-carbon (LC) options, therefore must be implemented rapidly. Research team suggests beginning 2 years after the actions on deforestation. | Yields can be more than 60% higher than under conventional tillage.<br>Conservation agriculture with fertilization increases the yield from 1.2 to 2.0 t/ha for maize, and from 0.5–0.7 to 1.1 t/ha for tef in Ethiopia (an annual grass crop harvested for grain) | Conservation tillage can sequester 0.1–1.3 t C/ha/yr globally | Years 1–3: 71<br>Following years: 21<br>It includes the public subsidies for seeds and fertilizers, which stops after 3 years, as well as the cost of extension services and the transaction expenses. | Year 1: 71<br>Years 2–3: –234<br>Following years: –218<br>The cost for producing the manure and purchasing the fertilizers is compensated by the 80% increase in yield. | Farmers need training and access to skilled advisory services.<br>Transition period (5–7 yr) before conservation agriculture reaches equilibrium.<br>Reduced tillage means having recourse to herbicides (farmers must be educated in correct use) or adopt integrated pest management (crop rotation, cover crop, cultural practices) (Pieri et al. 2002, 30).<br>Not successful in heavy clay soils, poorly drained sites, compacted soils, and arid areas. |

*table continues next page*

**Table 3.1 Mitigation Options Adopted in the Low-Carbon Scenario** (*continued*)

| *Description* | *Dynamic of adoption and year lag* | *Potential yield increase* | *Potential carbon benefits* | *Public costs $/ha/yr* | *Private costs and benefits $/ha/yr (negative = benefit)* | *Key constraints* |
|---|---|---|---|---|---|---|
| ***SLM practice: agroforestry*** | | | | | | |
| Establishing stands of trees on land not currently classified as forest (includes shelterbelts, windbreaks, and woodlots) | Gradual adoption rate (geometric)<br>Agroforestry should begin at the same time as conservation agriculture, as they are linked and work in synergy. The year lag is therefore 2 years. | Growth rate depends on the type of plantation, as well as its density.<br>The crop yield response is uncertain and variable due to competitive effects of the different cultures for light, water, and nutrients. Different studies show an increase by 50–200%; others no significant effect. | 0.86–3.75 t C/ha/yr for a Brazilian tropical plantation | Year 1: 166<br>Years 2–5: 300<br>Following years: 0<br>Government pays 25% of the plantation (live fencing, hedges, etc.) cost, and the protection costs. | Year 1: 906<br>Year 2: 357<br>Year 3: 280<br>Following years: –318<br>The first years, the farmer bears 75% of the plantation cost. For entire period, the maintenance cost of the live fences and the opportunity cost (because trees are planted on cropland and grassland surfaces) are taken into account. But the NTPF from the hedges (fodder, wood) and the 50% increase in the yield of adjacent crops largely compensate for the expenses. | In dry lands, planting of trees is difficult due to lack of water for nurseries in the dry season and absence of labor for protecting the trees.<br>Uncertain land tenure situations.<br>Land availability is limited, due to high population density and competition for land between agriculture and forestry.<br>Ongoing need for protection, as with natural forests.<br>Long period to grow industrial tree crops to merchantable size.<br>Risks of fungal or insect diseases |

*table continues next page*

**Table 3.1 Mitigation Options Adopted in the Low-Carbon Scenario** (*continued*)

| *Description* | *Dynamic of adoption and year lag* | *Potential yield increase* | *Potential carbon benefits* | *Public costs $/ha/yr* | *Private costs and benefits $/ha/yr (negative = benefit)* | *Key constraints* |
|---|---|---|---|---|---|---|
| ***SLM practice: Sustainable Rice Intensification (SRI) (flooded rice)*** | | | | | | |
| Rotational and intermittent irrigation<br>Use of genetically improved seeds that are transplanted instead of broadcasted<br>Application of organic fertilizers<br>Integrated Pest Management | Gradual adoption rate (geometric)<br>SRI is another important mitigation option, but may be less important than conservation agriculture and avoiding deforestation, since less surface is concerned. The research team therefore recommends starting SRI just after the other techniques have been introduced, e.g., starting from year 3. | Average yield increase 10–25% | Emission rates ranged from less than 100 kg $CH_4$ $ha^{-1}$ to more than 400 kg $CH_4$ $ha^{-1}$ for intermittent irrigation and continuous flooding, respectively. | Years 1–5: 42<br>Following years: 16<br>Subsidies for improved seeds, plus transaction and extension services costs | Year 1: 296<br>Year 2: 36<br>Following years: –64<br>Takes into account time for coordination, manure production, and an increase by 25% in the yield. | Due to great diversity in rice production systems, SRI will not be applicable invariably everywhere.<br>SRI requires excellent land preparation, timely availability of irrigation water during critical periods of growth, good irrigation infrastructure, and efficient weed control methods.<br>SRI is mainly suitable for increasing rice yields in environments with acid, iron-rich soils, high labor availability, and a generally low level of crop intensification. |

*table continues next page*

**Table 3.1 Mitigation Options Adopted in the Low-Carbon Scenario** (*continued*)

| *Description* | *Dynamic of adoption and year lag* | *Potential yield increase* | *Potential carbon benefits* | *Public costs \$/ha/yr* | *Private costs and benefits \$/ha/yr (negative = benefit)* | *Key constraints* |
|---|---|---|---|---|---|---|
| ***SLM practice: Sustainable grazing management (SGM) with inputs (gathered in the livestock and pastureland improvement category)*** | | | | | | |
| Restoration of degraded pastures with inputs such as mineral fertilizers, manure application, and irrigation<br>No use of fire | Gradual adoption rate (geometric)<br>Livestock and grassland management are linked; these three options should be implemented at the same time, after leaving about 3 years between the start of conservation agriculture and grassland improvements (so the farmers have time to integrate conservation agriculture practices and start seeing increased revenues before implementing other measures). | Increase varies depending on the type and quantity of improvements.<br>Herbage production can be increased 1- to 4-fold through timing and intensity of grazing. | Rates of carbon sequestration by type of improvement: 0.11–3.04 t $C{\cdot}ha^{-1}$ $yr^{-1}$, with a mean of 0.54 t $C{\cdot}ha^{-1}{\cdot}yr^{-1}$ (highly influenced by biome type and climate) | Years 1–3: 35<br>Years 4–5: 15<br>Following years: 2<br>Subsidies for fertilizers (during 3 years), for seeds (during 5 years), and extension services and transaction costs. | Years 1–3: 80<br>Following years: 96<br>The small pastoralist gain does not cover costs of fertilizers. | Requires community organization for limiting overgrazing.<br>Investments must be made the first years in fertilizers and irrigation systems. |

*table continues next page*

**Table 3.1 Mitigation Options Adopted in the Low-Carbon Scenario** (*continued*)

| *Description* | *Dynamic of adoption and year lag* | *Potential yield increase* | *Potential carbon benefits* | *Public costs $/ha/yr* | *Private costs and benefits $/ha/yr (negative = benefit)* | *Key constraints* |
|---|---|---|---|---|---|---|
| ***SLM practice: Sustainable grazing management (SGM) without inputs (gathered in the livestock and pastureland improvement category)*** | | | | | | |
| Restoration of degraded pastures without inputs, through the use of improved grass variety and rotational grassing<br>No use of fire | Gradual adoption rate (geometric)<br>5-year lag | Increase varies depending on the type and quantity of improvements. | 0.2–0.4 t C/ha/yr (improved species, controlled grazing, fire management) | Whole period: 2<br>Transaction and extension service cost | Whole period: 0.1<br>Small increase in the yield by the reduction of fire use (in the reference scenario, pastures are also improved without inputs, but fire is heavily used). | Need to develop grazing plans tailored to specific local conditions to encourage participative approaches |
| ***SLM practice: Livestock management (cattle, sheep, goats) (gathered in the livestock and pastureland improvement category)*** | | | | | | |
| Better feeding practices<br>Breeding management to select improved and more efficient animals<br>Limitation of the number of livestock | Gradual adoption rate (geometric)<br>5-year lag, as for sustainable grazing | Increase in meat and milk production per animal | Possible decreases in GHG production per unit of livestock product, about 1% per year<br>Methane production can be reduced by 10–40% | Year 1–3: 21<br>Following years: 0.2<br>Subsidies for prophylaxis and feed during 3 years, plus transaction and extension services costs. | Year 1–3: 26<br>Following years: 10<br>The costs of feed and prophylaxis are covered by the 33% increase in animal yield. | Techniques are often out of reach for smallholder livestock producers who lack the capital and often the knowledge to implement such changes.<br>Fewer animals reduce the amount of manure available to fertilize the crops, which may lead to the use of chemical fertilizers. |

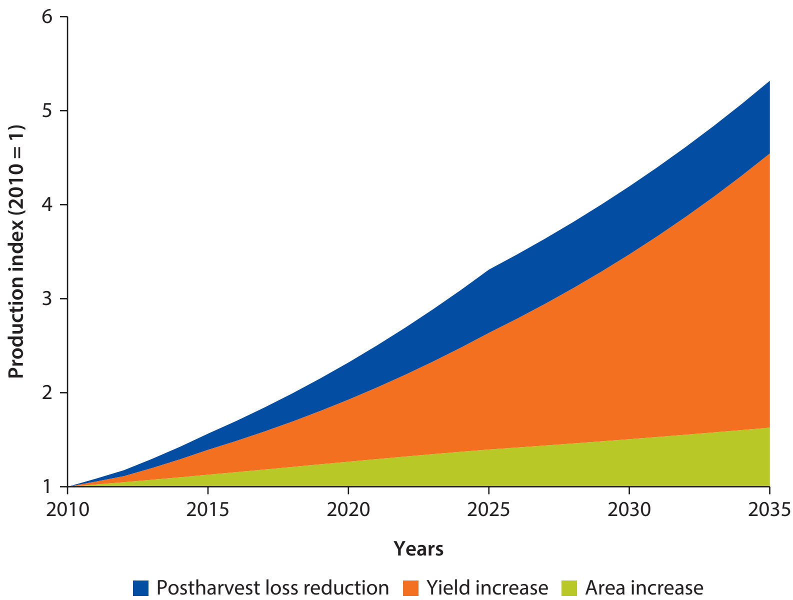
*Source:* Calculations based on sources in chapter 1 "Data Sources for the Agriculture and Land Use Sector" and tables 1.1–1.3.

**Table 3.2 Agricultural Growth Model of Low-Carbon vs. Reference Scenarios**

| | *Percent of total growth* | | | |
|---|---|---|---|---|
| | *2010–25* | | *2026–35* | |
| *Source of growth* | *Reference* | *Low-carbon* | *Reference* | *Low-carbon* |
| Area increase | 1.56 | 1.24 | 0.79 | 0.00 |
| Postharvest loss reduction | 2.48 | 2.48 | 0.03 | 0.03 |
| Yield increase | 4.07 | 5.07 | 4.00 | 6.00 |
| Total Production Growth | 8.30 | 9.00 | 4.86 | 6.04 |

*Source:* Calculations based on data sources listed in tables 1.1–1.3.
*Note:* The way in which the sources of growth interact in determining total production growth is nonlinear. So the last row in the table is not the result of adding the values reported in the three rows above it.

**Figure 3.1 Total Production Increase and Growth Sources for Low-Carbon Scenario**




*Source:* Calculations based on data sources listed in tables 1.1–1.3.

be the same as in the reference scenario for the first 5 years, then 1 point higher than the reference scenario for the following 5 years, and 2 points higher the next 5 years. This gives an annual compound growth rate close to 5.1 percent. After the implementation phase, 2025 and beyond, yield growth remains stable, at the same rate of 2025. This results in total production growth during the model period that is somewhat higher than that of the reference scenario.

## Emissions Models under Two Low-Carbon Scenarios

Introduction of SLM technologies is assumed to be an accelerating process (due to some of the initial implementation lags discussed in table 3.1), but one that is also subject to a technical constraint—that is, no more than 800,000 hectare per year on average can be brought under new SLM technologies.[2] Subject to this constraint, the study team explored two scenarios:

- **Scenario A:** Resources available to support the introduction of SLM technologies are targeted to maximize the total mitigation potential.
- **Scenario B:** Resources available to support the introduction of SLM technologies are targeted to maximize profitability (for example, seeking to increase net present value (NPV) of private investment) for farmers, according to the cost/benefit estimates in table 3.1.

In order to provide for a minimally balanced mix of mitigation options, the team devised additional constraints on the minimum rate of adoption for each SLM technology, in line with their anticipated intrinsic appeal to farmers.[3] These minimum rates of uptake by 2025 are as follows:

- Conservation agriculture: 13 percent of annual cropland area
- SRI: 3 percent of total rice area
- Avoided deforestation: 5 percent of secondary degraded forest partly with constraints
- Agroforestry: 3 percent of annual cropland area[4]
- Improved pasture management: 2 percent of existing pasturelands
- Improved livestock management: 51 percent (that is, 1 percent more than the 50 percent already included under the reference scenario).

The two different scenarios impact choices between available mitigation measures, but not the total land area subject to introduction of SLM technologies.

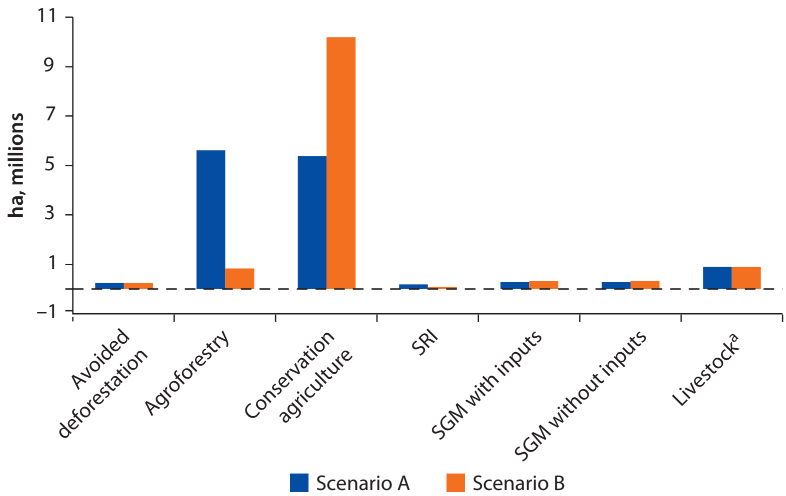
### *Land Use and Other Mitigation Factors*

In accordance with the revised growth model, the expansion of agricultural land is reduced under both low-carbon scenarios, compared to the reference scenario, as an increased proportion of the least suitable secondary forest is not converted to agriculture.

Under scenario B, SLM options selected favor profitability to the farmer over maximum GHG abatement potential. As conservation agriculture provides the largest private returns, it accounts for 82 percent of the 800,000 hectare per year area subject to new SLM technologies, resulting in 24 percent of the annual cropland being managed under conservation agriculture practices, compared to only 13 percent under scenario A (figure 3.2). Other SLM technologies are only adopted at their minimum rates under scenario B.

Scenario A favors high mitigation land uses, but the available area of avoided deforestation is limited to no more than that also involved in scenario B. Hence SLM investments under scenario A focus on agroforestry, with a little SRI. Other SLM technologies are introduced according to their assumed minima, although that still involves a considerable area of conservation agriculture.

**Figure 3.2 Adoption Rate of SLM Practices**




*Source:* Calculations based on sources in chapter 1 "Data Sources for the Agriculture and Land Use Sector" and tables 1.1–1.3.
*Notes:* SRI = Sustainable rice intensification; SGM = Sustainable grazing management.
a. Livestock = number of heads, thousands.

**Table 3.3 Land Use for Low-Carbon Scenarios (2025/2035) vs. Reference Scenario**

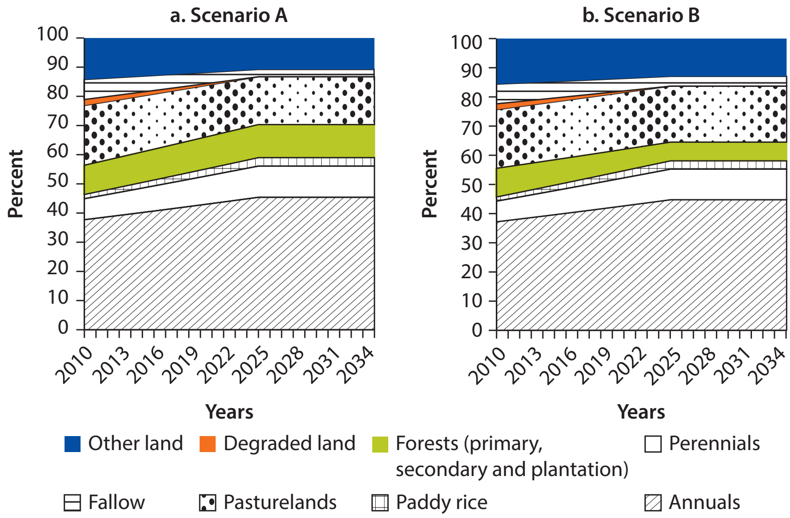
| | | 2025/2035 | | |
|---|---|---|---|---|
| *Land use* | *2010* | *Reference* | *Low-carbon scenario A* | *Low-carbon scenario B* |
| Annuals | 34,437 | 46,155 | 41,432 | 41,432 |
| Perennials | 6,552 | 12,419 | 9,721 | 9,721 |
| Wet rice | 1,313 | 2,919 | 2,625 | 2,625 |
| Forests | 9,101 | 2,700 | 10,301 | 5,929 |
| Secondary forests | 8,805 | 1,804 | 3,790 | 3,790 |
| Plantations | 296 | 896 | 896 | 896 |
| Live fencing/agroforestry | 0 | 0 | 5,615 | 1,243 |
| Pasturelands | 18,629 | 15,669 | 14,882 | 17,779 |
| Degraded lands | 1,849 | 0 | 0 | 0 |
| Fallows | 6,234 | 2,076 | 2,290 | 3,110 |
| Other lands | 12,941 | 9,116 | 9,803 | 10,459 |
| Total | 91,054 | 91,054 | 91,054 | 91,054 |

*Source:* Calculations based on data sources listed in tables 1.1–1.3.

The greater emphasis on agroforestry under scenario A results in changes to the final ratio of agroforestry-to-grassland area in comparison with scenario B. Largely due to the investment in agroforestry, scenario A ends up with over 4 times the area of secondary forest and live fences than the reference scenario and almost 2 times that of scenario B. Table 3.3 and Source: Calculations based on data sources listed in tables 1.1–1.3.

Figure 3.3 show the evolution of land use 2010–35, for the reference scenario and the two low-carbon simulations. The cropland area remains the same under

**Figure 3.3 Land Use Evolution in Low-Carbon Scenarios, 2010–35**




*Source:* Calculations based on data sources listed in tables 1.1–1.3.

both scenarios. (Appendix B, table B.1 presents the land use matrix for the reference scenario. Appendix D, tables D.1 and D.2 present the land use change matrixes for low-carbon A and B, respectively.)

Other land use changes (such as expansion of perennial crops and paddy and restoration of degraded land) remain the same as the reference scenario, as do other emissions model parameters (such as soil and climate characteristics, construction of new infrastructure, and introduction of technologies and improvements already included under the reference scenario). However, it is assumed that 75 percent of the existing perennial cropland will stop burning practices by 2025, as opposed to 50 percent in the reference scenario. Also there are some differences in the amounts of inputs and energy used in line with changes in cropland areas and extent of application of improved agronomic techniques.

## Low-Carbon Scenarios: Results

### *Mitigation Potential*

Total emissions accumulated over the model period remain positive under both low-carbon scenarios (tables D.3 and D.4 in appendix D present the gross GHG emissions for the different low-carbon simulations). Total mitigation potentials compared to the reference scenario are summarized in table 3.4.

Both low-carbon scenarios present a significant mitigation potential, of 1.0 and 0.6 billion t $CO_2e$, respectively, during the 25 years of the study.

In scenario A, various land use changes, including reduced net deforestation, agroforestry, and nonforest land use change, account for 77 percent of emissions reduction. In scenario B, the total mitigation potential is a little over half that of A, and contributions are more evenly spread across emissions classes, particularly from a much greater contribution from croplands to carbon sinks as conservation

**Table 3.4 Results for the Two Low-Carbon Simulations**

| *Scenario* | *A* | *B* |
|---|---|---|
| Emissions for entire 25-year period of model (Mt $CO_2$e) | 1,687 | 2,017 |
| Total mitigation potential (t $CO_2$e) | 976 | 646 |
| Average mitigation potential (t $CO_2$e/ha/year) | 0.4 | 0.3 |
| Public expenses during 20 years (gross/NPV in $, millions) | 10,211/3,207 | 6,983/2,228 |
| Private revenues during 25 years (gross/NPV), in M$ | 41,024/5 699 | 44,278/7,277 |

*Source:* Calculations based on sources in chapter 1 "Data Sources for the Agriculture and Land Use Sector" and tables 1.1–1.3.

**Table 3.5 Mitigation Potential of Various Activities**

| | *Scenario A mitigation* | | | *Scenario B mitigation* | | |
|---|---|---|---|---|---|---|
| *Activities* | *in Mt $CO_2$e* | *in Mt $CO_2$e/ha* | | *in Mt $CO_2$e* | *in Mt $CO_2$e/ha* | |
| Avoided deforestation | 207 | 833[a] | 18% | 207 | 830 | 30% |
| Afforestation and agroforestry (live fences) | 712 | 126[b] | 61% | 158 | 126 | 22% |
| Nonforest land use change | –142 | –11[c] | n.a. | –13 | –1 | n.a. |
| Annual crops | 124 | 3[d] | 11% | 222 | 5 | 32% |
| Perennial crops | 46 | 6 | 4% | 46 | 6 | 7% |
| Wet rice | 7 | 3 | 1% | 3 | 1 | 0% |
| Grassland | 34 | 2 | 3% | 34 | 2 | 5% |
| Livestock | 28 | 0[e] | 2% | 28 | 0 | 4% |
| Inputs | –39 | –1[f] | n.a. | –39 | –1 | n.a. |
| Other investment | 2 | 0[g] | 0% | 2 | 0 | 0% |
| **Total** | **976** | **6.8[h]** | | **646** | **4.6** | |

*Source:* Calculations based on sources in chapter 1 "Data Sources for the Agriculture and Land Use Sector" and tables 1.1–1.3.
*Notes:* Calculations based on the following: (a) surface, nondeforested; (b) ha planted; (c) ha changing land use; (d) total annual/perennial/rice/grassland surface; (e) number of heads; (f) surface area fertilized. (g) Calculated based on the tilled surface; even if there are more areas under conservation agriculture (no-tillage), the assumption is that 50% of the total annuals surfaces will be tilled, as in the reference scenario. n.a. = not applicable.

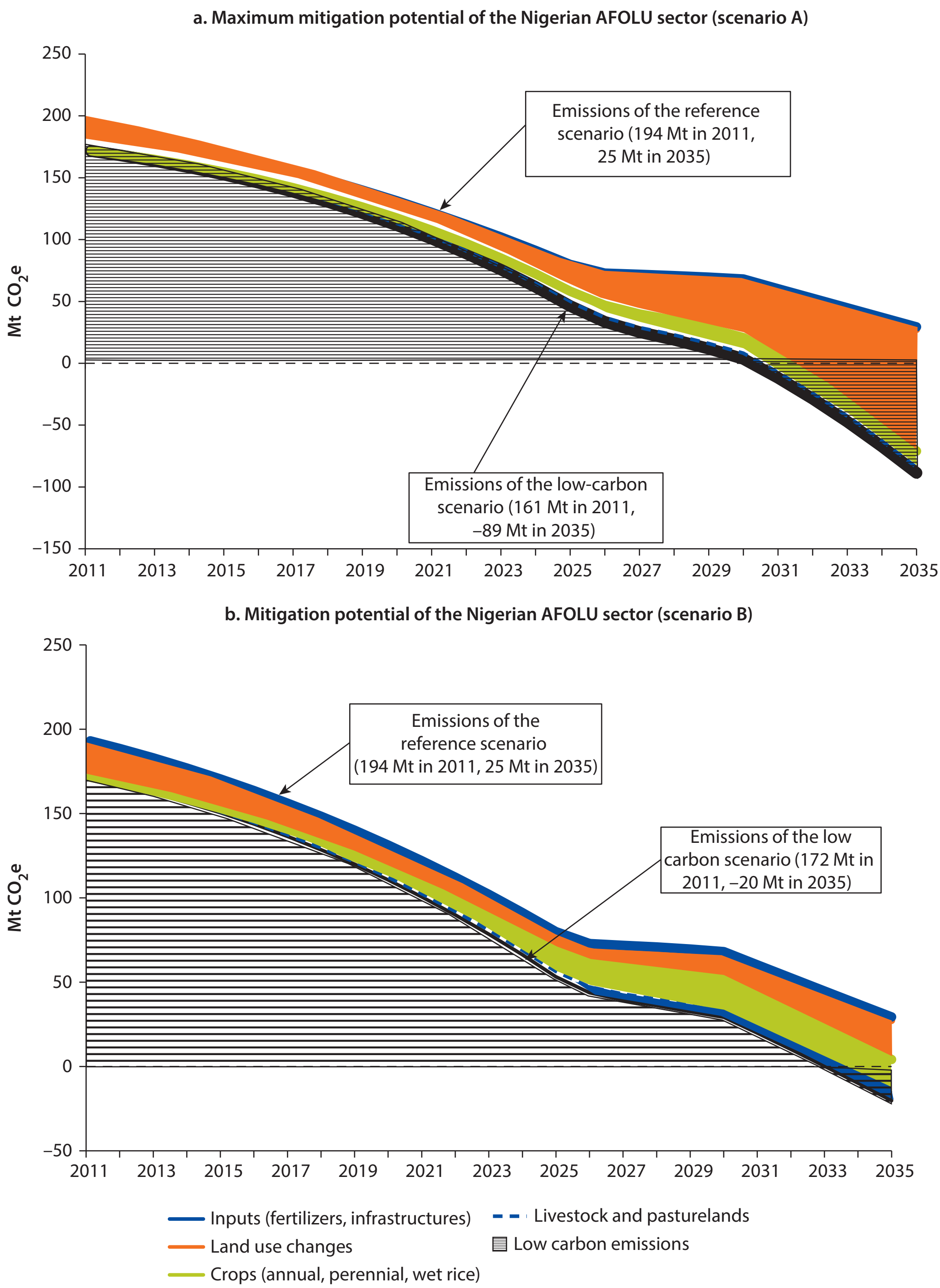
agriculture techniques increase soil and above-ground carbon level. In both low-carbon (LC) scenarios, the increased use of fertilizers emits more GHG than in the reference scenario, but it is really negligible compare to the reduction of other emissions. Energy and fuel consumption decrease a little compared to the reference scenario since less land area is tilled and more agricultural land is under conservation agriculture instead.

Table 3.5 and figure 3.4 illustrate the contribution of each subsector to the mitigation potential of the different LC scenarios. A negative figure indicates higher emissions compare to the reference scenario.

On a per hectare basis, mitigation potential differs among the different activities between the two scenarios:

- Annual crops sequester more C per hectare under scenario B, because a higher proportion is subject to conservation agriculture.
- Grasslands sequester more C per hectare under scenario A because the total extent of grasslands is lower, and therefore a higher proportion is subject to sustainable rangeland management.

**Figure 3.4 Agricultural Mitigation Potential by Subsector for Low-Carbon Scenarios**




*Source:* Calculations based on sources in chapter 1 "Data Sources for the Agriculture and Land Use Sector" and tables 1.1–1.3.
*Note:* AFOLU = agriculture, forestry, and other land use.

### *Marginal Abatement Costs*

The marginal abatement cost (MAC) is the NPV (calculated at a 10 percent discount rate) of cost of each mitigation option per unit of emissions reduction.[6] These were calculated separately for public and private costs in order to construct marginal abatement cost (mac) curves to visualize the cost-effectiveness of various mitigation options for government and for farmers. A MAC curve is a histogram that displays both the MAC (height of each bar) and the total mitigation potential (width of the bar) for each mitigation option. The bars are arranged in order of increasing unit cost along the x axis, so that the cheapest mitigation options intuitively considered first, and the total emissions abatement cost increase with the area under the curve as additional mitigation activities are undertaken.

However, the following should be taken into account:

- Only monetary costs and revenues were included in the analysis—no account was taken of externalities, such as positive or negative environmental or social effects.
- Negative costs imply that a mitigation option is profitable in its own right—that is, it would make financial sense to adopt it, even if there were no interest in reducing GHG emissions.
- The MACC should not be used to compare mitigation costs directly to current or projected carbon prices. For a valid comparison to be made, expected future carbon finance income would have to be discounted to its net present value.

The unit public costs to the FGN for the various mitigation options are always positive and do not vary between the two low-carbon scenarios, since government does not receive any direct revenue from agricultural production and there are no economies of scale included in the cost models for SLM support. However, the total mitigation available from each option varies with the adoption rate. The results are shown in table 3.6 and figure 3.5.

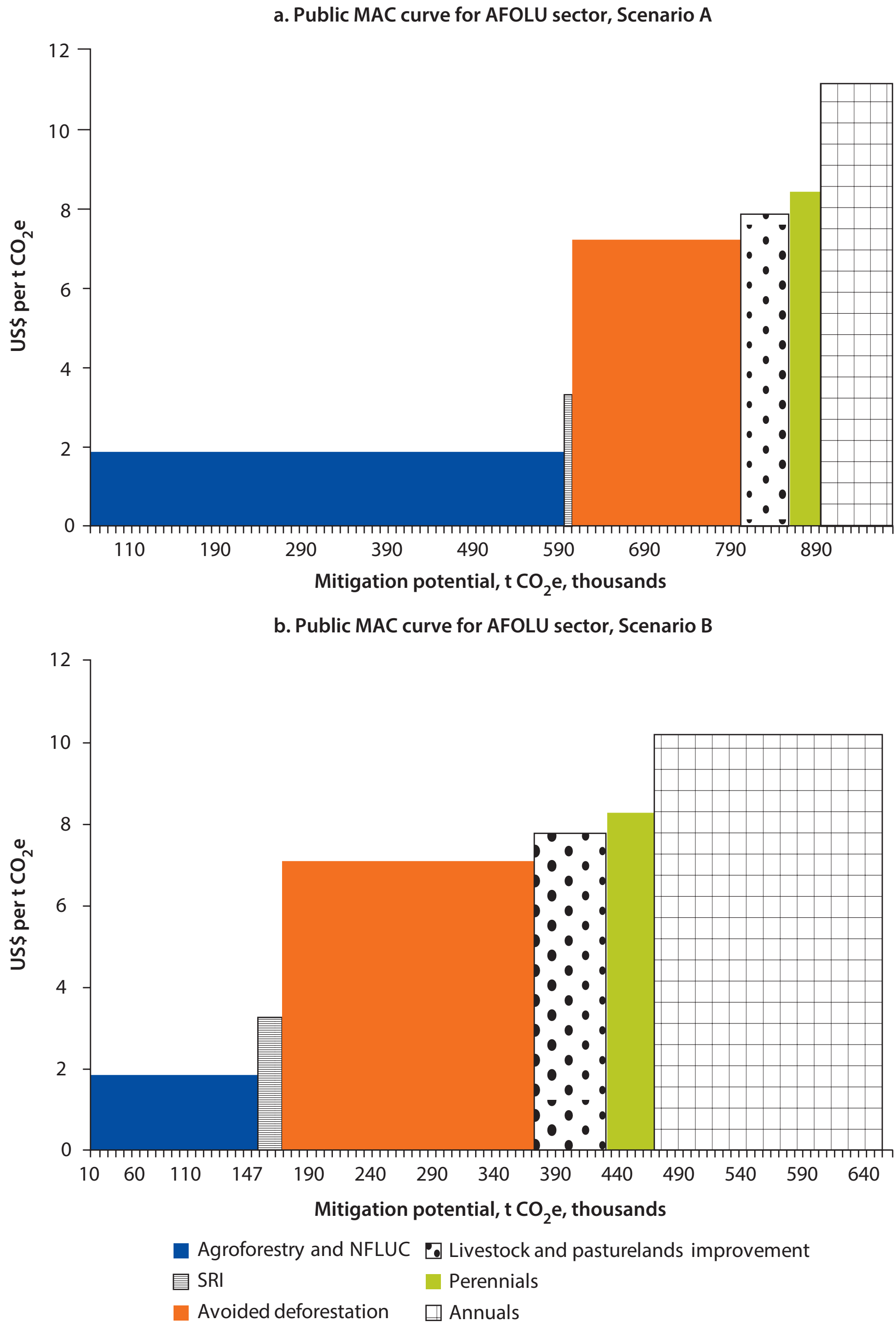
Some specific SLM measure, for example, conservation agriculture or agroforestry, have been included into a broader category to take into account the whole

**Table 3.6 Public Cost of Emissions and Mitigation Potential of SLM Measures, 2011–35**

| | *Mitigation potential, Mt $CO_2eCO_2$* | | *MAC, \$/t $CO_2eCO_2$* | |
|---|---|---|---|---|
| *Mitigation option* | *Scenario A* | *Scenario B* | *Scenario A* | *Scenario B* |
| Agroforestry and NFLUC | 569.4 | 144.7 | 1.86 | 1.86 |
| SRI | 6.7 | 2.8 | 3.31 | 3.31 |
| Avoided deforestation | 206.6 | 206.6 | 7.10 | 7.10 |
| Livestock and pasturelands improvement | 61.6 | 61.5 | 7.87 | 7.91 |
| Perennials | 38.5 | 38.5 | 8.42 | 8.42 |
| Annuals | 93.2 | 191.7 | 11.15 | 10.38 |
| Total | 975.9 | 645.8 | | |

*Source:* Calculations based on sources in chapter 1 "Data Sources for the Agriculture and Land Use Sector" and tables 1.1–1.3.

**Figure 3.5 Marginal Abatement Cost of SLM Practices for FGN**




*Source:* Calculations based on sources in chapter 1 "Data Sources for the Agriculture and Land Use Sector" and tables 1.1–1.3.

mitigation potential of the subcategory. Therefore, the following categories include the following:

- **Annuals:** conservation agriculture, no residue burning, higher fertilization on annual crops (in total, not per ha), reduced fuel consumption (in total, not per ha).
- **Perennials:** no residue burning, higher fertilization on perennial crops (in total, not per ha).
- **Livestock and pasturelands improvement:** pastures improved with and without inputs, reduced fire, livestock improvements.
- **Avoided deforestation:** only the surfaces of forest not converted into another land use
- **SRI**: only rice.
- **Agroforestry and NFLUC:** agroforestry and nonforest land use changes, since the plantation of trees on grass and crops will have an impact on other lands (for example, fallows have to be converted into crop to satisfy cropland expansion).

Between scenarios A and B, the average hectare of perennial, rice, agroforestry, pastureland, and protected forest is the same (or very slightly different), so the MAC curves are also identical. However, for annuals, the composition of an average hectare of annual differs: in scenario B, there is a higher proportion of conservation agriculture than in scenario A.

Agroforestry and sustainable rice intensification (SRI) are the most cost-effective mitigation options for the government, while livestock/pasturelands improvement, perennials, as well as annuals are more expensive to support. If FGN were to support all mitigation options, the total cost (in cash flow terms) would be about US$10 billion in scenario A and US$7 billion in scenario B, at an average cost of $10/t $CO_2$e (in cash flow terms).

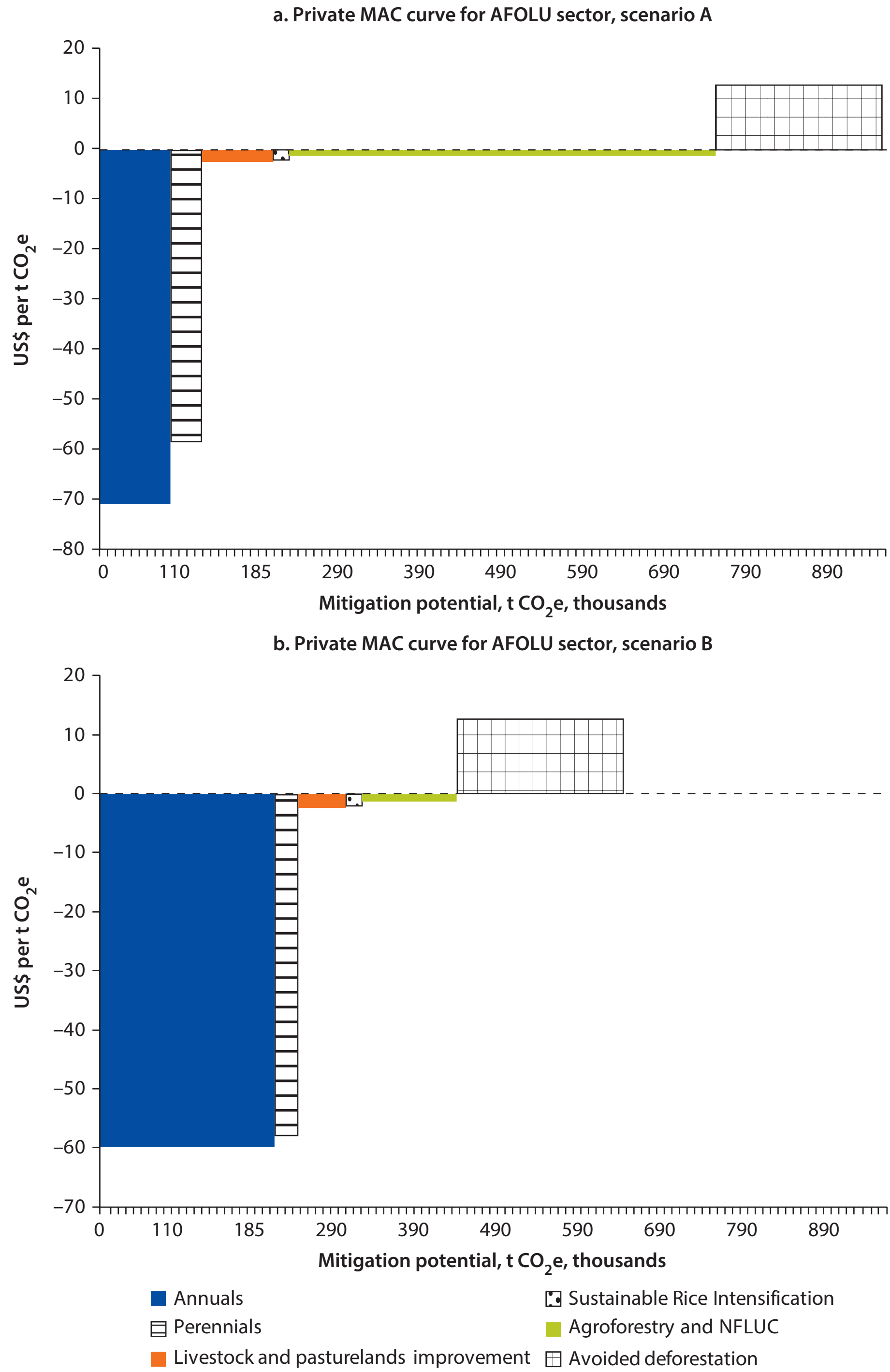
Net costs to farmers depend on the expenses for additional inputs (fertilizer, feed, fuel, labor, etc.) compared to the gain from higher yields. Negative costs shown in table 3.7 and figure 3.6 indicate that several mitigation options are

**Table 3.7 Private Cost of Emissions and Mitigation Potential of SLM Measures**

| | *Mitigation potential (Mt $CO_2$e)* | | *MAC (\$/t $CO_2$e)* | |
|---|---|---|---|---|
| *Mitigation option* | *Scenario A* | *Scenario B* | *Scenario A* | *Scenario B* |
| Annuals | 93.2 | 191.7 | –70.33 | –56.76 |
| Perennials | 38.5 | 38.5 | –58.18 | –58.18 |
| Livestock and pasturelands improvement | 61.6 | 61.5 | –2.49 | –2.50 |
| SRI | 6.7 | 2.8 | –2.04 | –2.04 |
| Agroforestry and Nonforest land use changes (NFLUC) | 569.4 | 144.7 | –1.32 | –1.32 |
| Avoided deforestation | 206.6 | 206.6 | 12.82 | 12.82 |
| Total | 975.9 | 645.8 | | |

*Source:* World Bank data.

**Figure 3.6 Marginal Abatement Cost to Farmers of SLM practices**




*Source:* Calculations based on sources in chapter 1 "Data Sources for the Agriculture and Land Use Sector" and tables 1.1–1.3.

intrinsically beneficial to farmers. There are significant differences in the likely attractiveness of the various options to FGN and farmers. Avoiding deforestation is not financially rewarding for farmers because they would benefit from converting the forest into more productive lands. And agroforestry is only marginally profitable, due to high implementation costs, which offset the significant downstream yield increases, despite these options offering the greatest mitigation potential per hectare and being most cost-effective for FGN. Conservation agriculture (part of the annuals category) is highly attractive to farmers, while it offers relatively little mitigation potential per hectare and is comparatively costly for FGN to support. The same observation can be made for perennial crops.

When public and private costs are combined, only two SLM measures, annuals (that is, mainly conservation agriculture) and perennials (no residue burning), are profitable without any additional carbon revenues. Agroforestry presents a small cost of 0.5 \$/t $CO_2$e, while avoiding deforestation is the most expensive option for the whole nation (20 \$/t $CO_2$e).

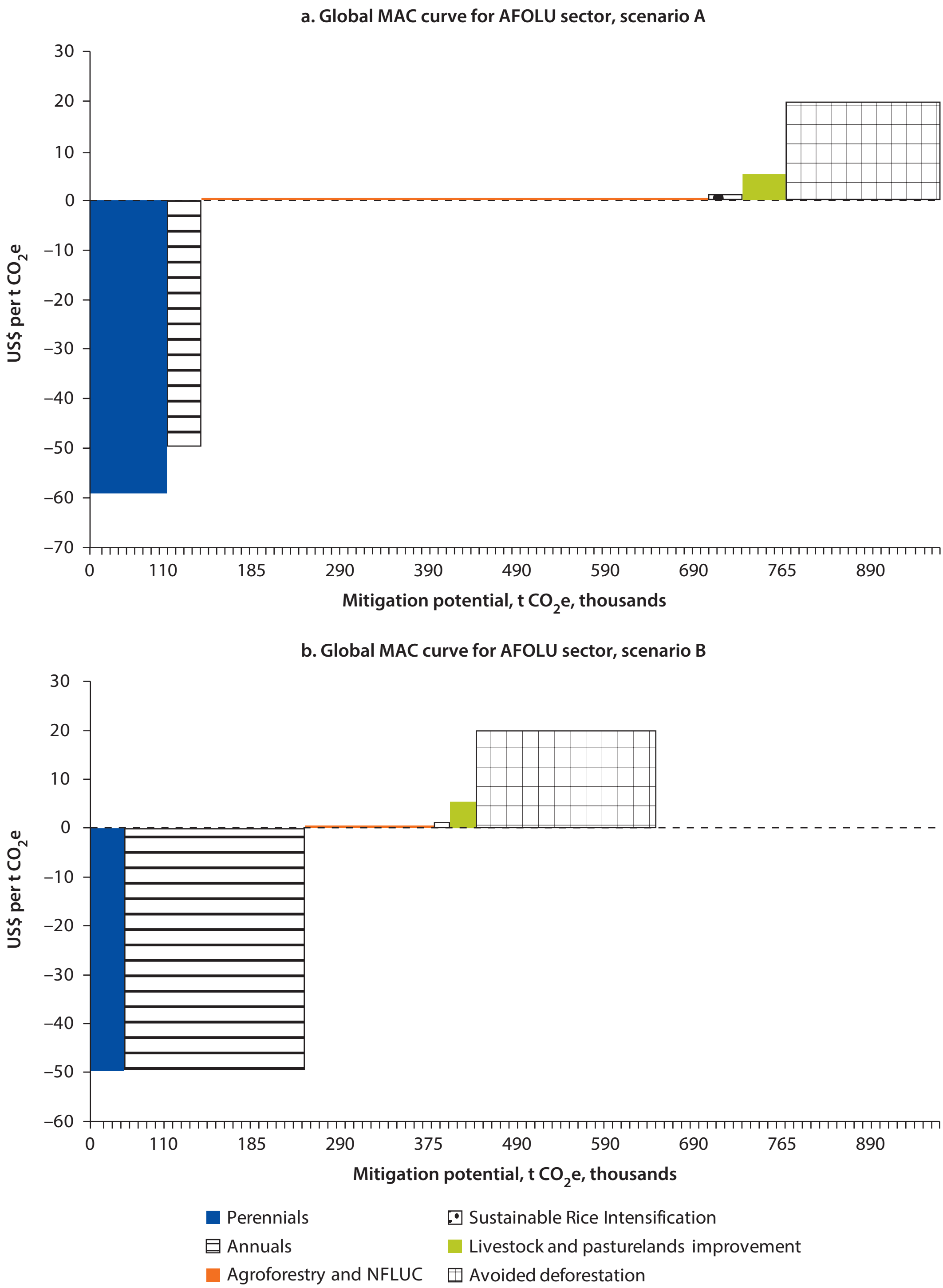
### *Incentivizing High Mitigation through Carbon Payments*

The NPV of the financial benefit to farmers from all the SLM measures introduced in scenario A is just over US\$5 billion (see figure 3.7). Under scenario B, where private benefits are maximized, this increases totals to almost \$7 billion. However, the additional GHG emissions reductions generated under scenario A make it possible to use carbon payments to incentivize landowners/farmers to adopt more carbon-intensive land uses. In fact, a minimum carbon price of \$6.1/t $CO_2$e paid to farmers[7] would be sufficient to increase the private financial benefit of the land use choices under scenario A to the same level as those enjoyed under scenario B, effectively compensating farmers for adopting SLM options with higher mitigation potential.

Figure 3.8 represents in the following the private and global MACs for scenario A with carbon payments to farmers of \$6.1/t $CO_2$e (the public MAC is the same as for the standard scenario A shown in figure 3.7). With carbon payments, conservation agriculture is still the most profitable option, but introducing a system of rice intensification (SRI) and livestock/pasturelands improvement are significantly more attractive, and avoided deforestation is relatively more attractive, although still not financially rewarding in isolation. Hence carbon payments at this level are not sufficient to incentivize private decisions to take up all SLM options in accordance with scenario A, but could be used to compensate to the foregone income at the macro level. Therefore, if governments were able to control the distribution of carbon incomes, then these incomes could potentially be used to selectively incentivize the most carbon-intensive options, such as avoided deforestation and agroforestry, as a strategy to provide for a more balanced mix of SLM technologies that would exploit the synergies between them,[8] as well as the additional positive environmental externalities from maintaining increased forest cover.[9]

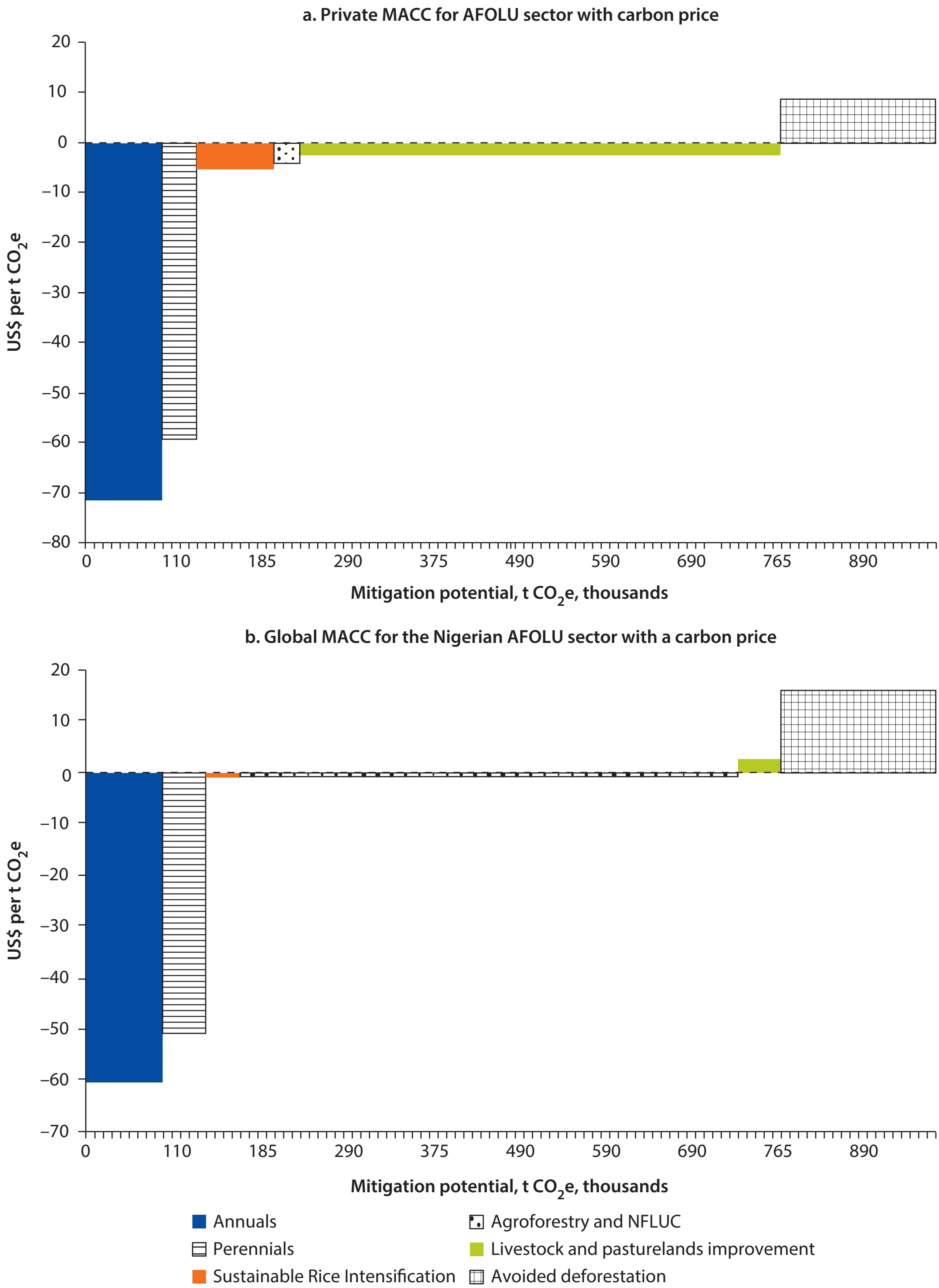
It is worth noting that at a global level—that is, from a public and private point of view—only two options result in a positive MAC: namely,

**Figure 3.7 MAC Curves of SLM Practices for All of Nigeria (public + private costs and benefits)**




*Source:* Calculations based on sources in chapter 1 "Data Sources for the Agriculture and Land Use Sector" and tables 1.1–1.3.

**Figure 3.8 MAC of SLM practices (scenario A), with Carbon Revenue Added for Farmers**




*Source:* Calculations based on sources in chapter 1 "Data Sources for the Agriculture and Land Use Sector" and tables 1.1–1.3.

**Table 3.8 MAC of SLM Measures, Depending on the Low-Carbon Scenarios**

| | *Public MAC* | *Private MAC* | |
|---|---|---|---|
| *MAC, in \$/t $CO_2e$* | *Public* | *Private* | *Private with carbon payment* |
| Annuals | For scenario A: 11.2<br>For scenario B: 10.4 | For scenario A: –70.3<br>For scenario B: –56.8 | –71.5 |
| Perennials | 8.4 | –58.2 | –59.2 |
| Livestock and pasturelands improvement | 7.9 | –2.5 | –5.3 |
| SRI | 3.3 | –2.0 | –4.2 |
| Agroforestry and NFLUC | 1.9 | –1.3 | –2.6 |
| Avoided deforestation | 7.2 | 12.8 | 8.7 |

livestock/pasturelands and avoided deforestation, compared to four options without the addition of a carbon price.

Table 3.8 summarizes the public and private MACs for each SLM option under various conditions.

## Notes

1. Conservation agriculture also tends to be more labor intensive for a given area of cropping.
2. At an average farm size of 2 hectares, this is equivalent to roughly 400,000 rural families adopting SLM options annually. This is ambitious, but not compared to the scale of sector reforms already needed to address the Vision 20: 2020 productivity goals.
3. Another scenario was also explored in which a realistic budget constraint was applied, but the technical constraint was still found to be more limiting.
4. A 3:1 ratio is also assumed for the introduction of live fences on annual cropland and pasturelands, respectively.
5. Note also that agroforestry investments provide for significant increases in productivity of the surrounding agricultural land. This largely compensates for the foregone yield increases that could otherwise have been achieved through additional investment in conservation agriculture, such that the sectorwide agricultural yield increase for both scenarios A and B are roughly equivalent and in line with the modified growth model for the low-carbon options.
6. That is,

$$MAC^i = \frac{NPV^i_{LC} - NPV^i_{ref}}{E^i_{ref} - E^i_{LC}}$$

where

- $MAC_i$ is the marginal abatement cost of the option i, expressed in \$/t $CO_2e$
- $NPV_{LC}$ is the Net Present Value of the technology i in the low-carbon scenario, expressed in \$
- $NPV_{ref}$ is the Net Present Value of the technology in the reference scenario, expressed in \$
- $E_{ref}$ is the total GHG emissions with the technology in the reference scenario, expressed in t $CO_2e$

- $E_{LC}$ is the total GHG emissions with the technology in the low-carbon scenario, expressed in t $CO_2$e.

7. That is, public goods such as maintenance of hydrological functions, which benefit local farmers and downstream water users, and provision of forest products.
8. The high number of small farmers and their scattering in rural areas are a main constraint to reach small farmers with both incentives and adequate extension support within manageable transaction costs. A key issue is to find an entry point that allows outreach to a wide number of small farmers. It can be farmer unions, cooperatives, value chains, or an existing project or program that covers a whole region or district with adequate services. The role of the aggregator is to deliver the whole range of services and support to a wide number of small farmers, including the possibility of channeling of payment of environment services.
9. EX-ACT (Ex Ante Carbon-balance Tool) http://www.fao.org/tc/exact/en/.

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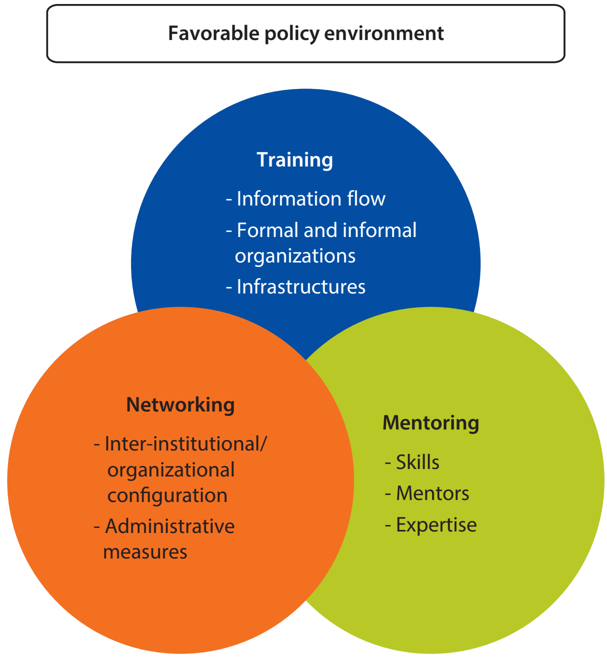
CHAPTER 4

# Recommendations for an Effective Low-Carbon Strategy in the AFOLU Sector

Despite the demonstrated benefits of sustainable land management (SLM) technologies, uptake for reforms in the AFOLU (agriculture, forestry, and land use) sector is still often slow, even for those options that involve significant private financial returns. According to the Fadama Project (Ike 2012), only 30 percent of farmers currently use manure, 4.6 percent compost, and 3.4 percent mulching practices. Several practical obstacles hinder rapid adoption, including the need to convince and train risk-averse farmers in new methods, and the frequent need for up-front investment that pay off over a number of years. Financial support, training, and demonstrations are all necessary to encourage farmers to radically changes in working and thinking needed to adopt new SLM techniques. A further practical issue for low-carbon scenarios is that they assume that higher productivity will offset expansion of cropland, whereas in reality increasing yields may increase the private incentives to convert more land to agriculture—with the risk that overexploitation of land may eventually lead to declining output. Hence, agricultural intensification is unlikely to result in avoided deforestation unless it occurs within a strong policy framework. This section discusses some of the policy and institutional steps needed to realize the potential of SLM.

Building the capacities and the political framework to mainstream climate change in agriculture and forestry strategies is a complex and dynamic process that involves numerous stakeholders, from national to field level. Figure 4.1 is a schematic of the minimum necessary elements (1) mentoring, that is, research institutions identifying problems and solutions; (2) training, which will bring to the field scientific knowledge; and (3) networking, that is, creating a conductive policy environment with interactions between experts and actors.

**Figure 4.1 Capacity Building Model**




*Source:* Design based on Sanni et al. 2010.

## Building a Network of Climate Smart Agriculture Partners

Implementation of a low-carbon policy within the agriculture and forestry sector will require mobilization of major public institutions, development partners, and federal, state, and local level stakeholders, including banks, the private sector, legislators, nongovernmental organizations and other actors. Specific recommended steps include the following:

- **Key institutions** to be mobilized include (1) Federal Ministry of Environment as the National designated Authority for Climate Change and Sustainable Development; (2) Federal Ministry of Agriculture and Water Resources (FMAWR) as the main coordinator; (3) River Basin Development Authorities (watershed management–reforestation); (4) Nigerian Agricultural Insurance Corporation (NAIC) on risk managements–weather based insurance; and (5) Nigeria Agricultural Cooperative and Rural Development Bank (NACRDB) for items such as fertilizer and other input-investment credits.

- **Farmer organizations** are one of the most important pillars of policy and institutional capability for agricultural development because they engage in dialogue with the government and can widely mobilize farmers. The participation of farmer associations in policy formulation, monitoring, and evaluation increases ownership and sustainability of policy measures. The All Farmers Association of Nigeria (AFAN), an umbrella body for Nigerian farmers, is the national platform for corporate and professional bodies, cooperatives, and commodity associations. Currently, 43 major farmers' associations in Nigeria have been formed along commodity lines (FGN 2011). The AFAN could act as a field support platform to promote climate smart agriculture practices and gather smallholders to channel carbon funding and payment of environment services.

## Effective Implementation Mechanisms

### *Supporting Agricultural Research*

Agricultural research has been shown to be one of the most effective forms of public investment (Fan and Rao 2003; Hazell and Haddad 2001). Compared to the popular recommendation that agricultural research spending should not be less than 2 percent of agricultural GDP, FGN's funding of agricultural research has been well below the average for Africa as a whole (0.85 percent of GDP (Enete and Amusa 2010). Moreover, private sector agricultural research in Nigeria is also negligible, as is the case throughout most of Sub-Saharan Africa (Mogues et al. 2008).

The Department of Agricultural Sciences (DAS) of the Federal Ministry of Agriculture is responsible for all aspects of agricultural research in Nigeria. DAS oversees the funding and management of 15 national agricultural research institutes located throughout the country. These institutes are tasked with generating improved agricultural technologies for use by farmers and agro-industries. However, DAS funding of agricultural science research and technology has been generally stagnant and has even decreased since the collapse of oil prices in the early 1980s.

The agricultural research capacity in Nigeria is highly dispersed and the country does not have a well-defined national strategy. Nonetheless, research is necessary to develop crop and livestock management practices aimed at enhancing the resilience and mitigation potential of smallholder farming systems, through adapting SLM approaches to local circumstances, as well as by meeting the overall growth targets under Vision 20: 2020.

Another key challenge involves extending the existing capacity in agro-meteorological disciplines to include agro-climatic competency. Local climate change adaptation platforms have been proposed by a number of development agencies, as a means of promoting collaboration between scientists and practitioners and enhancing local adaptation capacity. Such platforms enable collaborative action, mutual learning, and the exchange of a range of material, for example, from mailing lists, e-conferences, academic papers, policy briefs, or information sheets. It is essential that these institutions design their activities around local needs and not the funding or reporting requirements of the international climate change community (SEI 2008).

IFPRI (2010) assessed the level of innovation capacity of Nigerian agricultural research system and made the following recommendations to strengthen it:

- **Improve collaboration between researchers and promote communication on innovations.** Although research productivity seems high, the overall level of collaboration is low and there is a lack of monitoring and evaluating the use, influence, and impact of technologies and publications produced by organizations and individual researchers.
- **Increase interactions with farmers, the private sector, extension agents, and other actors within the innovation system.** Greater awareness and sensitization, as well as exposure to practical knowledge, good practices, and experiences on innovation systems in other countries, are urgently needed. The Agricultural Research Council of Nigeria can play a role in facilitating a platform or forum for greater interaction and collaboration.
- **Strengthen the abilities for fundraising and diversifying fund sources.** Current agricultural research organizations have substantive capacity and incentive gaps. Among research institutes, the timely release of funds is the top motivating factor identified by researchers in order for them to produce more and be more innovative.
- **Improve governance of research organization.** Good performance and innovation capacity are associated with the presence of fair and transparent hiring procedures; effective performance evaluation and reward systems; systems of career development and job security; systems of information sharing and knowledge management; clearly defined and communicated division of roles and responsibilities; systems of feedback from stakeholders; and provision of flexibility, freedom to do work, and mobility among researchers.
- **Establish a mechanism of continuous training and skill development.**

### *Capacity Building and Technology Transfer Platforms*

Diffusion of scientific and technical knowledge to farmers is a prerequisite to the adoption of SLM and climate-smart agriculture (CSA) practices. Agriculture needs to become professionalized, with better incentives for training and development of technical capacity in crop and livestock production.

Agricultural Development Projects (ADPs) are the main vehicle for the delivery of public extension services in Nigeria. Despite their name, ADPs are not “projects” in the conventional sense, but state-level parastatals working in the agricultural sector. The first generation ADPs were created during the mid-1970s and supported largely with donor funds. Their extension activities include establishing demonstration farms, identifying lead farmers, providing them with information about good farming practices, facilitating access to improved technology and inputs (for example, seeds of improved varieties, fertilizer, machinery services), and helping leading farmers teach other farmers.

ADPs could serve as platforms for capacity-building, to promote the adoption of climate-smart agriculture (CSA) techniques. They can network with local-level training institutions to serve both extension officers and regional/local planners for promoting CSA both at the planning and project design levels.

### *Field Support Platforms as Small Farmer Aggregators*

A key issue in exploiting carbon finance potentials in the agriculture sector is that, while the overall GHG emissions potential may be highly significant, the contribution of each individual farm is often small. Therefore a highly efficient approach to aggregating the contributions of individual farmers is required in order to avoid excessive transaction costs. Farmer federations with support from ADPs could be strengthened to become field platforms and potentially to channel carbon funds and payment of environment services. Their value chain–based structure and their capacity to gather small farmers give them a comparative advantage as a farmer's aggregator.[1] From this perspective, it is therefore important to accomplish the following goals:

- Build the capacity of these organizations to effectively and sustainably play a role in the promotion of improved practices and in the control and monitoring of applications programs and projects.
- Provide technical assistance to farmer organizations to enable the trade of carbon credits on the voluntary markets (and possibly on the compliance market as well). These carbon assets (including soil carbon) would result from the implementation of CSA activities.
- Develop effective and scalable tools to support partnerships and alliances between governments, private sector operators, and leading local farmer organizations and trade associations in order to broaden the access of smallholder farmers to commercial and technical services.
- Provide a platform to scale out participatory farmer-to-farmer learning and farmer champions. It is often difficult to identify well-connected and credible farmer champions that will hold on-farm demonstrations and learning events that are critical for scaling out, but this is typically an important part of any strategy to scale-up specific technologies.

### *Systematic Review and Carbon Appraisal of Sector Project and Program Proposals*

A reform with the potential to provide rapid results would be to request a systematic review of any new investment project or program, in terms of its impact on climate mitigation and its ability to foster resilience. It automatically raises these criteria within the choice of technical options by project designers.

The UN Food and Agriculture Organization's *FAO Guidance to Best Practices* (FAO 2007, 2009a, 2009b) and its guidance on carbon balance appraisal of projects and policies[2] could be used by the country to develop its climate change response and adaptation strategies down to project and strategy design and appraisal.

The development of country-specific planning tools (for example, a CSA Atlas) to identify and prioritize opportunities for adopting a triple-win agriculture management options (higher yields, higher climate resilience, reduced carbon emissions) should also be considered.

## Building a Strong and Coherent Policy Environment

### *Stability of the Policy Framework*

A stable policy environment is a key requirement for the effective development of the agriculture sector and its contribution to mitigating climate change. Unfortunately, this stability has generally been lacking in Nigeria, as successive governments have often reversed policies put in place by predecessors. Inconsistent agricultural policies have resulted in apathy on the part of the farmers regarding anything from government because they never know how long an incentive may last; import policies have been erratic, characterized by frequent changes in both import tariffs and quantitative import restrictions, creating much uncertainty for producers; and the government has failed to set up a satisfactory credit system for farming.

However, in the way of improvement, Nigeria has recently developed an Agricultural Transformation Agenda (ATA), which could be a key long-term vehicle to champion sustainable and climate-smart sector policies. The 2012 ATA is a comprehensive plan that aims to restore Nigeria's old glory as an agriculture powerhouse. To this effect, the ATA seeks to achieve dramatic increases in agricultural productivity, massive job creation in the agriculture sector, significant expansion of value-addition in processing, drastic reductions in agricultural imports, and improved penetration of international markets.

The ATA is an important point of departure for transforming Nigeria's agriculture sector by providing the following: (1) an in-depth analysis of root causes of poor performance of the agriculture sector along with quantification of lost opportunities caused by this poor performance; (2) a clear vision for transformation of the sector as a process, including import substitution, export orientation, value-addition through processing, and backward integration linkages; (3) an explicit focus on agriculture as a business, putting the private sector in the driver's seat and recognizing the critical role of women; (4) a comprehensive approach to change by focusing on value-chains; (5) a concrete and specific program of sector policy reforms, including reform of the fertilizer subsidy program that has been a major drain on sector expenditures; and (6) specific and quantified targets for expected outcomes in terms of jobs, income, food security, and productivity improvements.

### *Strengthening Capacity of Decentralized Institutions*

With its federal system of government, Nigeria faces a challenge to define the roles and responsibilities of each tier of government. All the agricultural research institutes are owned and managed by the Federal Government, while state and local governments, which provide extension services, have no research institutes. This means that all decisions on the funding, direction, and implementation of research activities are taken from FGN–Abuja (Agbamu 2000), resulting in a discrepancy between local needs and current R&D programs. The FGN should make an effort to decentralize research funding and activities to reduce concentration at the federal level and strengthen the linkage to extension services and farmer organizations.

### *Strengthening CSA Policy and Project Planning*

Policies and institutions also need coordination with initiatives in other sectors that could help to strength the climate resilience in agriculture. The FGN could undertake the following actions to achieve this:

- Technical assistance is required to consolidate and harmonize policies and legislation related to water resources management, as a prerequisite for organic and effective integration of climate change considerations into sector planning and development.
- Guidelines should be prepared to enhance climate resilience of water resource development projects in the irrigation and hydropower subsectors, including design criteria to enhance the reliability of water storage infrastructure under wider precipitation swings.
- Further attention should be paid to developing small-scale finance provisions such as micro insurance, savings and transfer of money building on the innovation practices introduced by IT development.
- If safety nets are to be part of the risk-reduction strategy in Nigeria, they need to be elaborated and carefully designed to ensure they contribute to growth, rather than competing for resources. Many elements of the NAIP and NFSP can provide social protection elements, for example, public works programs on building dams, food for work programs, food for school programs, conditional transfers of farm inputs for stimulating agriculture, asset transfers through livestock or vouchers, among others.

## Notes

1. See http://web.worldbank.org/WBSITE/EXTERNAL/COUNTRIES/AFRICAEXT/NIGERIAEXTN/0,,menuPK:368922~pagePK:141132~piPK:141109~theSitePK:368896,00.html.
2. Please refer to Batjes 2010, p. 9 and the European Soil Portal http://eusoils.jrc.ec.europa.eu/projects/RenewableEnergy/for soil maps of Nigeria.

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APPENDIX A

# Emissions Coefficients and Other Parameters Used in the Model

**Table A.1 Coefficients Used in the Model**

| *Type of vegetation concerned* | *Type of coefficient* | *Data sources* | *Value of the coefficients* | |
|---|---|---|---|---|
| Forests | Carbon content in above and below ground biomass for secondary forests | Henry 2010 | Secondary moist forest | AGB = 32.2 t C/ha/yr<br>BGB = 7.7 t C/ha/yr |
| | | | Secondary rain forest | AGB = 89.3 t C/ha/yr<br>BGB = 33.0 t C/ha/yr |
| | Emissions factors of forest biomass burning | IPCC 2006 | Secondary moist forest | % of biomass burned = 36%<br>GHG emissions: 6.8 g $CH_4$/kg dry matter (DM) burned<br>0.2 g $N_2O$/kg DM burned |
| | | | Secondary rain forest | % of biomass burned = 32%<br>GHG emissions: 6.8 g $CH_4$/kg DM burned<br>0.2 g $N_2O$/kg DM burned |
| | Aforestation/ reforestation: carbon pool content | IPCC 2006 | Plantation of 2sd moist forest | AGB = 4.70 t C/ha/yr<br>BGB = 0.94 t C/ha/yr |
| | | | Plantation of 2sd dry forest | AGB = 3.76 t C/ha/yr<br>BGB = 2.11 t C/ha/yr |

*table continues next page*

**Table A.1 Coefficients Used in the Model** *(continued)*

| *Type of vegetation concerned* | *Type of coefficient* | *Data sources* | *Value of the coefficients* | |
|---|---|---|---|---|
| Annuals, perennials, grasslands, degraded lands, other | Non-forest land use changes (initial and final carbon pool in biomass and soil) | IPCC 2006 | Annual | Biomass = 5 t C/ha<br>Soil = 22.6 t C/ha |
| | | | Perennial | Biomass = 2.6 t C/ha<br>Soil = 47 t C/ha |
| | | | Wet rice | Biomass = 5 t C/ha<br>Soil = 51.7 t C/ha |
| | | | Grassland | Biomass = 6.4 t C/ha<br>Soil = 47 t C/ha |
| | | | Degraded land | Biomass = 1 t C/ha<br>Soil = 15.5 t C/ha |
| | | | Other | Biomass = 0 t C/ha<br>Soil = 47 t C/ha |
| | | | Fallow | Biomass = 5 t C/ha<br>Soil = 38.5 t C/ha |
| Annuals | Carbon storage capacity of different agronomic practices | IPCC 2006; Lal (2004b) | Moist tropical climate, improved varieties | 0.24 t C/ha/year |
| | | | Moist tropical climate, water management | 0.31 t C/ha/year |
| | | Chivenge et al. 2007; Leite et al. 2009 | Moist tropical climate, conservation agriculture | 1.27–1.32 t $CO_2$e/ha/year<br>Model uses the average (1.3 t $CO_2$e/ha/year), which is equivalent to 0.35 t C/ha/year |

*table continues next page*

**Table A.1 Coefficients Used in the Model** *(continued)*

| *Type of vegetation concerned* | *Type of coefficient* | *Data sources* | *Value of the coefficients* | |
|---|---|---|---|---|
| Perennials | Above and below ground biomass growth rate (biomass accumulation rate) | IPCC 2006 | Tropical moist climate | AGB: 2.6 t C/ha/year<br>BGB: 0 t C/ha/year |
| | Emissions factors of biomass burning | IPCC 2006 | | % of biomass burned = 80%<br>GHG emissions: 2.3 g $CH_4$/kg DM burned<br>0.21 g $N_2O$/kg DM burned |
| Rice | Methane emissions | IPCC 2006 | Continuously flooded, non-flooded preseason <180 days | 1.3 kg $CH_4$/ha/day |
| | | | Intermittently flooded, non-flooded preseason >180 days | 0.69 kg $CH_4$/ha/day |
| Grassland | Soil carbon content after 20 years (in 02–30cm depth) | IPCC 2006 | Non-degraded | 47.0 t C/ha |
| | | | Severely degraded | 32.9 t C/ha |
| | | | Moderately degraded | 45.1 t C/ha |
| | | | Improved without inputs | 54.5 t C/ha |
| | | | Improved with inputs | 60.5 t C/ha |
| | Above ground biomass (AGB) | IPCC 2006 | Tropical moist, LAC soil | AGB = 6.2 t DM/ha |
| | Emissions factors of biomass burning | IPCC 2006 | | % of biomass burned = 77%<br>GHG emissions: 2.3 g $CH_4$/kg DM burned<br>0.21 g $N_2O$/kg DM burned |

*table continues next page*

**Table A.1 Coefficients Used in the Model** *(continued)*

| *Type of vegetation concerned* | *Type of coefficient* | *Data sources* | *Value of the coefficients* | |
|---|---|---|---|---|
| Livestock | Methane emissions from enteric fermentation | IPCC 2006 | Cattle | 31 kg $CH_4$/head/year |
| | | | Sheep | 8 |
| | | | Swine | 1 |
| | | | Goat | 5 |
| | | | Camel | 46 |
| | | | Horse | 18 |
| | | | Donkey | 10 |
| | | | Poultry | 0 |
| Livestock | Methane emissions from manure management | IPCC 2006 | Cattle | 1 kg $CH_4$/head/year |
| | | | Sheep | 0.37 |
| | | | Swine | 2 |
| | | | Goat | 0.26 |
| | | | Camel | 3.17 |
| | | | Horse | 3.13 |
| | | | Donkey | 0.9 |
| | | | Poultry | 0.02 |

*table continues next page*

**Table A.1 Coefficients Used in the Model** *(continued)*

| *Type of vegetation concerned* | *Type of coefficient* | *Data sources* | *Value of the coefficients* | |
|---|---|---|---|---|
| | Nitrous oxide emissions from manure management | IPCC 2006 | Cattle | 39.8 kg $N_2O$/head/year |
| | | | Sheep | 20.7 |
| | | | Swine | 16.8 |
| | | | Goat | 19.3 |
| | | | Camel | 36.4 |
| | | | Horse | 63.3 |
| | | | Donkey | 21.8 |
| | | | Poultry | 0.6 |
| | Mitigation potential of better feeding practices | IPCC 2006 | Reduction in enteric fermentation from feeding practices (for cattle and sheep/goat) | −1% |
| | | | Reduction in enteric fermentation from breeding practices (for cattle and sheep/goat) | −0.6% |
| Inputs | Carbon dioxide emissions from urea application | IPCC 2006 | | 0.2 kg $CO_2$e/t urea |
| | Nitrous oxide emissions from N application | IPCC 2006 | | 0.01 kg $N_2O$/t N |

*table continues next page*

**Table A.1 Coefficients Used in the Model** *(continued)*

| *Type of vegetation concerned* | *Type of coefficient* | *Data sources* | *Value of the coefficients* | |
|---|---|---|---|---|
| Other investments | $CO_2$ emissions of gasoil | IPCC 2006 | | 2.63 t $CO_2$e/$m^3$ |
| | $CO_2$ emissions of the installation of irrigation system | IPCC 2006 | Hand moved sprinkle | 60 kg $CO_2$e/ha |
| | $CO_2$ emissions from the construction of buildings and roads | IPCC 2006 | Office (concrete) | 0.469 kg $CO_2$e/$m^2$ |
| | | | Industrial building (concrete) | 0.825 |
| | | | Industrial building (metal) | 0.275 |
| | | | Agricultural building (concrete) | 0.656 |
| | | | Agricultural building (metal) | 0.220 |
| | | | Road | 0.073 |

*Source:* World Bank data.

**APPENDIX B**

# Land Use Changes in the Reference Scenario

**Table B.1 Land Use Change Matrix for Reference Scenario (ha, thousands)**

| | Initial 2010 | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| *Final 2025* | *Annuals* | *Wet rice* | *Perennials* | *Forests* | *Grasslands* | *Degraded lands* | *Fallow* | *Other lands* | *Total final* |
| Annuals | 33,124 | | | 4,641 | 2,063 | | 2,063 | 1,547 | **43,437** |
| Wet rice | 1,312 | 1,313 | | | | | | | **2,625** |
| Perennials | | | 6,552 | 475 | 317 | 951 | 634 | 792 | **9,721** |
| Forests | | | | 3,838 | 120 | 300 | 180 | | **4,438** |
| Grasslands | | | | 147 | 16,129 | 598 | 100 | | **16,974** |
| Degraded lands | | | | | | 0 | | | **0** |
| Fallow | | | | | | | 3,257 | | **3,257** |
| Other lands | | | | | | | | 10,602 | **10,602** |
| **Total initial** | **34,437** | **1,313** | **6,552** | **9,101** | **18,629** | **1,849** | **6,234** | **12,941** | **91,054** |

*Source:* World Bank data.

APPENDIX C

# Mitigation Options in the Low-Carbon Scenario

**Table C.1 Mitigation Options in the Low-Carbon Scenario: SLM Measures and Limits of Implementation**

| *SLM practice* | *Justification* | *Description* | *Impacts* | *Main constraints of implementation* |
|---|---|---|---|---|
| Conservation agriculture | Reference scenario already contained some improved agronomic practices, such as using improved varieties, but Nigeria needs to go further if it wants to reduce crop expansion (and thus deforestation) while in the meantime increasing productivity to achieve food security and limit food imports. | Land use concerned: **Cropland**<br>• Minimum or no-tillage<br>• Mulching (30% minimum of the crops residue remains on the soil surface after planting)<br>• Crop rotation integrating leguminous and crop association | • The "no-tillage" increases the soil organic content and soil properties (physical, chemical, and biological), thus leading to a more efficient use of precipitation, soil moisture, and plant nutrients, limiting erosion and storing carbon in soils.<br>• The surface mulch that develops protects the soil surface from the impact of heavy raindrops, reducing the erosive power of the water (Derpsch et al., 1991) and wind while protecting the surface from excessive heat.<br>• Increase yield within a single year and reduce inter-year variation in yields (FAO 2008). | • Farmers need extensive training and access to skilled advisory services. Compared to conventional farming, a fundamental change in approach is required.<br>• Typically there is a transition period of 5–7 years before a conservation agriculture system reaches equilibrium. Yields may be lower in the early years.<br>• One of the biggest issues with no-tillage is weed control: reduced tillage means having recourse to herbicides. Farmers must be educated in the correct use of these herbicides, to avoid the harmful effects to the environment of improper use, or they have to adopt integrated pest management (crop rotation, cover crop, cultural practices) (Pieri et al. 2002, 30).<br>• Farmers need to make an initial investment in specialized machinery, with initially increased labor (weeding); for example, Laikipia District in Kenya maintenance = \$93/ha/yr; Morocco maintenance = \$600/ha/yr.<br>• Conservation agriculture has not been successful in heavy clay soils, poorly drained sites, compacted soils, and arid areas due to insufficient carbon. |

*table continues next page*

**Table C.1 Mitigation Options in the Low-Carbon Scenario: SLM Measures and Limits of Implementation** *(continued)*

| *SLM practice* | *Justification* | *Description* | *Impacts* | *Main constraints of implementation* |
|---|---|---|---|---|
| Sustainable Rice Intensification (SRI) (Styger et al. 2011) | Rice is an important crop for Nigeria whose growers seek to increase its production (in yield and in surface), but it also contributes highly to climate change through methane emissions; therefore, adopting better water management practices is vital. | Land use concerned: **Irrigated rice**<br>• Rotational and intermittent irrigation (keeping a saturated condition, non-flooded)<br>• Use of genetically improved seeds that are transplanted instead of broadcasted<br>• Application of organic fertilizers<br>• Integrated pest management (use less pesticide) | • Transplantation reduces the number of plants and therefore of seeds (economical benefit).<br>• Organic fertilizers improve soil structure, organic matter content, and fertility.<br>• Reduce health hazards due to the use of pesticides.<br>• Increase in yields.<br>• Irrigation management reduces methane emissions. | • In view of the great diversity in rice production systems that operate under varied local biophysical and socioeconomic conditions, SRI methods will not be applicable invariably everywhere. Each situation will require research and validation of the various SRI components (Dobermann 2003).<br>• Higher labor requirements, especially for weed control, initial investments in machinery for direct seeding, and weeding operations. SRI requires excellent land preparation, timely availability of irrigation water during critical periods of growth, good irrigation infrastructure, and efficient methods of weed control. If land leveling and water management are poor, the risk for yield reduction due to temporary drought stress, weeds, or nutrient losses increases (Dobermann 2003).<br>• Other potential uncertainties include increases in soil greenhouse gas emissions ($N_2O$) in systems with alternate wet–dry conditions (Bronson et al. 1997).<br>• It appears that SRI is mainly suitable for increasing rice yields in environments with acid, iron-rich soils, high labor availability, and a generally low level of crop intensification. Benefits of SRI over conventional rice management are likely to be small on fertile rice soils with no constraints such as potential iron toxicity, provided that management follows known best practices (Dobermann 2003). |

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**Table C.1 Mitigation Options in the Low-Carbon Scenario: SLM Measures and Limits of Implementation** *(continued)*

| *SLM practice* | *Justification* | *Description* | *Impacts* | *Main constraints of implementation* |
|---|---|---|---|---|
| Livestock management | One Vision 20: 2020 target is to expand dairy production and milk yield from less than 2 t to 5 t per cow per lactation by 2015 (FGN 2010, 58). It will require a switch to more productive animals but also better livestock management in feeding and breeding. | • Better feeding practices (less forage, more concentrates and additives)<br>• Breeding management to select improved and more efficient animals | • Improving animal nutrition will increase the productivity of the livestock.<br>• Selecting more productive animals enables limitation of livestock numbers, therefore reducing the emissions from enteric fermentation (ruminants) and manure management.<br>• Dietary improvements reduce methane emission due to enteric fermentation and, through increased production efficiency, lead to a reduction of methane emitted per unit of production. | • Such techniques are often out of reach for smallholder livestock producers who lack the capital and often knowledge to implement such changes (Steinfeld et al. 2006).<br>• Limiting the number of animals also reduces the amount of manure available to fertilize the crops, which may lead to the use of chemical fertilizers.<br>• Regular extension services are not easily accessible for mobile pastoralists. |
| Sustainable grazing management *with* inputs | In line with the increase in livestock productivity targeted by Vision 20: 2020, improving grassland management and restoring degraded grassland will support livestock productivity. | Land use concerned: **Grassland**<br>• Restoration of degraded pastures with inputs such as mineral fertilizers, manure application, irrigation<br>• Less or no use of fire | • Maximize the capture, infiltration, and storage of rainwater into soils, thus promoting conditions that increase vegetation cover, improve soil organic content, and conserve above and below ground biodiversity.<br>• Improved grazing conditions will increase livestock productivity in rangelands, in turn increasing food security.<br>• Fires reduce soil organic content (SOC) (thus releasing carbon) and nutrients level, lead to erosion, and kill surface micro-organisms, limiting the soil capacity to reform. Limiting the use of fire limits all these drawbacks. | • Requires community organization for limiting overgrazing.<br>• Requires large investments the first years in fertilizers and irrigation systems. |

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**Table C.1 Mitigation Options in the Low-Carbon Scenario: SLM Measures and Limits of Implementation** *(continued)*

| *SLM practice* | *Justification* | *Description* | *Impacts* | *Main constraints of implementation* |
|---|---|---|---|---|
| Sustainable grazing management *without* inputs | FGN wants to establish at least 50 gazetted grazing reserves, (FGN 2010) thus a sustainable grazing management is needed to support this goal. | Land use concerned: **Grassland**<br>• Restoration of degraded pastures without inputs through the use of improved grass variety and rotational grassing<br>• Less or no use of fire | • Maximize the capture, infiltration, and storage of rainwater into soils, thus promoting conditions that increase vegetation cover and soil organic content and conserve above and below ground biodiversity.<br>• Improved grazing conditions will increase livestock productivity in rangelands, in turn increasing food security.<br>• Fires reduce SOC (thus releasing carbon) and nutrients level, lead to erosion, and kill surface micro-organisms, limiting the soil capacity to reform. Limiting the use of fire limits all these drawbacks. | • Need to develop grazing plans tailored to specific local conditions (inter alia the pattern of local rainfall, area of land available, location of water supplies, numbers, and types of livestock) by using participative approaches with entire communities developing, for example, new systems and regulations involving communities gathering their livestock into a group, then moving from one portion of their grazing lands to another during the year.<br>• Costs in Ethiopia in improved grazing land management = $1,035/yr establishment, and $126/yr maintenance; range closure for rehabilitation = $390/ha establishment, and $90/yr maintenance (TerrAfrica 2009). |
| Avoided deforestation | Deforestation is the biggest GHG emissions source in the reference scenario; therefore, it is an important improvement point. | Land use concerned: **Forest**<br>The forest is preserved | • Avoiding deforestation prevents the important release of $CO_2$ in the atmosphere (from clearing and burning).<br>• Preserving the forest will preserve biodiversity.<br>• Deforestation can affect the flux of moisture to the atmosphere, regional convection, and regional rainfall. | • In many instances, the sole option to preserve forested area is to intensify agricultural production on other land. This raises complexities; for example, when intensification involves increased fertilizer inputs, there will be increased emissions related to the fertilizer (TerrAfrica 2009).<br>• Need to find and provide more affordable fuel-efficient stoves or sustainable alternative fuels to decrease the pressure on wood resources.<br>• For some countries timber can be an important export revenue that they might not want to lose. |

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**Table C.1 Mitigation Options in the Low-Carbon Scenario: SLM Measures and Limits of Implementation** *(continued)*

| *SLM practice* | *Justification* | *Description* | *Impacts* | *Main constraints of implementation* |
|---|---|---|---|---|
| Reforestation/ Afforestation and Agroforestry (live fences, alley cropping) | FGN objective is a proactive policy of afforestation, reforestation, and erosion control programs (FGN 2010, 62). | Land use concerned: **Forest**<br>• Reforestation is planting new trees in previously forested areas (where old tress have been recently cut or burned).<br>• Afforestation involves planting stands of trees on land that is not currently classified as forest.<br>• Both reforestation and afforestation can include shelterbelts, windbreaks, and woodlots.<br>• The alley-cropping technique involves growing annual crops in spaces (4- to 6-meter-wide "alleys") between rows of leguminous trees or shrubs maintained as hedges. | • Tree planting sequesters carbon in the biomass and the soil, while conserving soil and water quality and quantity.<br>• Increased tree cover will improve the functioning of the hydrological system and protect wild biodiversity.<br>• Reforestation and afforestation will increase the amount of sustainably sourced wood for fuel and timber and non-woody forest products (medicinal plants, wild food, fodder, and so on), which would bring economic benefits to local people.<br>• The hedges are heavily pruned throughout the crop season to prevent them from shading the crops. The prunings and crop residues are used as mulch to conserve moisture and enrich the soil in the cultivated alleys. Soil nutrients and nitrogen fixed by the tree roots similarly enrich the soil in the alleys. The technique allows for continuous cultivation of food crops because soil productivity is restored throughout the cropping cycle, thus eliminating the need for a fallow period. (USAID 1989).<br>• For agroforestry, benefits are numerous: erosion control, runoff barrier, improvement of soil fertility and moisture content, and control of drought and desertification. | • In dryland areas, purposeful planting of trees is difficult due to lack of water for nurseries in the dry season and absence of labor for protecting the trees (TerrAfrica 2009).<br>• Uncertain land tenure situations certainly had an adverse impact on farmers' attitudes toward tree planting in several countries (Spears 1983).<br>• A common constraint is land availability, particularly where there is high population density and competition for land between agriculture and forestry, and especially in those countries where a high proportion of the land suitable for forest is under fragmented private ownership (Spears 1983).<br>• Given the fact that it takes 20–25 years in many countries to grow industrial tree crops to merchantable size, this long time period before any income is obtained can act a disincentive to small farmers participating in industrial forestry (Spears 1983).<br>• The risks of fungal or insect diseases associated with large-scale plantation monocultures have created problems in some countries (for example, *Dothistroma pinii* in Kenya and the ravages of the Pine Shoot moth in the Philippines) (Spears 1983).<br>• Regarding agroforestry, the demand for labor is high (pruning). |

*Source:* World Bank data.

**Table C.2 Impact of SLM Measures on GHG Emissions and Yield**

| *SLM practice* | *Potential yield augmentation* | *Potential impact on GHG emissions and carbon sequestration* |
|---|---|---|
| Conservation agriculture | • Regarding the carbon storage in soil, changes in yield due to conservation agriculture will vary depending on the site characteristics. Researches shows that yields often decreased in the first years, before increasing.<br>• Yields can be more than 60% higher than under conventional tillage (FAO 2007).<br>• Studies in East and Southern Africa show that conservation agriculture with fertilization increases the yield from 1.2 to 2 t/ha for maize and from 0.5–0.7 to 1.1 t/ha for *tef* (grass crop) in Ethiopia (Rockström 2008). | • It is difficult to make definitive quantitative statements on the effects of reducing tillage on SOC, because the effects are highly dependent on the individual site (*inter alia* soil type, climate, crops grown, previous intensity of tillage, new regime).<br>• A change from conventional tillage to no-till can sequester 0.57 ± 0.14 t C/ha/yr (West and Post, 2002). The IPCC (2006) estimated that conservation tillage can sequester 0.1–1.3 t C/ha/yr globally.<br>• A field monitoring site in western Nigeria recorded that no-tillage combined with mulch application increased SOC from 15 to 32.3 t/ha in four years (Ringius 2002).<br>• Levels can be expected to peak after 5–10 years, with SOC reaching a new equilibrium in 15–20 years. Overall, rates of SOC are lower in hotter climates. |
| Sustainable rice intensification | Average yield increase by 10–25% (Ramasamy 1997):<br>• From 2.5t/h to 5–7.5t/ha in Gambia and Sierra Leone Ceesay et al. 2006.<br>• up to 15 t/ha in Madagascar (Stoop, Ubhoff, and Kasam 2002).<br>• Maximum SRI yields in the range of about 8–12 t/ha appear to be more common in other studies (Dobermann 2003). | • Emission rates ranged from < 100 kg $CH_4$ $ha^{-1}$ to > 400 kg $CH_4$ $ha^{-1}$ for intermittent irrigation and continuous flooding respectively (Wassmann et al. 2000).<br>• Yue et al. (2005) compared continuous flooding with intermittent flooding and their role on $CH_4$ and $N_2O$ emissions in Southern China and found that intermittent flooding showed a 17% lower Global Warming Potential (GWP) compared to continuous flooding, while there was no significant differences between yields.<br>• The soil carbon pool can be enriched with 401 kg C $ha^{-1}$ annually, with a rice yield of 3.96 t $ha^{-1}$ and input of crop residues amounting to 2.67 t $ha^{-1}$ (Jarecki and Lal 2003). |
| Livestock management | Increase in meat and milk production; Example: in Kenya, genetic improvement program: the average lactation milk yield in the stud has gone up from 1,042 kg in 1965 to 1,527 kg in 1971.<br>With the present selection procedure, annual genetic gain is projected to be 0.12 genetic standard deviations, or 43.4 kg (Meyen and Wilkins 1973). | • Recent modeling studies in the United Kingdom by Genesis-Faraday (Genesis-Faraday Partnership 2008; Jones et al. 2008) have indicated that past selection for production traits, such as growth rate, milk production, fertility, and efficiency of feed conversion, has resulted in decreases in GHG production per unit of livestock product of about 1% per year.<br>• Depending on the nature of the intervention, methane production can be reduced 10–40%. Increasing DMI (dry matter intake) and the proportion of concentrate in the diet reduced methane production (–7 and –40%, respectively). Methane production was also decreased with the replacement of fibrous concentrate with starchy concentrate (–22%) and with the utilization of less ruminally degradable starch (–17%). The use of more digestible forage (less mature and processed forage) resulted in a reduction of methane production (–15 and –21%, respectively). Methane production was lower with legume than with grass forage (–28%), and with silage compared to hay (–20%).<br>• Supplementation or ammoniation of straw did not reduce methane losses, but had a positive impact on the efficiency of rumen metabolism (Benchaar, Pomar, and Chiquette 2001). |

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**Table C.2 Impact of SLM Measures on GHG Emissions and Yield** *(continued)*

| *SLM practice* | *Potential yield augmentation* | *Potential impact on GHG emissions and carbon sequestration* |
|---|---|---|
| Sustainable grazing management *with* inputs | • Increase in yield will vary, depending on the type and quantity of improvements (level of fertilization, amount of water, presence of leguminous, species, level of plants diversity, and so on).<br>• Herbage production can be increased one- to four-fold through timing and intensity of grazing (Bryant 1985). | • Rates of C sequestration by type of improvement ranged from 0.11 to 3.04 t $C{\cdot}ha^{-1}$ $yr^{-1}$, with a mean of 0.54 t $C{\cdot}ha^{-1}{\cdot}yr^{-1}$, and were highly influenced by biome type and climate (Conant, Paustian, and Elliott 2001).<br>• Stocking rates increased by 50% (from 0,8 to 1,2 AU/ha/year) in Brazil, mainly due to the better grazing efficiency associated with rotational grazing (Corsi. Do Nascimento, and Balsalobre 2001). |
| Sustainable grazing management *without* inputs | Increase in yield will vary depending on the type and quantity of improvements (level of fertilization, amount of water, presence of leguminous, species, level of plants diversity, and so on). | From 0.2 to 0.4 t C/ha/yr (improved species, controlled grazing, fire management) (Lal 2004). |
| Avoided deforestation | | • It depends on the type of forest, its density, and the use after conversion (emissions will be higher if the forest is converted into annual crops versus perennial crops or grassland).<br>• From 0.75 to 4.25 t C/ha/yr (Masera 1995) for a Brazilian tropical forest. |
| Reforestation/afforestation and agroforestry (live fences, alley cropping) | Growth rate depends on the type of plantation, as well as its density:<br>• Broad leaves plantation: 1 t DM/ha/yr (Koch, Dayan, and Mey-Marom 2000)<br>• Conifer plantation: 4 t DM/ha/yr<br>• Eucalyptus plantation: 7 t DM/ha/yr<br>• Fodder (tree + shrubland): up to 6.9 t DM/ha/yr in Tanzania (Mbwambo 2004).<br>Agroforestry (alley cropping, contour hedge-row farming) increases the yield of millet, maize, and other grains by 45–200%, according to some studies (Kang et al. 1999; ILCA and IITA I986). Other researchers suggest that alley cropping has no significant effect on crop yields in most cases (Junge 2008). The crop yield response is uncertain and variable due to competitive effects of the different cultures for light, water, and nutrients. | • From 0.86 to 3.75 t C/ha/yr (Masera 1995) for a Brazilian tropical plantation.<br>• The C sequestration potential of agroforestry systems is estimated at 12–228 Mg/ha with a median value of 95 Mg/ha (Albrecht and Kandji 2003). |

*Source:* World Bank data.

**Table C.3 Sources of Data And Assumptions to Calculate Costs for Each SLM Option**

| *Required investment* | *Mitigation option concerned* | *Assumptions* | *References* |
|---|---|---|---|
| Fertilizer need | • Conservation agriculture and annuals<br>• Sustainable grazing management with inputs<br>• Perennials | FGN supports farmers in using fertilizers with subsidies. Subsidies represent 17% of the total cost of buying fertilizers. Farmers pay 83% of the total cost to buy these fertilizers. | • Federal Fertilizer Department, FGN 2006<br>• Federal Ministry of Agriculture and Rural Development<br>• University of Calabar 2002<br>• International Food Policy Research Institute (IFPRI) Nigeria Agriculture Public Expenditure Review (World Bank 2008) |
| Organic fertilizer | • Conservation agriculture<br>• Sustainable rice intensification | Prices (US$23/bag) and quantities obtained from records of the Soil Science Department, Organic Fertilizer Unit, University of Calabar<br>Cost born 100% by farmers | Bisong 2010 |
| Agric. extension agent | • Conservation agriculture and annuals<br>• Perennials<br>• Sustainable Rice Intensification<br>• Sustainable grazing management with and without inputs<br>• Livestock management | • Number of visits/production rotation = 20<br>• Cost born at 100% by FGN | University of Calabar 2002 |
| Seed development cost | • Conservation agriculture<br>• Sustainable Rice Intensification<br>• Sustainable grazing management with and without inputs | • Cost based on market prices for matured seedlings<br>• Cost born at 100% by FGN | • University of Calabar 2002<br>• National Programme for Food Security: Federal Ministry of Agriculture and Water Resources |
| Administrative cost | • For all measures | Assumed to be 20% of all other costs, based on qualitative feedback from the Fadama project, born 100% by FGN | Ike, 2012. |
| Higher yield | • Sustainable grazing management with and without inputs<br>• Livestock management<br>• SRI<br>• Conservation agriculture and annuals<br>• Perennials<br>• Agroforestry | Assumed to be 80% of the traditional yield for conservation agriculture, 50% for agroforestry, 25% for SRI, 33% for livestock,10–66% for grassland | University of Calabar 2002<br>Junge et al. 2008; Kang et al. 1999;Ramasamy 1997;<br>Infonet/Biodivision http://www.infonet-biovision.org/default/ct/268/livestockSpecies;<br>Federal Fertilizer Department, FGN 2006. |

*table continues next page*

**Table C.3 Sources of Data And Assumptions to Calculate Costs for Each SLM Option** *(continued)*

| *Required investment* | *Mitigation option concerned* | *Assumptions* | *References* |
|---|---|---|---|
| Feed and management (prophylaxis and breeding) | • Livestock management | FGN gives subsidies to farmers to help them improve feeding and breeding practices. Subsidies represent 17% of the total cost, therefore farmers still have to pay 83%. | No specific data was found in the scientific literature, so the figures used are based on the scheme for fertilizers subsidies. |
| Planting cost | • Reforestation/afforestation and agroforestry | Cost born at 100% by FGN for afforestation, and at 25% for agroforestry. Thus farmers need to pay 75% of the cost of planting live fences and hedges. | Federal Department of Forestry, Nigeria<br>Tewari 2008 |
| Protection cost (against animals, during growing time, and forest management and enforcement) | • Reforestation/afforestation | Cost born at 100% by FGN | Federal Department of Forestry, Nigeria |
| Opportunity cost | • Reforestation/afforestation and agroforestry<br>• Avoided deforestation | • The cost of nonconverting the forested area into a more productive crop is born by the farmers, while the cost of non-harvesting is supported by the Government.<br>• It is the value of the next-highest-valued alternative use of that resource—the benefits that could have been received by taking an alternative action, for example, deforestation. | International Institute for Environment and Development (IIED 2008) |
| Non-Forest Timber Product (NFTP) | • Reforestation/afforestation and agroforestry<br>• Avoided deforestation | NFTP to benefit the farmers, includes the economical value of flora and fauna (picking, hunt), for the forest plantation, and the value of grass, fodder, and wood for the agroforestry/live fencing. | Yaron 2001 (Data are for Cameroon);<br>Tewari 2008 |
| Fuel costs | • Annuals | 0.77$/liter in 2010 | WB country data<br>Trading Economics http://www.tradingeconomics.com/nigeria/pump-price-for-diesel-fuel-us-dollar-per-liter-wb-data.html |

*Source:* World Bank data.

## APPENDIX D

# Further Details on Low-Carbon Scenarios A and B

## GHG Emissions in Scenario A

The total emissions of scenarios A and B for the whole 25-year period go up to 1,687 Mt $CO_2$e, that is, 0.74 t $CO_2$e/ha/yr—or 1.6 times less than the reference scenario. However, from 2030, the agriculture, forestry, land use (AFOLU) sector begins to be a net sink, thanks to greenhouse gases (GHG) abatement and carbon storage from the land use change component. Indeed, emissions from deforestation and other land use changes (LUCs) are offset by the sequestration of carbon in tree plantations.

Gross emissions come from LUC until 2029 (56 percent of total), from livestock and pasturelands (37 percent), and from inputs (7 percent). Gross sinks are divided between crops and LUC with a ratio of almost 4:1 (73 percent and 27 percent, from 2030 for LUC). Perennials and agroforestry/afforestation especially account for the carbon sequestration, respectively, 33 percent and 47 percent. Even if reduced, deforestation still contributes strongly to gross emissions (53 percent), followed by livestock (29 percent). For further details of scenario A see table D.3 and figure D.1.

## GHG Emissions for Scenario B

Total emissions for the whole period reach 2,017 Mt $CO_2$e, which is equivalent to an average of 0.89 t $CO_2$e/ha/yr. Net emissions are positive until 2033, after which 2034 and 2035 are the first years where the agricultural and forestry sector becomes a sink. The main sources of gross emissions are LUC with 59 percent, followed by livestock and grass (35 percent). This is essentially due to deforestation and enteric/manure management emissions. Crops provide the great majority of abatement through annuals and conservation agriculture (31 percent) as well as perennials (45 percent). Since in this low-carbon scenario agroforestry is not as important as in the previous ones, the contribution of this mitigation option is more limited (21 percent instead of 47 percent).

**Table D.1 Land Use Change Matrix for Scenario A**
*Hectares, thousands*

| | Initial 2010 | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| *Final 2025* | *Annuals* | *Wet rice* | *Perennials* | *Forests* | *Grasslands* | *Degraded lands* | *Fallow* | *Other lands* | *Total final* |
| Annuals | 28,913 | | | 4,381 | 2,504 | | 3,130 | 2,504 | **41,432** |
| Wet rice | 1,312 | 1,313 | | | | | | | **2,625** |
| Perennials | | | 6,552 | 634 | 475 | 792 | 634 | 634 | **9,721** |
| Forests + live fences/ agroforestry | 4,211 | | | 4,086 | 1,524 | 300 | 180 | | **10,301** |
| Grasslands | | | | | 14,126 | 757 | | | **14,882** |
| Degraded lands | | | | | | 0 | | | **0** |
| Fallow | | | | | | | 2,290 | | **2,290** |
| Other lands | | | | | | | | 9,803 | **9,803** |
| **Total initial** | **34,437** | **1,313** | **6,552** | **9,101** | **18,629** | **1,849** | **6,234** | **12,941** | **91,054** |

*Source:* World Bank data.

**Table D.2 Land Use Change Matrix for Scenario B**
*Hectares, thousands*

| | Initial 2010 | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| *Final 2025* | *Annuals* | *Wet rice* | *Perennials* | *Forests* | *Grasslands* | *Degraded lands* | *Fallow* | *Other lands* | *Total final* |
| Annuals | 32,192 | | | 3,234 | 1,848 | | 2,310 | 1,848 | **41,432** |
| Wet rice | 1,312 | 1,313 | | | | | | | **2,625** |
| Perennials | | | 6,552 | 634 | 475 | 792 | 634 | 634 | **9,721** |
| Forests + live fences/ agroforestry | 932 | | | 4,086 | 431 | 300 | 180 | | **5,929** |
| Grasslands | | | | 1,148 | 15,875 | 757 | | | **17,779** |
| Degraded lands | | | | | | 0 | | | **0** |
| Fallow | | | | | | | 3,110 | | **3,110** |
| Other lands | | | | | | | | 10,459 | **10,459** |
| **Total initial** | **34,437** | **1,313** | **6,552** | **9,101** | **18,629** | **1,849** | **6,234** | **12,941** | **91,054** |

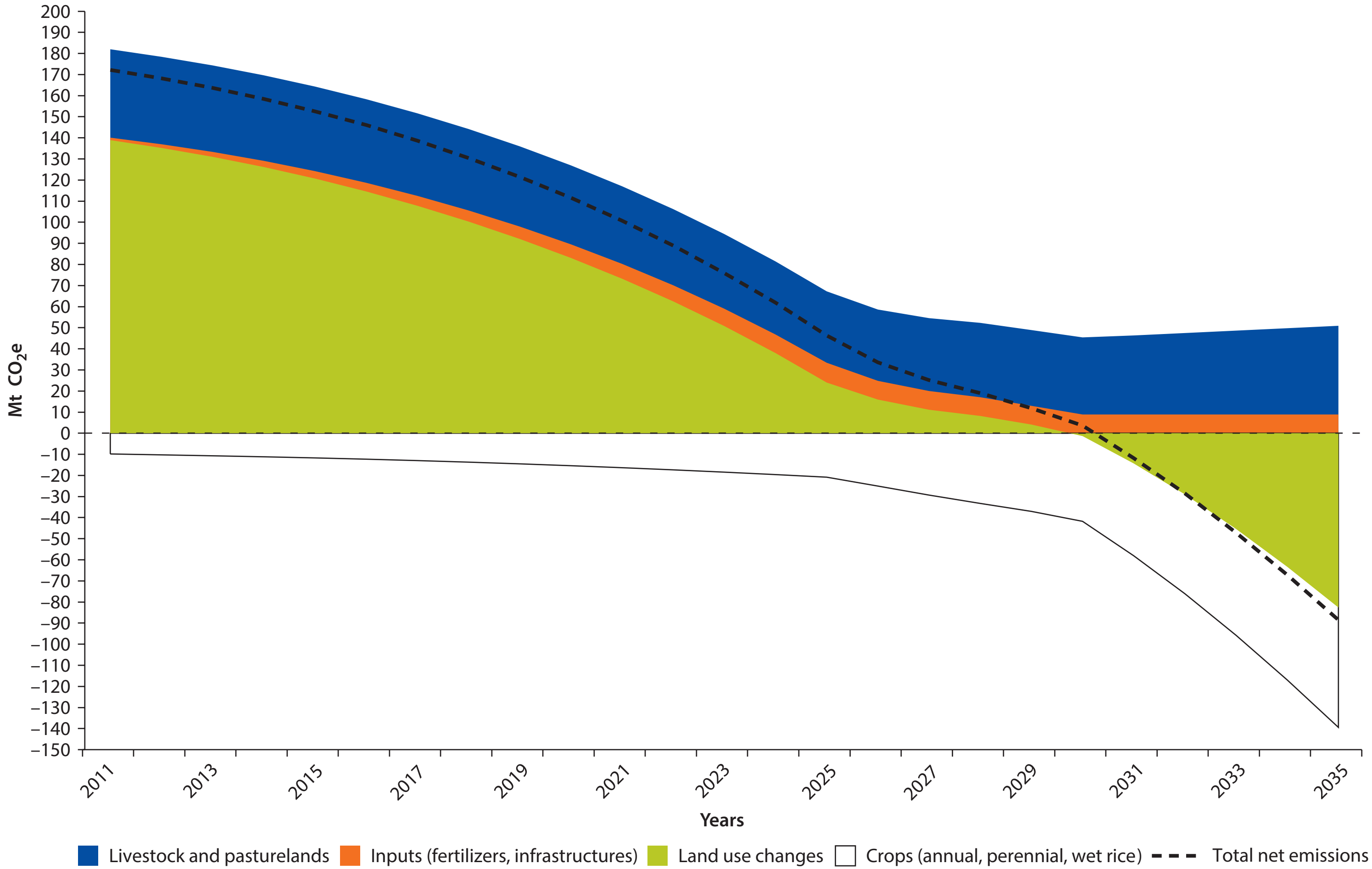
*Source:* World Bank data.

**Table D.3 Annual Emissions of 2010 vs. 2035 in Scenario A (Mt $CO_2$e/yr)**

| | | 2035 | | Percent difference | |
|---|---|---|---|---|---|
| *Activities* | *2010* | *Baseline* | *Low carbon* | *Baseline* | *Low carbon* |
| Land use changes | 127.1 | 15.6 | –82.6 | –88 | –165 |
| Crops | –9.4 | –43.6 | –56.8 | –364 | –504 |
| Livestock and grassland | 42.4 | 46.4 | 42.0 | +10 | –1 |
| Other | 0.6 | 6.7 | 8.9 | +1,068 | +1,439 |
| **Total** | **160.6** | **25.2** | **–88.5** | **–84** | **–155** |

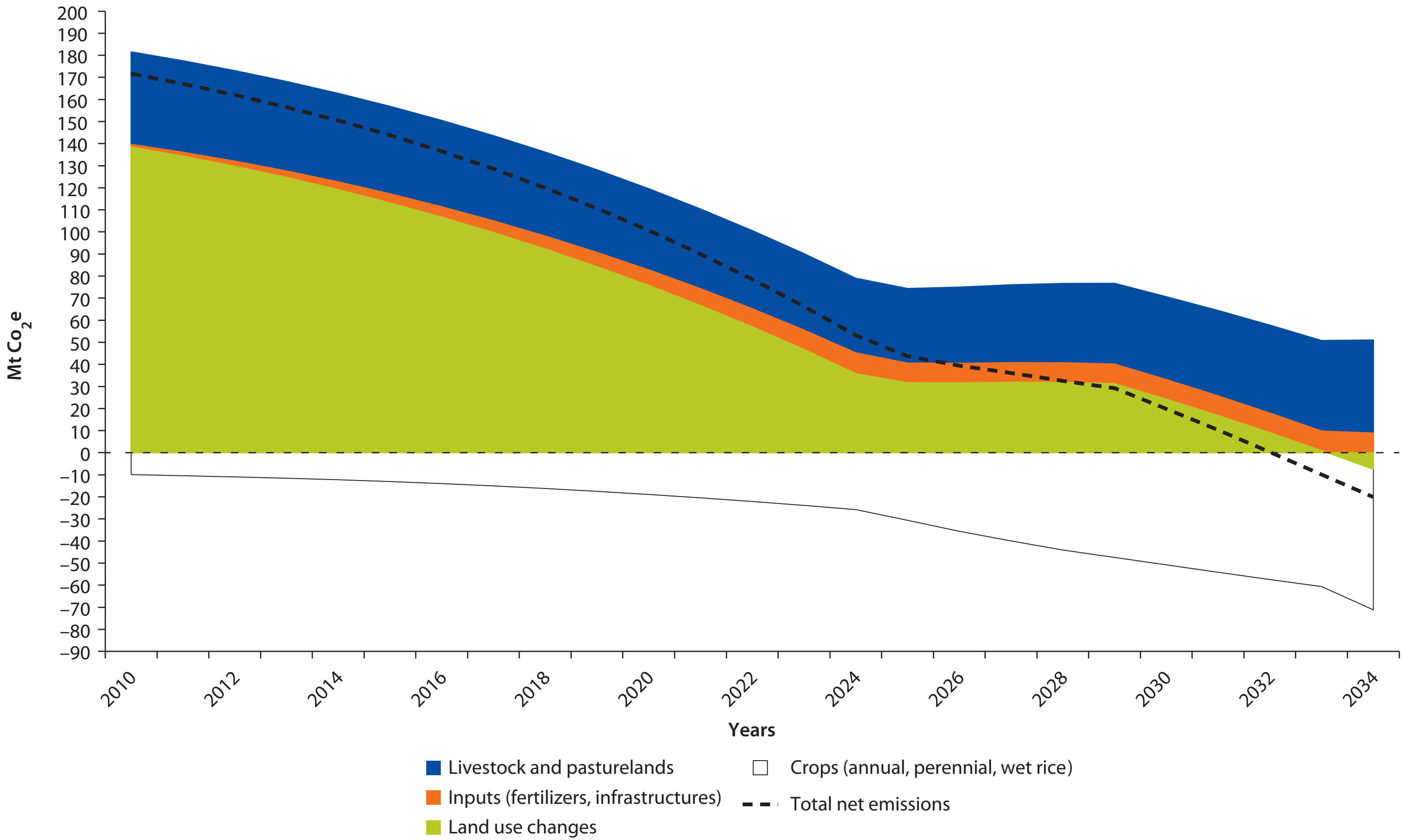
*Source:* World Bank data.

**Figure D.1 Evolution of Annual Emissions, by Activity, in Scenario A, 2010–35**




*Source:* World Bank data.

**Figure D.2 Evolution of Annual Emissions, by Activity, in Scenario B, 2010–35**




*Source:* World Bank data.

Total emissions for the whole period reach 2,017 Mt $CO_2$e, equivalent to an average of 0.89 t $CO_2$e/ha/yr. Net emissions are positive until 2033, after which 2034 and 2035 are the first years where the agricultural and forestry sector becomes a sink. The main sources of gross emissions are LUC (59 percent of total), followed by livestock and grass (35 percent), due to deforestation and enteric/manure management emissions. Crops provide the great majority of sequestration, through annuals and conservation agriculture (31 percent) as well as perennials (45 percent). Since in this low-carbon scenario, agroforestry is not as important as in the previous ones, the contribution of this mitigation option is more limited (21 percent instead of 47 percent).

**Table D.4 Annual Emissions of 2010 vs. 2035 in Scenario B**

*Mt $CO_2$e/yr*

| | | *2035* | | *Percent difference* | |
|---|---|---|---|---|---|
| *Activities* | *2010* | *Baseline* | *Low carbon* | *Baseline* | *Low carbon* |
| Land use changes | 127.1 | 15.6 | –7.5 | –88 | –106 |
| Crops | –9.4 | –43.6 | –63.7 | –364 | –577 |
| Livestock and grassland | 42.4 | 46.4 | 42.1 | +10 | 0 |
| Other | 0.6 | 6.7 | 8.9 | +1068 | +1439 |
| **Total** | **160.6** | **25.2** | **–20.2** | **–84** | **–113** |

*Source:* World Bank data.

**APPENDIX E**

# Sensitivity Analysis of the Model Results

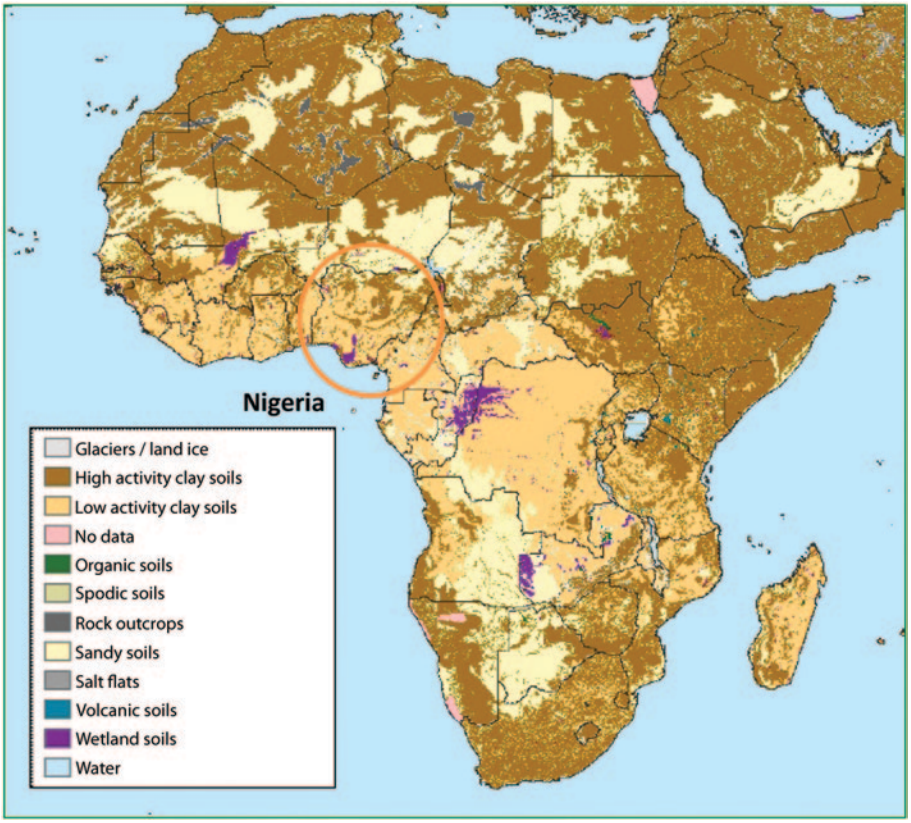
The results presented in this study depend, among others, on assumptions made about climate and soils. Given the study's limited timeframe, climate and soil variables have been selected at a coarse scale of aggregation, selecting a single value for the country as a whole from the options defined by the IPCC (2006) (maps E.1 and E.2)[1] at the global scale. Specifically, a tropical moist climate and LAC soil have been chosen because they best represent the bulk, but not all, of Nigeria's territory. To gauge the bias due to selection of single values for these parameters, the research team undertook a sensitivity analysis using different combinations of climate and soil parameters (tropical wet/moist climate, and low activity clay/high activity clay (LAC/HAC) soil).

Tables E.1 and E.2 display the detailed changes in overall emission results as following from different assumptions of climate and soil.

Changing only the type of soil (from LAC in the initial analysis to HAC) does not significantly affect the emission estimates; the difference is only 0 to 1 percent. However, the type of climate has an important impact on the emissions: the tropical wet climate gives figures that are 2 to 12 times lower than the tropical moist climate.

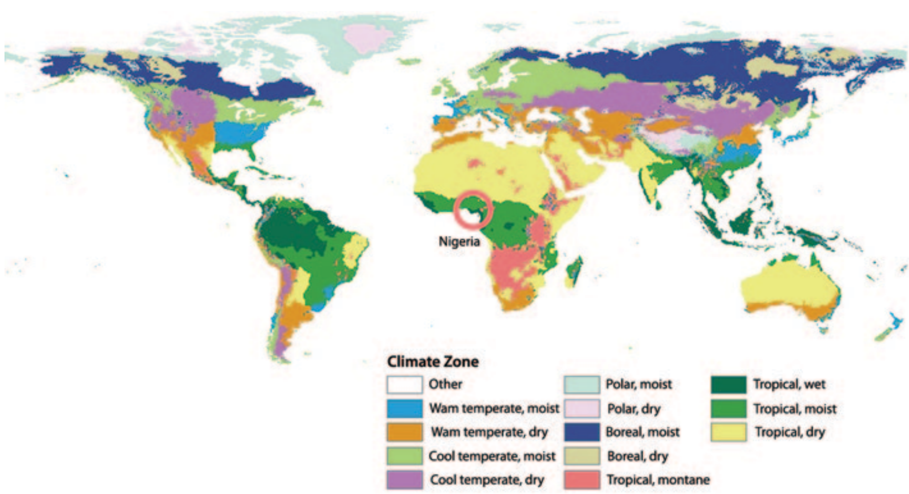
Differences in mitigation potential, however, are low (less than 3 percent). This is not considered significant compared to the uncertainty surrounding emissions factors for a single set of soil and climatic conditions (generally at least 30 percent). Therefore, the selection of soil and climate parameters is not considered to have significantly affected the results in terms of the sector mitigation potentials.

**Map E.1 Distribution of Spatially Dominant IPCC Soil Class for Africa**




*Source:* Batjes 2010.

**Map E.2 IPCC (2006) World Climatic Zones**




*Source:* Joint Research Center, European Soil Portal, http://eusoils.jrc.ec.europa.eu/projects/RenewableEnergy/.

**Table E.1 Discrepancy in GHG Emissions Depending on Climate and Soil Types**

*(Thereby case 1 stands for the climate and soil parameters of the main analysis presented in this study, while case 2–4 are variations as part of the sensitivity analysis)*

| *Case* | *Climate* | *Soil* |
|---|---|---|
| 1 | Tropical moist | LAC (low activity clay) |
| 2 | Tropical moist | HAC (high activity clay) |
| 3 | Tropical wet | HAC |
| 4 | Tropical wet | LAC |

| | *Reference scenario* | | *Low-carbon scenario A* | | *Low-carbon scenario B* | |
|---|---|---|---|---|---|---|
| *Case* | *GHG emissions for the whole 25 year-period in Mt $CO_2$e* | *Percent difference (relative to case 1)* | *GHG emissions for the whole 25 year-period in Mt $CO_2$e* | *Percent difference (relative to case 1)* | *GHG emissions for the whole 25 year-period in Mt $CO_2$e* | *Percent difference (relative to case 1)* |
| 1 | 2,663 | | 1,687 | | 2,017 | |
| 2 | 2,682 | 0.7 | 1,696 | 0.5 | 2,019 | 0.1 |
| 3 | 1,112 | –58.3 | 138 | –91.8 | 469 | –76.8 |
| 4 | 1,128 | –57.6 | 146 | –91.3 | 471 | –76.7 |

*Source:* World Bank data.

**Table E.2 Discrepancy in Mitigation Potential Depending on Climate and Soil Types**

| | *Scenario A* | | *Scenario B* | |
|---|---|---|---|---|
| *Case* | *GHG avoided for the whole 25 year-period in Mt $CO_2$e* | *Percent difference (relative to case 1)* | *GHG avoided for the whole 25 year-period in Mt $CO_2$e* | *Percent difference (relative to case 1)* |
| 1 | 976 | | 646 | |
| 2 | 986 | 1.07 | 662 | 2.5 |
| 3 | 973 | –0.3 | 643 | –0.5 |
| 4 | 982 | 0.6 | 657 | 1.8 |

*Source:* World Bank data.

## Note

1. Available at: http://web.worldbank.org/WBSITE/EXTERNAL/COUNTRIES/AFRICAEXT/NIGERIAEXTN/0,,menuPK:368922~pagePK:141132~piPK:141109~theSitePK:368896,00.html.

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PART 2

# Oil and Gas Sector

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# Abbreviations

| | |
|---|---|
| AEO | *Annual Energy Outlook* (U.S. Department of Energy) |
| AG | associated gas (gas produced in association with oil) |
| CCS | carbon capture and storage |
| $CH_4$ | methane |
| CNG | compressed natural gas |
| $CO_2$ | carbon dioxide |
| $CO_2e$ | carbon dioxide equivalent emissions |
| CPX | capital costs |
| DPR | Department for Petroleum Resources |
| EE | energy efficiency |
| EIA | Energy Information Agency |
| EOR | enhanced oil recovery |
| ESMAP | Energy Sector Management Assistance Program (World Bank) |
| EU | European Union |
| FGN | Federal Government of Nigeria |
| GDP | gross domestic product |
| GOR | gas-to-oil-ratio |
| GPF | gas processing facilities |
| GPP | gas processing plant |
| GTL | gas to liquid |
| GW | Gigawatt |
| GWP | global warming potential |
| IEA | International Energy Agency |
| IPCC | Intergovernmental Panel on Climate Change |
| IPP | independent power producer |
| JV | joint venture |
| kW | Kilowatt |
| LCOE | levelized cost of electricity |
| LNG | liquefied natural gas |

| | |
|---|---|
| mln bbl/d | million barrels per day |
| MMBtu | million British thermal units |
| MMSCFD | million standard cubic feet per day |
| Mt $CO_2$e | million metric tons of carbon dioxide equivalent emissions |
| MW | megawatt |
| MWh | megawatt-hour |
| NAG | nonassociated gas (gas not produced in association with oil) |
| NNPC | Nigerian National Petroleum Corporation |
| NPV | net present value |
| O&M | operations and maintenance |
| OPX | operating expenditures |
| PSC | production sharing contracts |
| PV | Photovoltaic |
| SCF | Standard cubic foot |
| T&D | transmission and distribution |
| TCF | trillion cubic feet |
| t $CO_2$e | ton of carbon dioxide equivalent |
| TVE | total venting emissions |
| UN | United Nations |
| UNDP | United Nations Development Programme |
| UNFCCC | United Nations Framework Convention on Climate Change |
| USD | United States dollars |
| WAGP | West Africa Gas Pipeline |
| WB | World Bank |

# Executive Summary

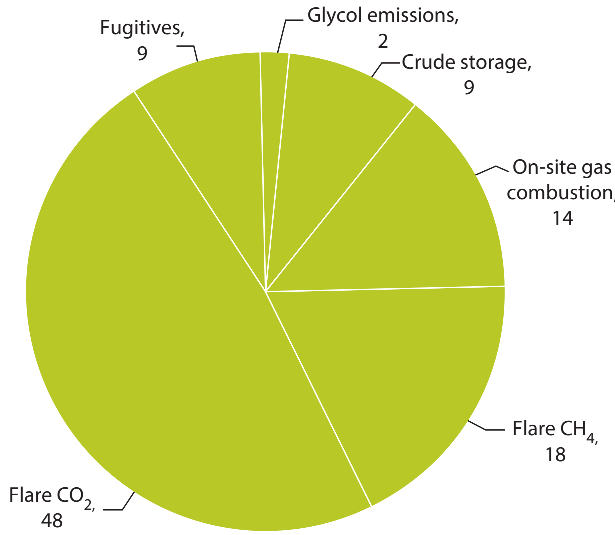
As part of the broader multisector analysis of low-carbon development opportunities in Nigeria, this part of the book evaluates how the country can continue to develop the oil and gas industry, making better use of Nigeria's gas resources, while at the same time reducing the sector's carbon footprint. The analysis consists in the development of a reference scenario for the upstream and midstream (liquefied natural gas, or LNG; and gas to liquid, or GTL) segments of Nigeria's oil and gas industry for the period 2009–35, based on past trends and the current plans of the Federal Government of Nigeria (FGN), including current plans to reduce flaring of associated gas (AG). In addition, an alternative low-carbon scenario is developed, which is also consistent with current production plans, but featuring accelerated reduction of flaring and other options to reduce carbon emissions.

The two scenarios—reference scenario and low-carbon scenario—produce the same volumes of oil and gas over the study period, but the low-carbon scenario does so through increased use of AG and less nonassociated gas (NAG). The low-carbon scenario reduces emissions by 750 $MtCO_2e$ (million metric tonnes of carbon dioxide equivalent emissions) or 34 percent of the reference emissions. The capital cost of implementing the emission reduction options included in the low-carbon scenario is estimated at US$17 billion; however, with the revenues from sale of the additional gas and associated liquid petroleum gas (LPG), it is estimated to generate a positive net present value (NPV) of $7.5 billion at a 10 percent real discount rate. Thus, the low-carbon scenario not only significantly reduces emissions but also generates higher economic returns from Nigeria's gas resources.

## Reference Scenario: More $CO_2$, Produced with Flat Emissions

The oil and gas sector has historically been one of the main sources of greenhouse gas (GHG) emissions in Nigeria. The estimated annual emissions in 2010 were approximately 90 $MtCO_2e$. The dominant emission source is gas flaring; other major sources are on-site combustion of gas, mainly for power generation to run the oil and gas production, transportation, and processing facilities; fugitive methane emissions through leaks; and venting from oil storage tanks (see figure ES 2.1).

**Figure ES 2.1 Oil and Gas GHG Emissions by Source, 2010**
*Percent*



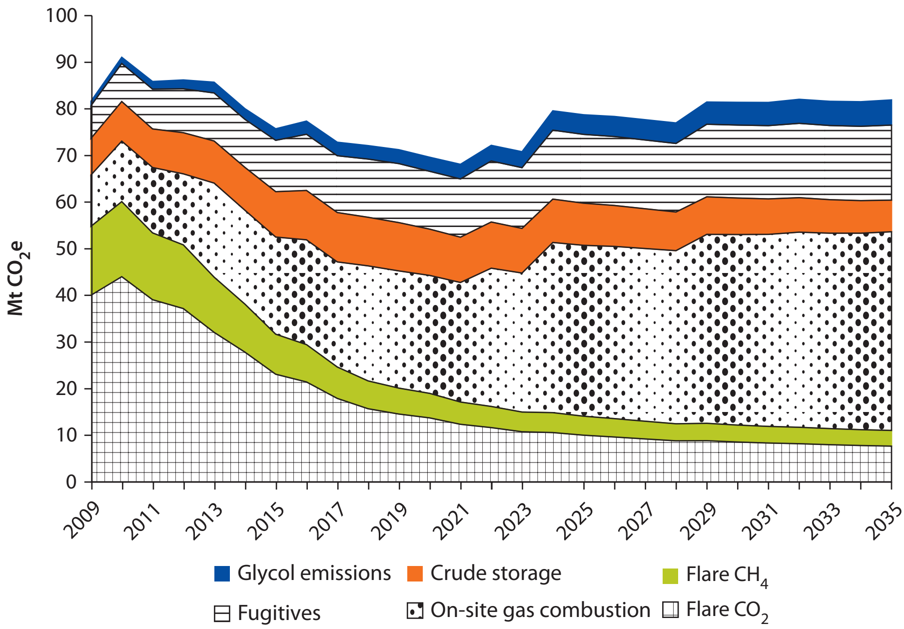

*Source:* World Bank data.

The reference scenario projects future production of oil and gas and associated emissions based on current trends and FGN plans, including existing plans for reduction of AG flaring. The assumptions were developed based on extensive interactions with, and feedback from, the Nigerian National Petroleum Corporation (NNPC) and oil industry representatives. Figure ES 2.2 illustrates the projected emissions over the study period for the reference scenario. Flaring (as share of total emissions) are projected to decline from over 35 percent to 5 percent over the period. Hence the emissions of carbon dioxide ($CO_2$) and methane ($CH_4$) from flaring are projected to decline substantially, despite increased oil production. On the other hand, emissions from other sources are projected to increase. Major drivers of this increase are the expected growth in on-site use of gas to fuel power generation and other processes, particularly in LNG and liquefied natural gas and plants, and increased gas production to meet domestic and export demand.

While flaring sources are clearly identified mitigation targets, and the 2010 *NNPC Annual Statistical Bulletin* gives an estimate of the current efficiency of on-site gas utilization for energy generation, no specific data are available on the fields and facilities in the Nigerian oil and gas industry. It is possible, therefore, that some emission mitigation options may have already been implemented, in which case the emission estimates in the reference case scenario and their reduction potential may be overstated.

Based on the production projections and assumptions described in the following chapters, emissions for the next 25 years from the oil and gas sector are expected to remain in the range 70–80 Mt $CO_2$e per year.

**Figure ES 2.2 GHG Emissions by Source for Reference Scenario**




*Source:* World Bank data.

## Low-Carbon Scenario: Gas Utilization Improved and Emissions Greatly Reduced

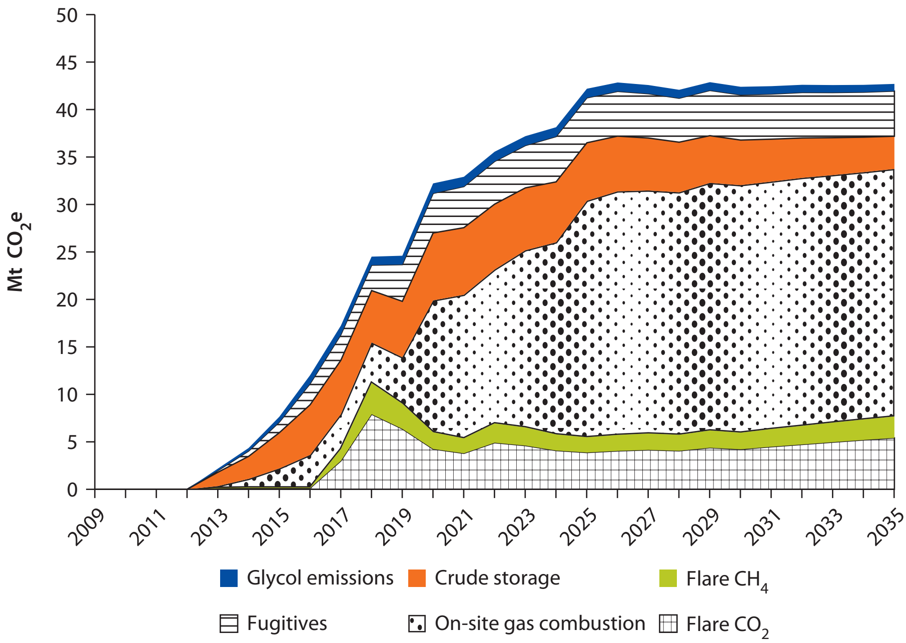
The study identified a large number of potential mitigation options for each part of the oil and gas production, transportation, and processing chain, with estimates of the costs (capital and operating) and emissions reductions through their implementation.

The low-carbon emissions projection is obtained considering selected low-carbon interventions from a larger range of candidate options, assuming an annual budget ceiling of $3 billion/year—or about 5 percent of projected net revenues from oil and gas production. Engineering capacity was also assumed to limit the number of "significant" low-carbon options that can be implemented annually—for example, limiting flare reduction projects to no more than 35 per year. The analysis shows that the early low-carbon options generate sufficient revenue to fund further low-carbon options after 2016.

Emissions are significantly reduced in the low-carbon scenario, as illustrated in figure ES 2.3, with better utilization of Nigeria's gas resources through reduced wastage of AG. The total potential abatement over the 2010–35 period is estimated to be 750 Mt $CO_2$e.

Early implementation of low-carbon options is very important, particularly those addressing flaring, as declining production reduces the economic

**Figure ES 2.3 Emission Reductions from Low-Carbon Options**




*Source:* World Bank data.

attractiveness of the low-carbon investments. Implementation of low-carbon options, for example, to improve energy efficiency or reduce fugitive emissions in fields where flaring is continuing, will have limited or no impact because the gas saved would then be flared. Therefore elimination of routine flaring should precede implementation of other low-carbon options.

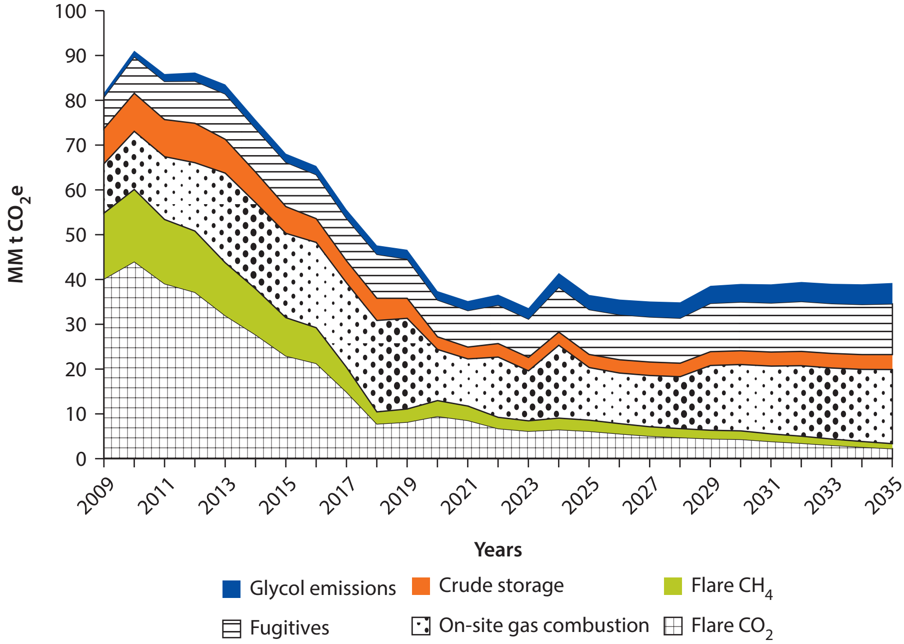
The resultant emission projection for the low-carbon scenario is illustrated in figure ES 2.4.

The emissions reductions attributed to reducing gas flaring in the low-carbon scenario are significant. However, it should be noted that the main flare reduction has already been included in the reference scenario. Without these reductions, reference scenario emissions would be significantly higher. Reduction in gas flaring is the single most effective activity to increase AG utilization and reduce emissions.

## A Low-Carbon Scenario Can Be Self-Financing

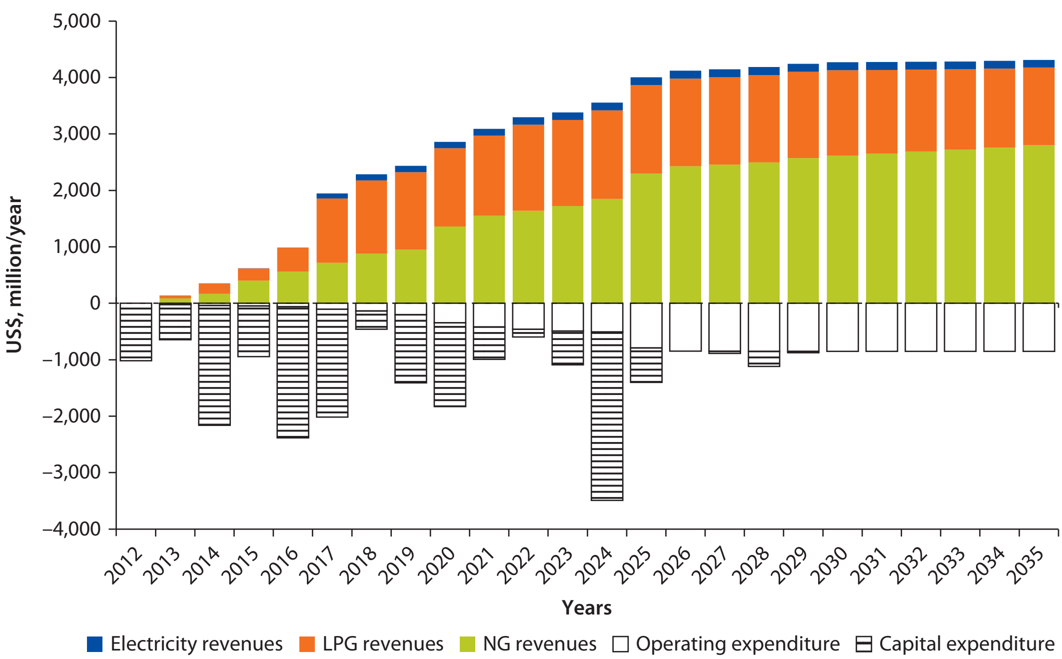
Figure ES 2.5 shows the costs and revenues for the low-carbon scenario. The largest capital costs occur in the early years. Revenues are dominated by gas sales, but significant contributions come from the sale of LPG. If these estimated LPG revenues cannot be fully realized, the marginal abatement costs (MAC) for most

**Figure ES 2.4 Low-Carbon Scenario: Oil and Gas $CO_2$e Emissions by Source**




*Source:* World Bank data.

**Figure ES 2.5 Revenues and Costs for Low-Carbon Scenario**




*Source:* World Bank data.

low-carbon options would be larger and the overall economic benefits of the low-carbon scenario would decrease.

As the graph shows, the early low-carbon options generate sufficient revenue to fund implementation of further low-carbon options after 2016.

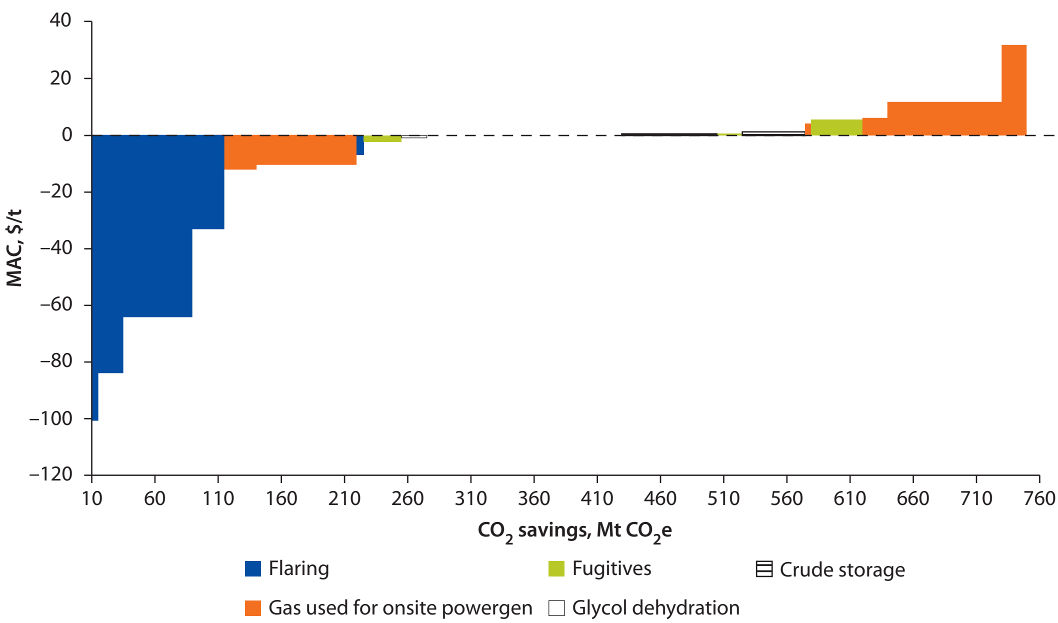
## MAC Demonstrates Benefits of Mitigation

The marginal abatement cost (MAC) of a low-carbon technology is the incremental cost per unit reduction in emissions. Figure ES 2.6 illustrates the MAC curves. Each vertical bar identifies a group of mitigation options. The bars are ordered from lowest MAC (lowest net cost per unit of emissions) to highest MAC, with the cumulative total emissions reduction in millions of tonnes (Mt) of $CO_2$e on the horizontal axis.

The study analyzed flare reduction options on a cluster basis. That is, combining gas supplies and sharing costs, as this is typically more economical than addressing individual flares. Flaring emissions are expected to incur significant penalties (not included in current calculations) following enactment of the proposed Petroleum Industry Bill, which would make the economics of flare reduction even more attractive. The net cost of implementing the low-carbon options also excludes the impact of any deferral of oil or gas sales that may occur due to the shutdown of the facilities/equipment to implement the options.

In the longer term, use of alternative low-carbon energy sources for on-site power generation would be attractive if this power can be produced at less than

**Figure ES 2.6 Marginal Abatement Cost (MAC) Curve for Classes Of Mitigation Options**




*Source:* World Bank data.

$60 per megawatt-hours. As well as reducing emissions, use of alternative sources for on-site energy frees up gas for sale, thereby reducing the need for investment in other sources of the gas to meet demand.

The study estimated that some 425 Mt $CO_2$e of emissions could be mitigated by implementing low-carbon options that have negative MAC values, that is, those that are economically attractive even in the absence of carbon credits. A real-term discount rate of 10 percent was used when calculating these MAC values, and it is recognized that this may be considered low when evaluating oil and gas investments. At a discount rate of 15 percent, it is estimated that some 275 Mt $CO_2$e can still be reduced, again in the absence of carbon credits.

## Recommendations for the Short Term

### *Policy Recommendations for the Federal Government of Nigeria*

- Consider setting up a joint government-industry group to develop a low-carbon strategy and action plan for the oil and gas industry.
- Ensure that NNPC's annual budget includes sufficient funding for implementation of at least the high-priority mitigation options.
- Consider implementing a fast-track budget approval process for mitigation options.
- For many emission estimates, the study relied on realistic assumptions regarding the oil and gas facilities in Nigeria and their condition. In order to develop better and more detailed emission estimates that can form the basis of a detailed plan for their mitigation, it is recommended that FGN promotes
  – Creation of a sectorwide inventory of emission sources, which in addition to information on current GHG emissions, should include the status of each source—for example, age, condition, emission reduction actions already taken, and identified potential emission reduction options.
  – Application of the facility-specific Tier 1 methodology to establish the current level of emissions. If Tier 1 is considered to be unrealistic to carry out in a reasonable timeframe, at least a Tier 2 estimate should be prepared. (Tier 1 and Tier 2 estimation methodologies are described in the American Petroleum Institute's *Compendium of Greenhouse Gas Emissions Estimation Methodologies for the Oil and Gas Industry*.)

## Recommendations for the Medium Term

### *Actions to be Taken by the Oil And Gas Industry (including NNPC)*

*Flaring*

- Address gas flaring reduction as the highest priority action, not only to reduce the direct emissions from the flaring but also to extract maximum benefit from delivering gas.
- Because of the high cost of installing gas gathering and processing facilities at small flare sites, consideration should be given to collecting the small volumes of AG in clusters for processing and export of the dry gas and LPGs.

*Energy efficiency*

- Consider replacement of older and/or smaller on-site power plants with new equipment.
- Consider use of variable-speed drives on pumps and compressors to improve efficiency.

*Other recommendations for reducing emissions*

- Where not already done, consider replacing fixed roof tanks with floating roof tanks with gathering systems for the liberated gas.
- Enhanced and directed inspection and maintenance programs have been very effective in reducing emissions in other oil and gas ventures. Consider gradually implementing such programs.
- Since some flaring will still occur, for example, for safety, consider improving combustion efficiency of remaining flares.

## Recommendations for the Long Term

A number of technologies that may become economically attractive in the longer term include alternative energy sources such as wave power to replace on-site gas/diesel combustion and carbon capture and storage (CCS). The cost trend for these technologies should be monitored and, when they appear to be viable, their potential for implementation in Nigeria should be considered.

CHAPTER 5

# Introduction

Nigeria ranks among the top 10 nations worldwide in oil and natural gas reserves with proven reserves of 37.2 billion barrels of oil and 186.9 trillion cubic feet (tcf) of gas, as of January 1, 2011 (BP 2011). Oil production started in Nigeria in the 1950s, reaching about 1 million barrels per day (mln bbl/d) by 1970, and since 1995 ranging between 2.0 and 2.5 million barrels per day (BP 2011).

Revenues from oil exports have grown from around $700 million in 1970 to $70 billion (more than 90 percent of Nigeria's foreign exchange receipts) in 2010 (CBN 2010). Oil exports have been supplemented since 2000 by gas exports in the form of liquefied natural gas (LNG) from the Bonny LNG facility. In 2010, oil and gas exports accounted for 96 percent of Nigeria's total exports. The oil and gas sector's share of Federal Government of Nigeria's (FGN's) fiscal revenues has also increased significantly from 26 percent in 1970 to over 80 percent in 2009 (Nigeria Vision 20: 2020; FGN 2010). However, the sector's share of gross domestic product (GDP) has declined over recent years to 17 percent in 2008, partly as a result of negative growth since 2005 combined with rapid growth in the nonoil and gas sectors (FGN 2010).

## Industry History

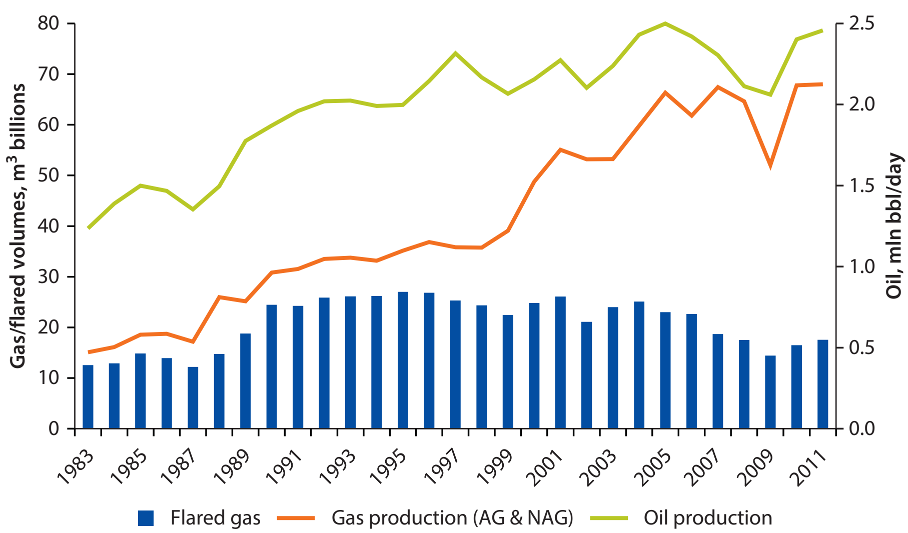
The oil and gas industry started onshore in Nigeria in the 1950s, with oil and gas acreage awarded in the form of licenses. Following its creation in 1977, the national oil company Nigeria National Petroleum Corporation (NNPC) acquired a nonincorporated interest in these licenses that became joint ventures (JVs); this interest now averages around 60 percent. A similar arrangement also holds for midstream assets, such as Bonny LNG facility, where NNPC has a 49 percent interest. While this investment structure ensures the State a significant direct interest in Nigeria's oil and gas industry, it also requires the NNPC (and hence the FGN) to fund up to 60 percent of all JV and Bonny LNG investments. As investment requirements have grown, this funding requirement has become increasingly onerous; in recent years, there was a shortfall in the funding of NNPC's share of investments.

As attention moved to the shallow offshore in the 1970s, a number of JVs with an NNPC interest continued to be awarded; however, as activity moved into deeper water with increasingly expensive exploration and development costs, new acreage was awarded in the form of production sharing contracts (PSCs). In these PSCs, all investments are made by private industry in return for a sufficient share of the subsequent oil and gas revenues to recover these costs, with the remaining revenues shared between private industry and the government. The state retains ownership of the oil and gas; the PSC merely entitles private industry to develop the resources and share in the revenues. This PSC arrangement therefore relieves the FGN of any funding requirement while retaining ownership.

A restructuring of the industry is proposed in new legislation presently being drafted, the Petroleum Industry Bill. While details of the current version of this bill are not available, the scope of the bill is expected to be very broad, ranging from restructuring of the JV arrangements to revision of fiscal terms; it is also expected to include penalties for gas flaring. These potential changes will significantly affect the rights and obligations of the private industry. Passage of the bill was awaited for a number of years, which perhaps has had an adverse impact on investment, with private industry being reluctant to invest until the new terms and conditions are clear.

In terms of emission reduction, while commitment of new investments for AG utilization may have slowed, ongoing construction and start-up of AG gathering facilities, as well as an increase in own-use of gas, for example, for reinjection, continues to reduce gas flaring even as oil and gas production has increased (figure 5.1).

**Figure 5.1 Historical Oil and Gas Production and Flared Gas Volumes**




*Source:* NNPC 2010–12; BP 2010.
*Note:* AG = associated gas; NAG = non-associated gas.

## Study Objectives and Methodology

The objectives of the study were to identify sources of carbon emissions in Nigeria's oil and gas sector, to identify and calculate the cost of options to reduce these emissions (the low-carbon options), and to rank them in terms of net cost of carbon emission reduction using marginal abatement costs (MACs).

The methodology used to estimate the reference scenario emissions was based on emission factors provided for specific sector operations in the American Petroleum Institute's *Compendium of Greenhouse Gas Emissions Estimation Methodologies for the Oil and Gas Industry* (API 2009). The specific relationships and equations used to estimate the emissions are detailed in the appendix.

The study team used a bottom-up approach to analyze low-carbon mitigation options. The potential mitigation options for the over 200 existing oil and gas fields in Nigeria were assessed, taking account of their size, location, and maturity. As the production forecasts will require development of new fields over the evaluation period (2010–35), the team also made assessments for them, assuming their size and location distribution is similar to the existing fields. The analyses include evaluation of emission reductions achievable and their costs, as well as construction of marginal abatement cost curves for the mitigation options.

However, the study team encountered a lack of information regarding the current status of the infrastructure in the sector—for example, the extent to which on-site power generation facilities may have already been upgraded to low-carbon efficient units and whether compressor seal replacements and other actions to reduce fugitive emissions may have already been implemented. This lack of information introduces a level of uncertainty in the baseline conditions against which low-carbon options can be assessed, as well as in the emission estimates in the reference and low-carbon scenarios.

## Study Sources and Assumptions

The study builds on a wide variety of existing literature and planning reports. Wherever possible, it is based on information and assumptions from key documents developed by FGN such as the *Vision 20: 2020 Report* (FGN 2010) and the *Roadmap for Power Sector Reform* (FGN 2010) in building the draft reference scenario. The other sources for the data on which projections were built for this sector are listed below and referenced throughout this book.

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**CHAPTER 6**

# Production of Oil and Natural Gas

To project a realistic scenario for oil and natural gas production over the study period (2009–35), the team first reviewed a production projection in NNPC's "Growth Projections in Nigeria's Oil and Gas Sector" (NNPC 2011). In this projection, after increasing, the oil and condensate production will then decline from a plateau of just over 3 million barrels per day (mln bbl/day) in 2020 to under 0.9 mln bbl/day by 2035. The oil and condensate production forecasts in the NNPC projection are the dashed lines in figure 6.1.

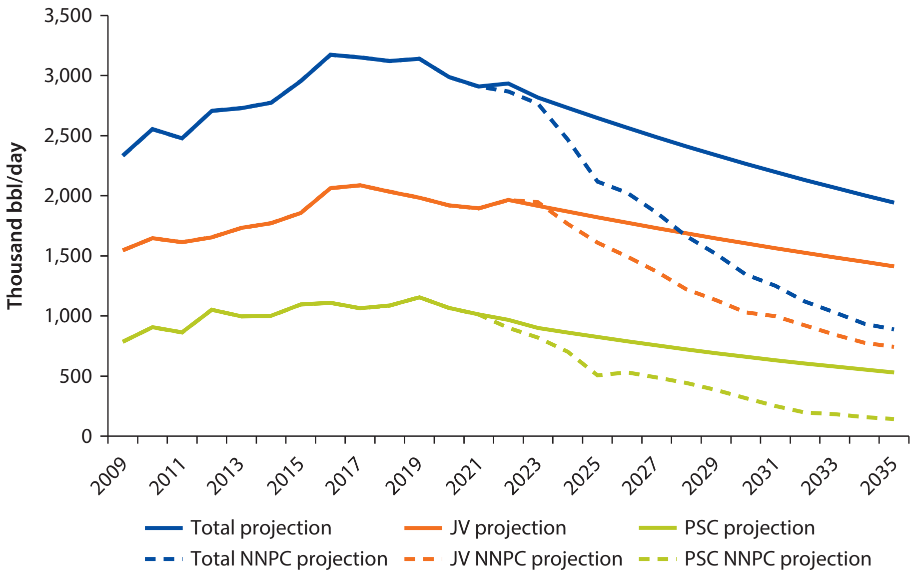
The NNPC projection was based on an assumption of constrained investment in the oil and gas sector post-2020. However, Nigeria has more than sufficient proven oil and condensate reserves to sustain a higher level of production, and it seems unlikely that the FGN would allow the decline projected in the NNPC data to take place for an essential source of revenue. Therefore, following discussions with stakeholders, the study team developed a modified projection where oil and condensate production after 2020 declines less quickly than in the NNPC projection. This projection takes account of the following data provided by NNPC:

- Proven oil and condensate reserves at end-2009 were 37 bln bbls.
- The decline in "base oil and condensate production" post-2010 for JV and PSC fields combined is close to 25 percent a year. This is interpreted to be the decline in total production when there is no investment.
- The decline in total oil and condensate production post-2022 in the NNPC projection is approximately 9 percent. This decline is a combination of decline in PSC production post-2022 of approximately 13 percent and decline in JV production post-2022 of approximately 7.5 percent. From the accompanying investment profile, these declines occur when there is limited investment.

Based on these statistics, the *modified production projection* assumes the following:

- The NNPC projection of oil and condensate production is valid for 2009–22.

**Figure 6.1 Projected Oil and Condensate Production, Original NNPC vs. Modified Projections**




*Source:* NNPC 2011.

- After 2022, total oil and condensate production declines at an annual rate of 3 percent (that is at one-third the rate of decline in the NNPC projection). This decline rate is a weighted average of
  - A decline in PSC oil and gas production at an annual rate of 4.33 percent and
  - A decline in JV oil and gas production at an annual rate of 2.5 percent.

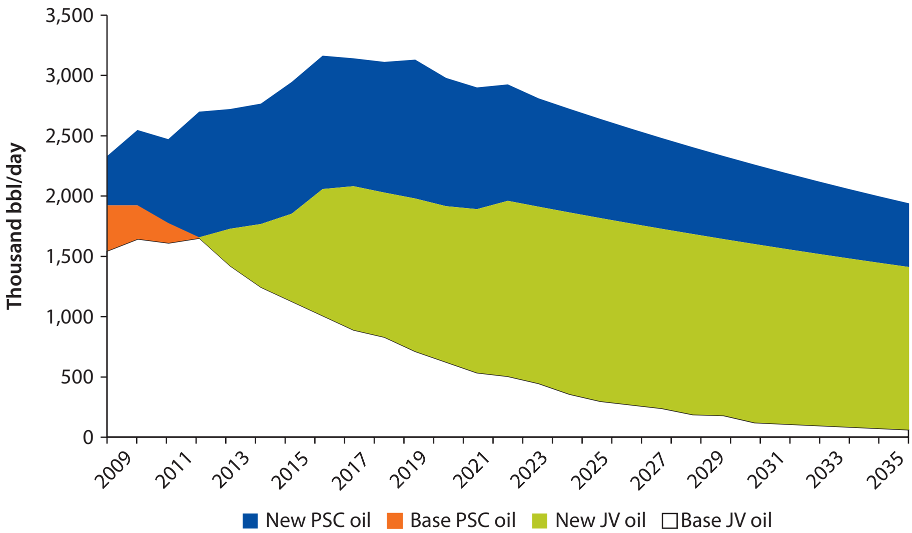
This projection results in production of 24.9 bln bbl of oil and condensate over the period 2009–35. This is well below the end-2009 proven reserves of 37 bln bbls.

The resulting modified production projections, shown as the solid lines in figure 6.1, are used as the basis for the GHG emission estimates.

The analysis in this volume divides oil and condensate production into four categories: Old and new JV fields, and old and new PSC fields. The separation of oil fields into old (producing before 2009) and new (starting production after 2009) allows the higher cost of implementing the low-carbon options in existing fields, which require retrofitting, to be properly addressed. Identifying PSC and JV fields separately allows the significantly lower flaring rate in PSC fields than JV fields, as advised by Nigeria's Department of Petroleum Resources (DPR 2011) and observed from satellite data, to be respected.

The resulting production profiles used for this analysis are presented in figure 6.2.

**Figure 6.2 Projected Oil and Condensate Production, Old (pre-2009) vs. New Fields**




*Source:* NNPC 2011 and this study.

## Gas Production and Gas Demand

Total gas production in Nigeria is a combination of the associated gas (AG) produced with the oil and nonassociated gas (NAG).

### *Associated Gas Production Projection*

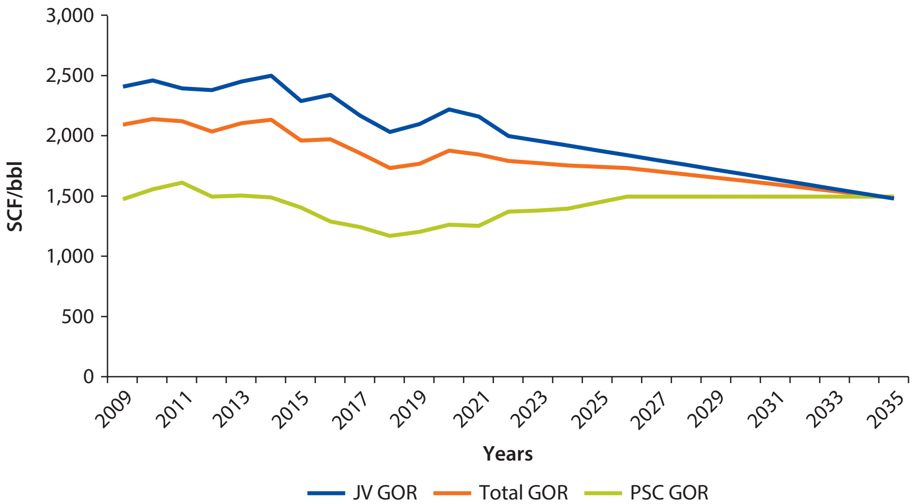
The AG production used for the period 2009–22 is from the projection provided by NNPC (NNPC 2011). However, this number declines unrealistically after 2022, so an AG production projection was derived from the modified production projection for oil and condensate using a gas-to-oil ratio (GOR) projection provided by NNPC, modified somewhat post-2022 to reflect the increased production in the modified oil and condensate production projection (figure 6.3). The resulting AG production projection is presented in figure 6.4.

### *Nonassociated Gas Production Projection*

The NAG production projection provided by NNPC (NNPC. "Growth Projections in Nigeria's Oil and Gas Sector") declines after 2020 and, together with the above AG projection, will be insufficient to meet projected demand for power generation, supply to liquefied natural gas (LNG) and gas to liquid (GTL) plants and to industrial users, and to the West Africa Gas Pipeline (see Section "Gas Supply/Demand Balance"). Therefore, additional NAG will be needed, as shown in figure 6.5. This will require development of new NAG fields before the year 2020 to meet the demand for natural gas for both the domestic and export markets.

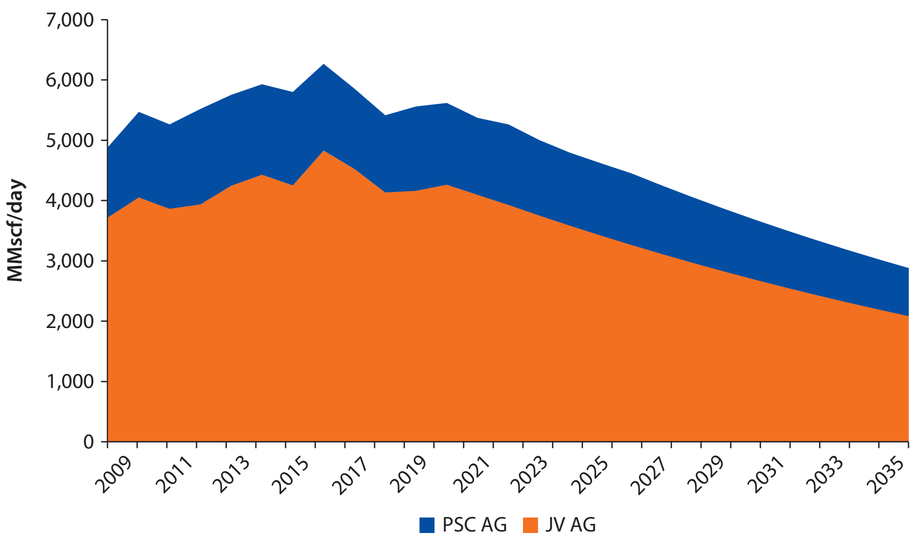
The resulting total gas production, and its build-up of AG/NAG components, is illustrated in figure 6.6. These projections were used in the analysis to estimate GHG emissions.

**Figure 6.3 Gas-to-Oil Ratio Projections**




*Source:* NNPC 2011 and this study.

**Figure 6.4 Associated Gas (AG) Production**



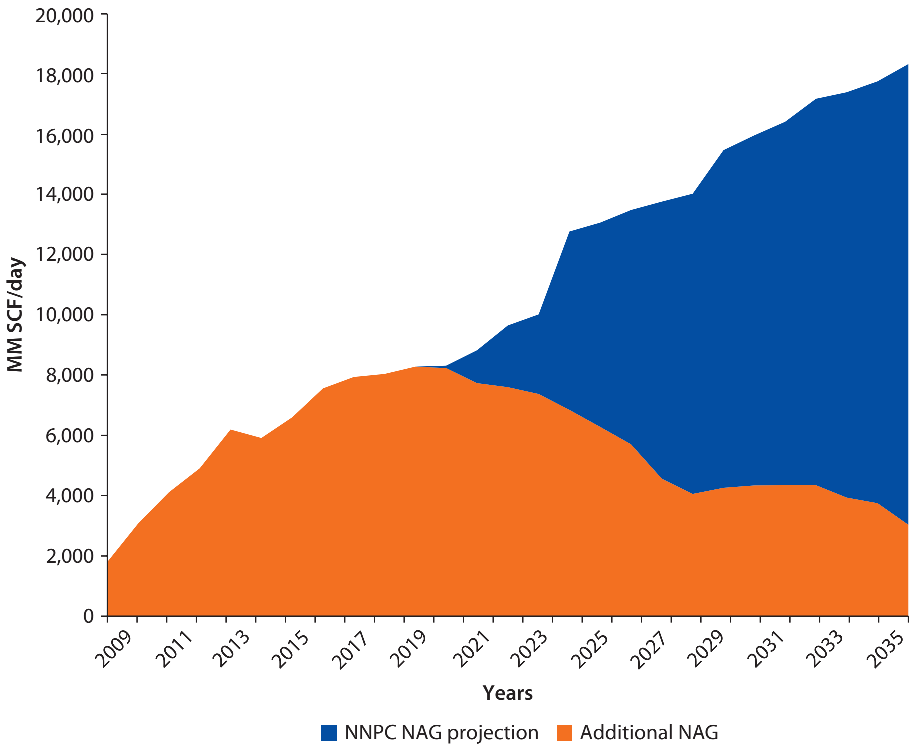

*Source:* NNPC 2011 and this study.

## Gas Demand

In order to develop a gas balance, a gas demand projection was developed using the following statistical assumptions and projections.

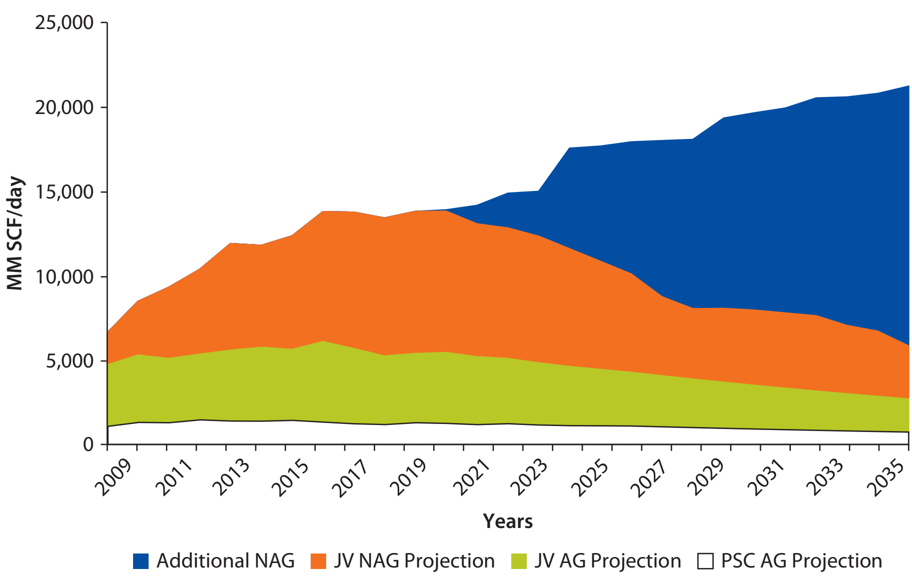
**On-site use.** In the absence of other data, on-site use of gas for power generation, reinjection, and so on, was assumed to mirror current own-use (NNPC

**Figure 6.5 Nonassociated Gas Production**




*Source:* NNPC 2011 and this study.

**Figure 6.6 Projection of Total Gas Production**




*Source:* NNPC 2011 and this study.

Annual and Monthly Statistical Bulletins) throughout the study period, adjusted to take account of the changes in production levels over time.

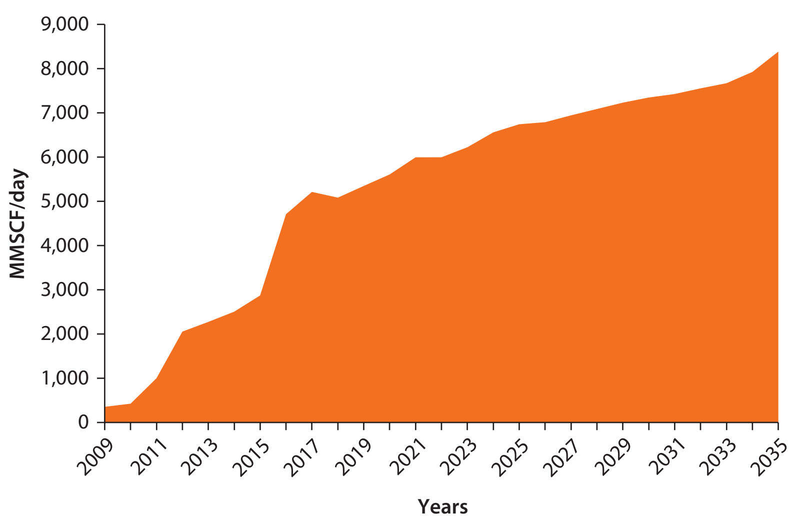
**Flaring.** Flaring is assumed to reduce steadily over time. However, the assumptions for the two oil and gas production regimes—JVs and PSCs—are different. In JV fields, flaring is projected to decrease over the study period, from the current 37 percent of AG production (Department of Petroleum Resources, "Gas Flare-down updates) to 5 percent by 2035. This reflects the high level of legacy flaring in these older fields. PSC fields, having been developed relatively recently, are assumed to have had gas-gathering infrastructure incorporated in their design, therefore are currently flaring only 5 percent of the AG.

**Power generation.** Nigeria's gas-fired power generating capacity is projected to increase rapidly; the rate of increase was taken from the reference case in Part 3, Power Sector, developed for this low-carbon report. The gas demand is based on the assumptions made in the Power Sector reference case on the number of open-cycle and combined-cycle plants. The gas demand for power generation is illustrated in figure 6.7.

**Liquefied natural gas.** Liquefied natural gas (LNG) exports are asssumed to grow both through addition of more trains at Nigeria LNG Limited and through Brass and OK plants coming on stream. The timing of the LNG export increases is taken from a recent global LNG report (Wood Mackenzie 2011). Gas requirements assume 9 percent of the into-plant gas is required for on-site power generation, among other uses. The resultant demand forecast is illustrated in figure 6.8.

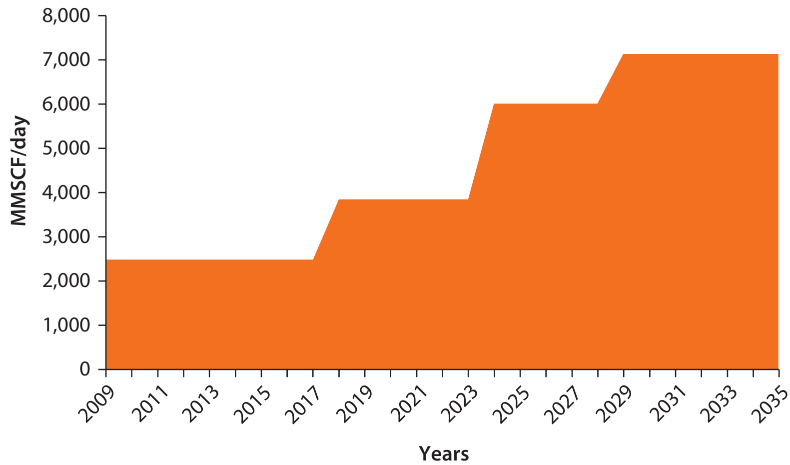
**Industrial use.** In the absence of other data, the volume of gas for industrial use was assumed to increase at approximately 10 percent a year. The resultant demand forecast is illustrated in figure 6.9.

**Figure 6.7 Gas Demand for Power Generation**



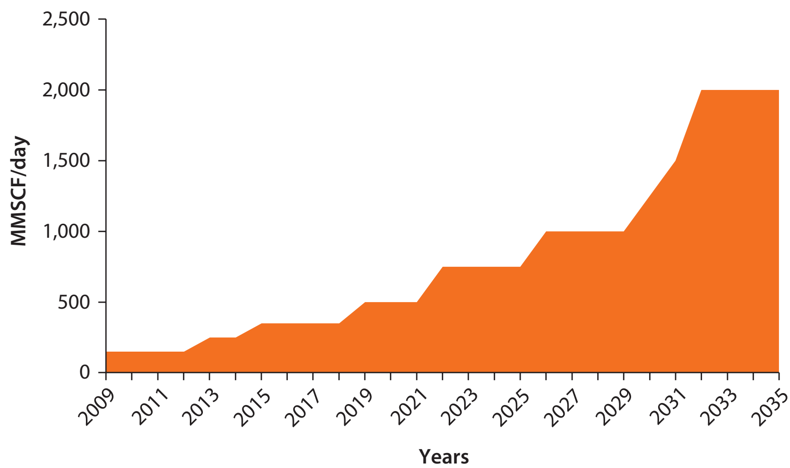

*Source:* Calculations based on data sources listed in chapter 5 and in Part 3, Power Sector, in this volume.

**Figure 6.8 LNG Gas Demand**




*Source:* Wood Mackenzie 2011.

**Figure 6.9 Industrial Sector Gas Demand**

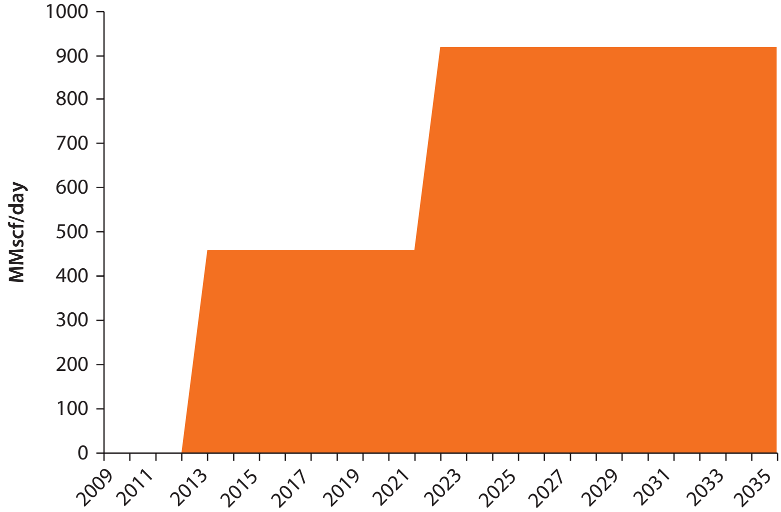



*Source:* Wood Mackenzie 2011.

**Gas-to-liquid plants.** The Escravos Gas–to–Liquids (GTL) plant is assumed to come on stream in 2013 with a capacity of 34 kbbl/day. A second plant (or expansion) of the same size is assumed to come on stream in 2022. Gas requirement assumes 35 percent of the into-plant gas is the volume assumed to be used for on-site power generation and other uses. The resultant demand forecast is illustrated in figure 6.10.

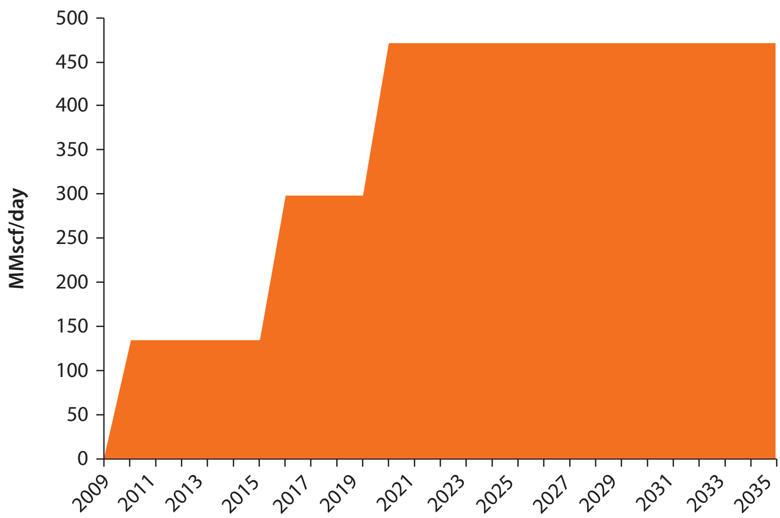
**West Africa Gas Pipeline (WAGP).** The WAGP started exporting gas in 2010. Volumes are assumed to gradually reach by 2020 474 million cubic standard feet per day, the current capacity of the line. The resultant demand forecast is illustrated in figure 6.11.

**Figure 6.10 GTL Gas Demand**




*Source:* Wood Mackenzie 2011.

**Figure 6.11 WAGP Gas Demand**

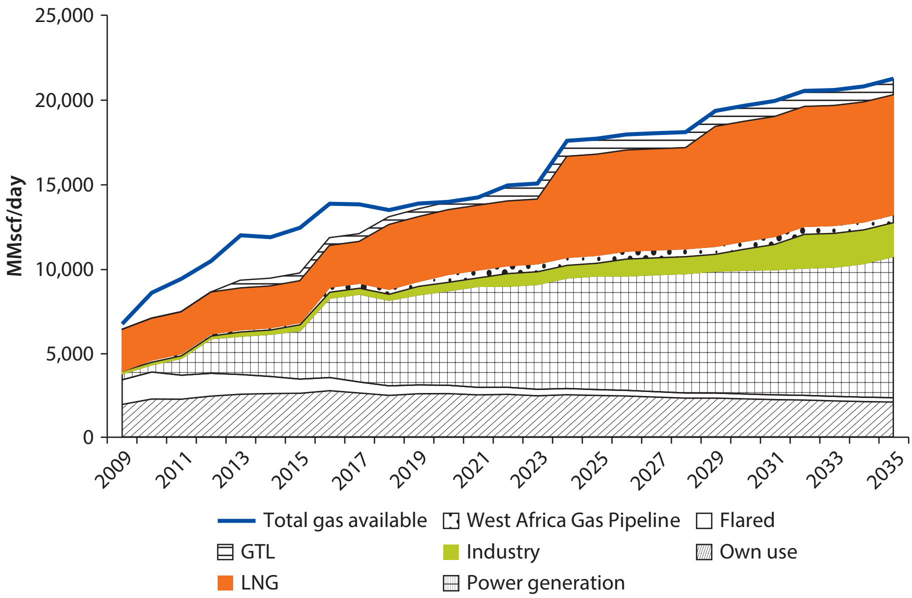



*Source:* Wood Mackenzie 2011.

## Gas Supply/Demand Balance

Total demand for natural gas from the individual demand elements is shown in figure 6.12. Also shown is the projected gas supply availability. As the figure shows, the estimated supply and demand projections suggest that there will be an excess of gas supply available before approximately 2020. Thereafter, as NAG

**Figure 6.12 Gas Supply and Demand by Type**




*Source:* This volume, Part 3, Power Sector; Wood Mackenzie 2011; NNPC 2011.

production is assumed to increase as required to meet demand, supply and demand are in balance.

## References

DPR (Department of Petroleum Resources). 2011. "Gas Flare-Down Updates: DPR Perspective." Oil and Gas Sector LC Workshop, Abuja, Nigeria, June 14.

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CHAPTER 7

# Emissions Sources

Greenhouse gases (GHG) emissions from oil and natural gas systems comprise primarily carbon dioxide ($CO_2$) and methane ($CH_4$). For methane a Global Warming Potential (GWP) of 25, as currently advocated by the United Nations Framework Convention on Climate Change (UNFCCC), was used to calculate the emission equivalents of carbon dioxide.

## Major Emission Sources

### *Combustion of Fuels*

In oil and gas production, processing, and transportation, fuel is combusted to generate the energy needed, for example, to power drilling equipment and to supply energy to separation processes. Significant volumes of fuel (primarily gas) are also used in liquefied natural gas (LNG) and gas to liquid (GTL) plants to generate the energy required to run the processes. For emissions from on-site fuel combustion, complete combustion—that is, 100 percent of the fuel combusts to $CO_2$—was assumed.

### *Flaring of Gas*

Gas is flared in oil and gas operations for a variety of reasons. Routine flaring of AG is a means of disposal when there is lack of markets for the gas, while intermittent flaring takes place as a result of process upsets or unsafe situations. Flaring takes place in most segments of Nigeria's oil and gas industry, including oil and gas production facilities, gas processing facilities, LNG and GTL plants, and refineries.

During flaring, emissions of $CO_2$ are formed as products of combustion, with $CH_4$ emissions occurring as a result of the incomplete combustion. The effectiveness of combustion in a flare is called "flare efficiency." Under ideal conditions, flare efficiency can be as high as 98 percent. In practice, flare performance can be highly variable because it depends on flame stability, which in turn depends on the gas velocity and energy content, flare stack diameter, and wind conditions (Johnson et al. 2002). With no data available on flare efficiencies in Nigeria—and with doubt that flares operate at maximum efficiency in Nigerian conditions—the study team assumed a flare efficiency of 94 percent for an average flare for the purposes of this analysis.

### *Venting of Gas*

Venting of gas is an important source of GHG emissions, since the methane ($CH_4$) content of the gas has a GWP of 25. Venting sources considered significant, and addressed in this book include the following:

- Glycol dehydrator facilities that are used to remove water from produced gas (both associated gas [AG] and nonassociated gas [NAG]) at the fields, at gas processing facilities, and along the gas transmission system. Methane emissions occur from glycol dehydration because a small amount of $CH_4$ absorbed by the glycol is driven off into the atmosphere during glycol regeneration
- Electric and gas-assisted pumps commonly used to circulate glycol in the dehydrator systems
- Crude oil storage tanks used to store the oil following oil gas separation in the refinery. After separation, the oil remains in storage tanks until shipped from the facility; however, its pressure is slightly above atmospheric pressure when it enters the tank, so gas is liberated as the pressure reduces to atmospheric pressure. This gas is vented into the atmosphere unless the tanks are fitted with vapor recovery units to capture it.

### *Fugitive Emissions*

Fugitive emissions are emissions from equipment leaks, where any pressurized equipment has the potential to leak. These leaks generally occur through valves, flanges, seals, or related equipment. Fugitive emissions also include nonpoint evaporative sources such as wastewater treatment, pits, and impoundments. A facility-level approach as described in Section 6.5 of the *API Compendium* (API 2009) was used to estimate fugitive emissions in this book. Applying average facility-level emission factors is the only method that can be used when no equipment-specific information is available, but it is also the least accurate.

### *Other Emission Sources*

Other emission sources are considered relatively insignificant and are not included in the emissions inventory in this work. These include $CH_4$ emissions from standing and working losses in oil tanks; $CH_4$ emissions from cold venting; $CH_4$ emissions from produced water, $CO_2$ and $CH_4$ emissions from maintenance and facility turnaround activities; and $CH_4$ and $CO_2$ emissions from exploratory drillings and well testing.

While flaring sources are clearly identified mitigation targets, and an estimate of the current efficiency of on-site gas utilization for energy generation was obtained from the 2010 *NNPC Annual Statistical Bulletin*, no specific data are available on the fields and facilities in the Nigerian oil and gas industry. It is possible, therefore, that some of the emission mitigation options identified in this book may have already been implemented. If this is the case, the reference scenario emission estimates and the potential for their reduction, may both have been overstated.

## Estimation of GHG Emissions

As stated in the *API Compendium* (API 2009), the purpose of the GHG analysis and the availability of data will generally determine the level of detail and the estimation approach selected. For many calculations carried out as part of this study, including estimated emissions from glycol pumps, crude storage, transmission systems fugitives, the lowest tier methodology was adopted using general emission factor data from the *API Compendium* coupled with the projections for oil and natural gas production. This approach was dictated by the limited data available on facilities, transmission infrastructure, and so on.

### *Use of Emission Factors*

GHG emissions for the reference scenario have been calculated by applying emission factors as follows:

$$E_{GHG} = AC * EF * GWP_{GHG}$$

where:

$E_{GHG}$ = emissions of GHG (where the GHG can be $CO_2$, $CH_4$ in $tCO_2e$)

AC = a measure of the activity that is resulting in GHG emissions (for example, MMSCF of wet natural gas through a glycol dehydrator)

EF = emission factor (for example, $tCO_2e$/MMSCF of gas processed)

$GWP_{GHG}$ = Global warming potential of the GHG gas under consideration (1 for $CO_2$, 25 for $CH_4$).

An emission factor (EF) is defined as the average emission rate of a given GHG for a given source, per unit of activity. The activity selected for each emission type/source is one that was considered an appropriate scaling factor when the general emission factors were derived. The typical activities used are throughput volumes. The general emission factor approach was used for most industry segments; significant exceptions are fuel combustion emissions and flaring where combustion calculations have been employed.

### *Data Requirements*

#### *Oil and condensate and gas production data*

The projections of oil and condensate, AG and NAG production in the “modified production scenario,” derived as described earlier, have been used.

**Table 7.1 Assumptions of Average Percentage of AG Flared in JV and PSC Fields**

| *Years/% flared* | *2009* | *2010* | *2011* | *2012* | *2015* | *2020* | *2025* | *2030* | *2035* |
|---|---|---|---|---|---|---|---|---|---|
| JV fields | 37 | 37 | 34 | 31 | 24 | 16 | 11 | 7 | 5 |
| PSC fields | 5 | 5 | 5 | 5 | 5 | 5 | 5 | 5 | 5 |

*Source:* Calculations based on data sources listed in chapter 5.
*Note:* JV = joint venture; PSC = production sharing contracts.

**Table 7.2 Key Input Parameters, Assumptions**

| *Parameter* | *Value utilized* | *Comment on the basis of the value* |
|---|---|---|
| Specific fuel consumption of energy during crude oil production fields | 121.10 MJ/barrels of crude oil produced | Data on crude oil and AG production and fuel utilization at JV and PSC fields available in NNPC 2009 and 2010 were used in the estimation of this specific fuel utilization; 99.9% of the fuel combusted at the field is natural gas with the balance assumed to be diesel. |
| Specific fuel consumption of energy during NAG production | 0.0571 MJ/SCF of NAG produced | Data obtained from discussions with an expert on Nigerian oil and gas; 99.9% of the fuel combusted at the field is natural gas with the balance assumed to be diesel. |
| Percent of JV crude oil tanks with vapor recovery units | 50 | No specific data available |
| Percent of PSC crude oil tanks with vapor recovery units | 75 | No specific data available |

*Source:* Calculations based on data sources listed in chapter 5.
*Note:* AG = associated gas; JV = joint venture; PSC = production sharing contracts; NNPC = Nigerian National Petroleum Corporation; NAG = nonassociated gas; SCF = Standard cubic foot.

### *Model parameter/assumptions*

Tables 7.1 and 7.2 show key assumptions and data used in developing the reference scenario GHG emission forecast.

The assumptions for the reduction in gas flaring for the joint venture (JV) and production sharing contracts (PSC) fields are presented in table 7.1. The percentage of AG flared in 2009 and 2010 are from the *NNPC Annual Statistical Bulletins* (NNPC 2010) and information provided by DPR (2011). It was assumed that gas flaring in JV oil fields will gradually decline to 5 percent of the AG produced. Based on experience of other countries (for example, Canada), 5 percent is considered to be the lowest achievable level, taking account of safety and other reasons for nonroutine flaring.

Gas flaring at PSC oil fields was assumed to be 5 percent throughout the study period. The PSC fields were relatively recently developed so lack the flaring legacy of the JV fields, thus it is assumed for the PSC fields that developments conform to the regulation recently implemented in Nigeria that requires minimization of gas flaring.

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# Reference Scenario

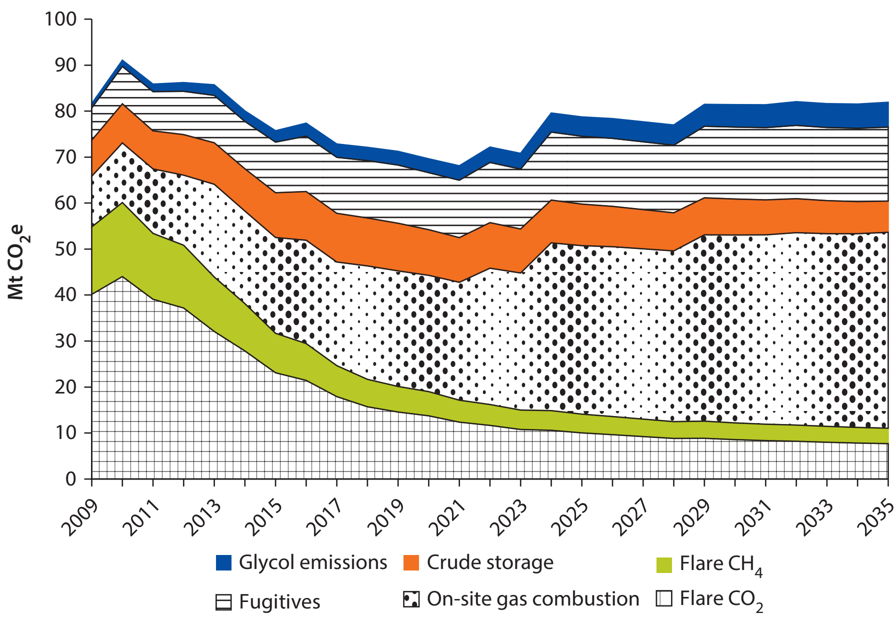
The appendix provides details of the equations and emissions factors used in conjunction with the oil and gas projections, to estimate greenhouse gases (GHG) emissions for the reference scenario.

## Results of the GHG Emissions Forecast for the Reference Scenario

GHG emission forecasts by activity source are presented in figure 8.1.

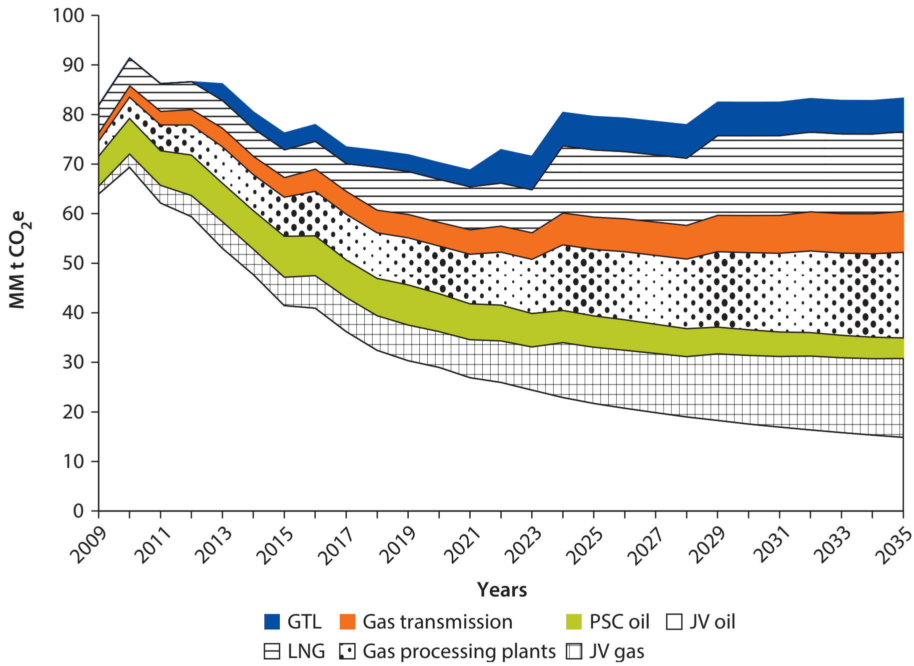
As can be seen, emissions are initially dominated by flaring. This is projected to decrease over the study period from the current 37 percent of AG production

**Figure 8.1 Reference Scenario: Oil and Gas GHG Emissions by Source**




*Source:* Calculations based on data sources listed in chapter 5.

**Figure 8.2 Reference Scenario: Oil and Gas GHG Emissions by Subsector**




*Source:* Calculations based on data sources listed in chapter 5.

to 5 percent by 2035. However, emissions from all other sources are forecast to increase. Major drivers of this increase are the expected increase in on-site use of gas to fuel power generation and other processes, particularly in liquefied natural gas (LNG) and gas-to-liquid (GTL) plants, as well as increases in gas production to meet domestic/export demand.

Figure 8.2 shows that the bulk of the current emissions are in the joint venture (JV) oil fields, reflecting their age and the high level of legacy flaring in these fields. The JV fields, being predominantly onshore, also potentially represent locations where low-carbon options can be more easily be implemented, and at lower cost, than in the offshore production sharing contracts (PSC) fields.

CHAPTER 9

# Low-Carbon Scenario

More than 30 potential carbon mitigation options have been identified by the study team. The study team estimated for each option: capital and operating costs, emission reductions, volumes of gas saved for utilization, and the revenues generated by this utilization. To establish a potential low-carbon emission profile, a phased implementation of the mitigation options was developed assuming annual constraints with respect to available funding and engineering capacity.

## Data and Assumptions

The analysis addressed approximately 200 existing oil and gas fields[1]; 40 main pipeline segments; gas processing, liquefied natural gas (LNG) and gas to liquid (GTL) plants; and compressor stations. Data on gas volumes produced, flared, and processed were taken from the 2010 NNPC Annual Statistical Bulletin (NNPC 2010) and the "modified production forecast" developed in this study. The Nigerian National Petroleum Corporation (NNPC) report also includes fuel use at the fields, which enabled study team to estimate the 2010 emissions at the fields; for the projection, this estimate of fuel use was scaled based on oil/gas production levels.

As well as the existing fields and related infrastructure, development of an additional 200 fields was assumed to be required to maintain oil and gas production over the 2010–35 period. Mitigation options for these fields were developed as for the existing fields.

### *Capital Costs*

The capital costs for mitigation options are based on available U.S. data, supplemented by estimates from first principles, using proprietary models[2] from Energy Redefined Ltd., or from discussions with individual vendors. These U.S.-based costs have been modified to take account of the following:

- Cost of importing oilfield equipment into Nigeria, including import taxes
- Cost of labor in the Nigerian oil and gas market
- Higher cost of laying pipelines and associated work in swamp or other difficult conditions

- Offshore vs. onshore cost differences, where applicable
- Security issues (for example, security fencing, electronic monitoring, security staff).

The resulting capital cost estimates are some 1.25–2 times higher than the equivalent U.S. costs, depending on the option type and specific field conditions and location.

These capital cost estimates assume the mitigation options are implemented in existing facilities, that is, retrofitted and therefore apply to "old" fields (those producing before 2009) and facilities. Retrofitting carbon mitigation options is more expensive than implementing during initial construction. Based on international experience, for "new" fields and facilities (2009 and after) it is assumed that the capital costs would be 30 percent lower.

### *Product Prices*

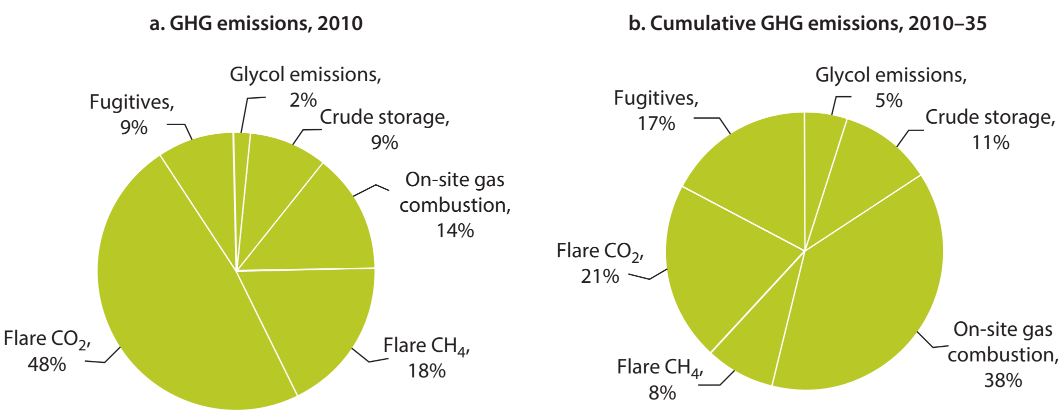
Bulk and residential electricity prices were obtained from current publications from Nigerian ministries of Energy and Power. Prices for export products have been estimated from current European prices (EU 2011).[3] The price for small-volume liquefied petroleum gas (LPG) sales to local markets was assumed to be discounted from the international price to reflect the lower product quality resulting from the low-cost extraction process assumed.

## Carbon Mitigation Options

The main emissions from oil and gas operations are estimated in the reference scenario to come from gas flaring, gas burnt used for power generation and compression, fugitive emissions, and venting from oil storage tanks (figure 9.1).

A number of mitigation or low-carbon options are available to reduce these emissions, some costly and others relatively inexpensive. This section describes the impact of around 30 different mitigation options on the emissions from upstream

**Figure 9.1 GHG Emissions by Source for Oil and Gas Sector**




*Source:* Calculations based on data sources listed in chapter 5.

and midstream[4] oil and gas field operations. Flaring in 2010 generated 66 percent of the carbon emissions in the Nigerian oil and gas sector; the second largest emitter, on-site combustion, contributed 15 percent. However, over the entire study period, with the expected decline in flaring and increase in on-site combustion for oil and gas operations, cumulative flaring emissions represent only 29 percent of total emissions, while on-site combustion represents some 38 percent.

The mitigation options are in four categories:

- Flaring
- Energy efficiency and alternative on-site power generation
- Fugitive emissions and venting
- Other.

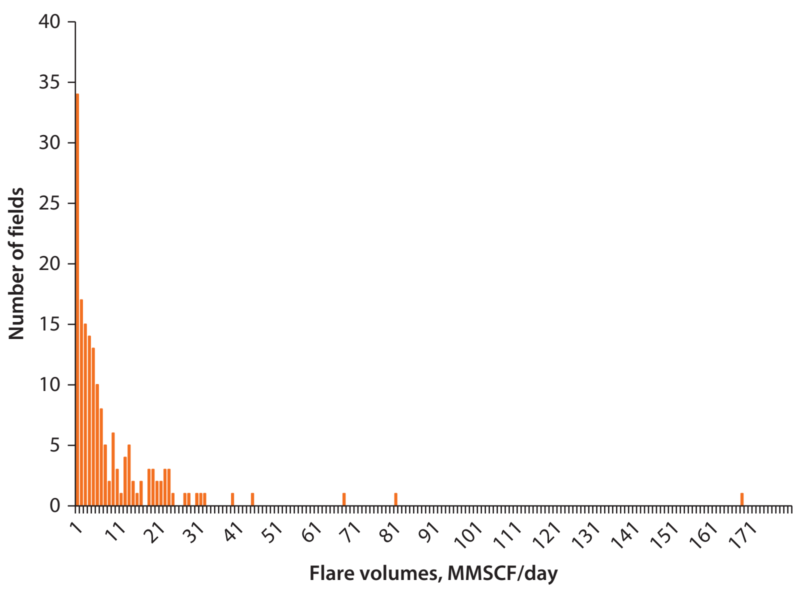
Early implementation of low-carbon options is very important, particularly those addressing flaring, as declining production reduces the economic attractiveness of the low-carbon investments.

The sequencing of mitigation options can have a large impact on their effectiveness. Flare reduction is the first priority. Not only is it currently the largest emission source, but reducing venting or fugitive emissions has less impact if the conserved gas is then only sent to flare.

### *Flaring*

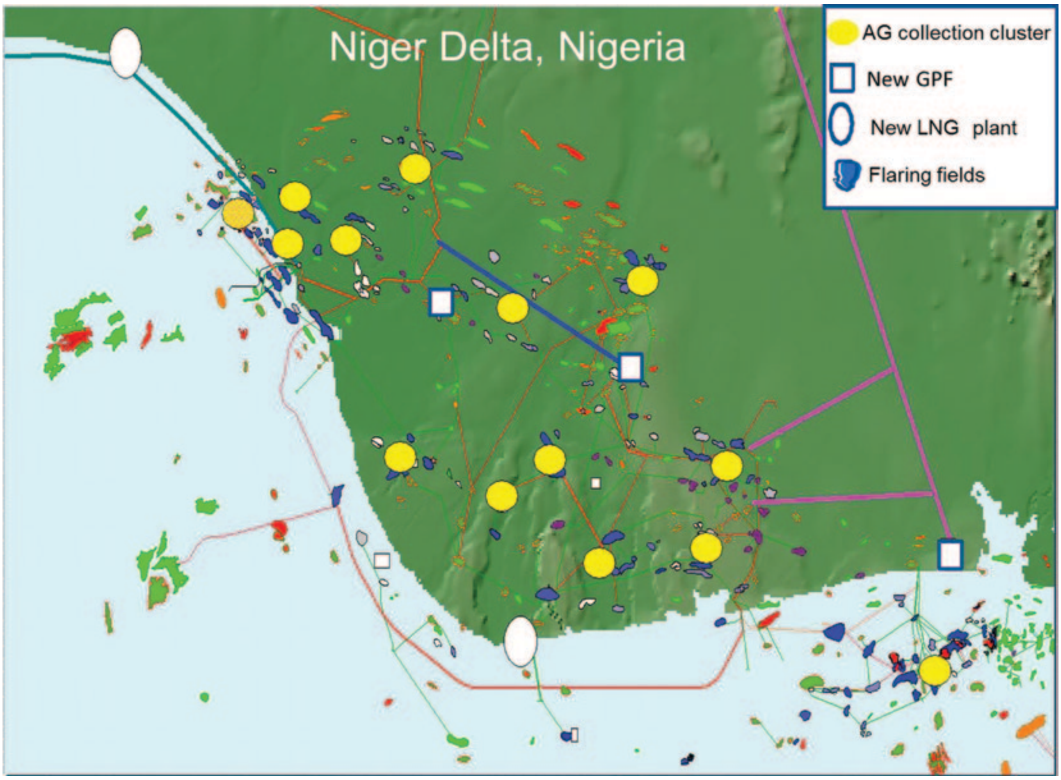
Nigeria currently flares about 1,500 MMSCF per day from around 170 fields (NNPC 2010). A small number of fields flare large volumes of gas, but many flares are small and quite widely distributed, as illustrated in figure 9.2.

**Figure 9.2 Distribution of Gas Flare Sizes, 2010**




*Source:* NNPC 2010.

**Map 9.1 Clustering of Flared Gas for Utilization**




*Source:* Energy Redefined and this study.
*Note:* GPF = gas processing facility.

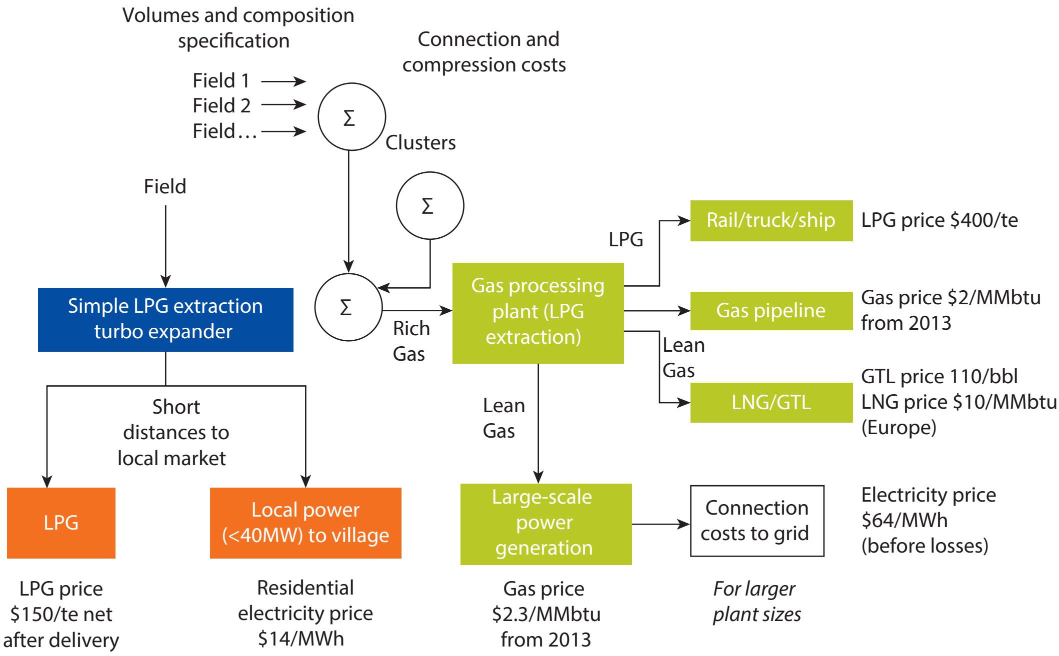
The high cost of installing gas gathering and processing facilities at small flare sites, as well as distributing the resultant products, makes utilizing the gas at each individual flare relatively unattractive. Therefore, the study evaluated several mitigation with the assumption that gas is collected into clusters for processing (map 9.1).

Each field and its options were modeled to estimate both capital and operating costs as well as revenues (Howorth 2012). Figure 9.3 illustrates the flaring reduction options considered.

### *Flared Gas Utilization with Clustering*

Flared gas comprises many components, including methane, ethane, propane, butane and heavier components. Compositions vary from field to field. The Gas Master Plan (NNPC 2011) assumes three new gas processing facilities. Costs are based on these large plants sized to take gas collected from the various clusters, and shared pro-rata based on volumes. Flared gas may be used with or without clustering. Clustering combines gas supplies and shares costs, which is typically more economical than addressing individual flares.

**Figure 9.3 Options for Utilization of Flared Gas**




*Source:* Design based on data sources listed in chapter 5.

- **Flared gas to gas processing facility (GPF), dry gas into gas trunk-lines.** Flared gas from each field is collected at a cluster point (to be discussed in next section) for onward piping to a gas processing facility.
- **Processing and transport costs.** Costs for the collection and transport of the gas are estimated for each field/cluster based on gas volume and composition and distances. Liquids, primarily LPG, are extracted at the gas processing plant and sold at a price of $400 per tonne and the dry gas is sold into the gas trunk-lines. The price paid for the dry gas is assumed to be US$2.0/MMBtu (per million Btu) in 2013.
- **Flared gas to GPF, dry gas to gas-fired power plant.** Gas collection and processing are as in the two options above, but the dry gas is sold to large central power generation plants at an expected price of US$2.3/MMBtu in 2013.
- **Flared gas to GPF, dry gas to LNG plant.** Gas collection and processing are as described in the three options above, but the dry gas is sold to an LNG plant for liquefaction and export to international markets. Current European market prices for LNG are around US$10/MMBtu. The costs of transporting and regasifying this LNG were estimated. Deducting these and the marginal operating costs of the LNG liquefaction plant gives a net-back price for gas into the LNG plant of approximately US$6.5/MMBtu.

### *Flare Gas Utilization without Clustering*

Where local markets for the products are attractive, it may be preferable to collect and process the gas from individual flares.

- **Flare gas used on-site with products sold to local communities.** The flared gas is processed on-site, extracting the LPGs using a simple, low-cost process such as turbo expansion. Such a process results in relatively "low-quality" LPGs, which are assumed to be sold to local markets at $150 per tonne. The dry gas is used to generate electricity for local communities and sold at the price for residential customers, US$14 per megawatt-hour (after losses and credit payment adjustments). Costs for the (small) power plant and turbo-expander are estimated for each field based on gas volume and composition.

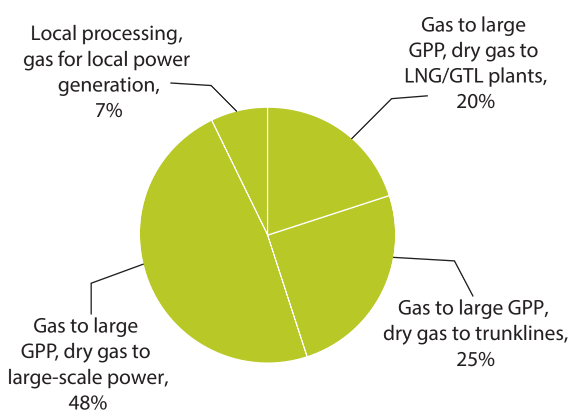
- **Flared gas-to-methanol, with products sold to local communities**. Gas processing and LPG sales are as in the previous options, but the dry gas is now converted to methanol. This is assumed to be sold at a price of $150 per tonne, lower than the netted-back international price, to reflect the quality, location, and potential uses of the product. At the assumed costs and product prices, this option is uneconomical and was not pursued further.

Options that have not been evaluated are sale of gas to large GTL plants and hydrocarbon gas reinjection.[5]

LPG recovery and sale make gas processing a very attractive option, on both large and small scales, in some cases generating sufficient revenues to more than cover the cost of flare reduction.

As they are mutually exclusive, only the most economically attractive of the above options was selected for each field/cluster when generating the low-carbon scenario. The distribution of the different options for flare reduction selected for the low-carbon scenario is illustrated in figure 9.4.

**Figure 9.4 Flare Reduction Options Selected for Low-Carbon Scenario**




*Source:* Calculations based on data sources listed in chapter 5.

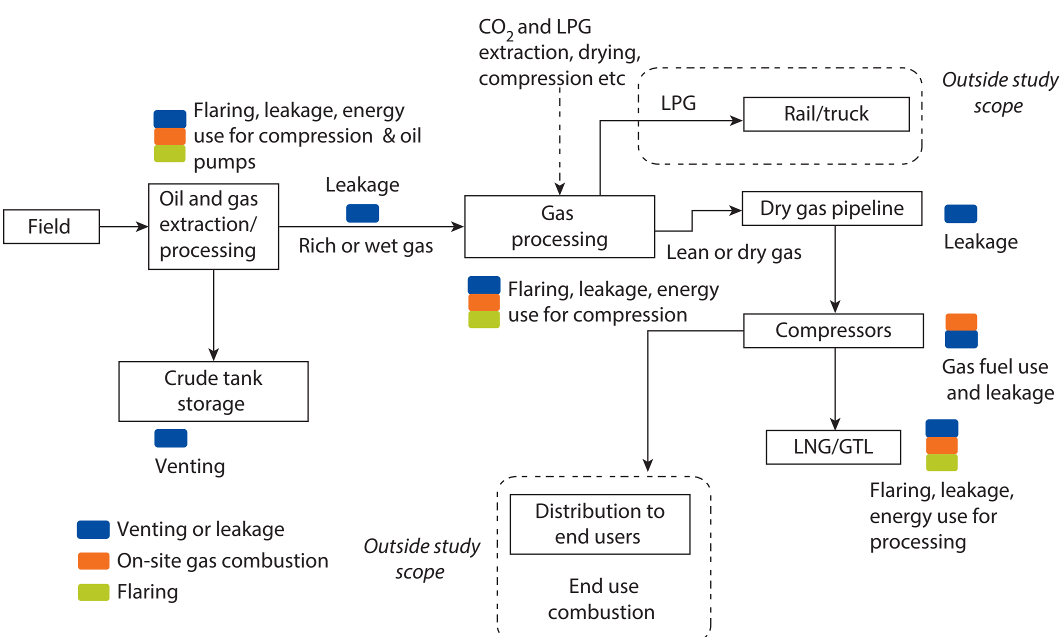
Flare reduction could reduce emissions by some 30 million tonnes per year with marginal abatement costs (MACs) of less than \$20/t$CO_2$e if projects are implemented in the short term. Delay in implementation, with declining flared gas volumes in maturing fields, significantly reduces the potential emission reductions.

### *Energy Efficiency and Alternative On-site Power Generation*

In the typical oil and gas chain (see figure 9.5), there are many places that burn gas to generate the energy needed to move or process the oil and gas. Major energy requirements are for gas compression (at oil/gas facilities, pipelines, processing plants, and so on), to provide utilities (for example, lighting at the site), for power to pump oil. Inefficient generation of this electrical or mechanical power will typically result in more $CO_2$ emissions. Older and smaller plants typically have lower efficiencies; new gas turbines can be up to twice as efficient as those built 20–30 years ago. The implementation of variable-speed pumps and compressors will also improve energy efficiency.

Alternative low-carbon power sources could also be used to reduce emissions from burning gas for energy generation and also to free up gas for other uses, for example, for sale to LNG facilities. A number of promising technologies, such as large wave power, wind (with battery backup), or even mini nuclear power units,

**Figure 9.5 Oil and Gas Emission Sources Model**




*Source:* Diagram based on data sources listed in chapter 5.

could potentially generate electricity for as low as $60 per megawatt-hour by 2025. At these prices, the use of alternative power sources becomes an attractive mitigation option.

Import of power from the grid has not been evaluated. This is assumed to be untenable until generation capacity more closely meets domestic electricity demand. However, it may be an attractive scenario in the longer term.

### *Fugitive Emissions: Leaks and Vents*

Fugitive emissions include gas vented from valves, flanges and process/transportation equipment. Typically, fugitive mitigation options are numerous and low cost, but may require significant engineering effort to locate and implement.

In the typical oil and gas chain (figure 9.5) there are also many places that leak gas. As the equipment types that leak fugitives are typically the same in each place, the mitigation options are also the same, for example, replacing seals with more effective ones. The study analysis evaluated the various mitigation options for each location.

While it is expected that no deliberate venting of gas takes place in the Nigerian oil industry, with gas that is not used going to flare, venting of $CH_4$ from oil storage tanks can be significant. These vented volumes can be significantly reduced by use of floating roof tanks to reduce emissions. The potential emission reductions and costs of retrofitting such tanks in the "old" fields, and using this design in all "new" fields, were estimated. However, the status of storage tanks in Nigeria is not known, in particular, the number of tanks that already have emission collection equipment installed. In this regard, rather arbitrary assumptions had to be made in this analysis.

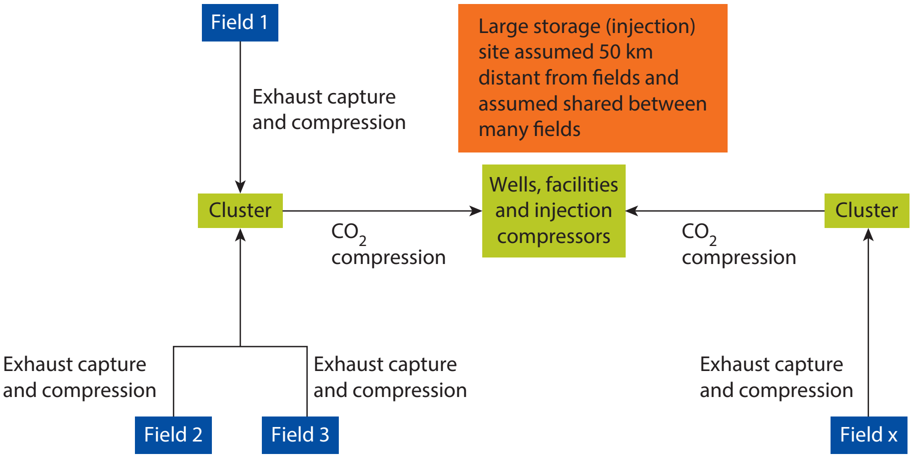
Reducing fugitive emissions in a field that is flaring the AG will have only limited benefit, for example, as with the reduced Global Warming Power (GWP) resulting from burning the $CH_4$ in the flare rather than venting it. For full benefit, mitigation of fugitives should be done only when routine flaring is eliminated and the gas saved can be used.

### *Other Mitigation Options*

**Process improvements.** As recommended by the Interstate Natural Gas Association of America (INGAA 2000), implementing a process of enhanced directed inspection and maintenance can result in significant emission reductions at low cost.

**Flare efficiency improvement.** While the preferred mitigation is reduced gas flaring, it may be possible to improve the combustion efficiency of the remaining flares at low cost, for example, by replacing flare tips, which will reduce the volume of unburnt $CH_4$ being emitted. For the current study, flare efficiencies are assumed to be 94 percent; emission reductions from an improvement to 98 percent efficiency have been modeled.

**Figure 9.6 Carbon Capture and Sequestration Scenario**




*Source:* Diagram based on data sources listed in chapter 5.

Eliminating the pilot flare, normally required for ignition of intermittent flares, and replacing it with the "flare bullet," which ignites the flare only when needed, can also reduce emissions.

**Carbon capture and sequestration (CCS).** Underground gas storage is a relatively old concept, and originally $CO_2$ injection was performed in a limited number of locations for enhanced oil recovery (EOR). The cost of injecting around 200 MMSCF per day of $CO_2$ for EOR was estimated, assuming a suitable site could be found at least 50 km from a gas cluster. The CCS scenario assumed is illustrated in figure 9.6.

A thorough assessment of the potential increase in oil recovery from $CO_2$ injection was beyond the scope of the research, so an indicative 10 percent increase in current oil production (valued at $80 per barrels) was modeled for a random selection of Nigerian fields. As prior work has shown that it can be exorbitantly expensive to capture all losses, only turbine exhaust is assumed captured at oil and gas sites, with estimated capture costs as per the International Energy Agency (IEA) report on gas turbine exhaust capture (Finkenrath 2011).

## Potential Impact of Mitigation Options

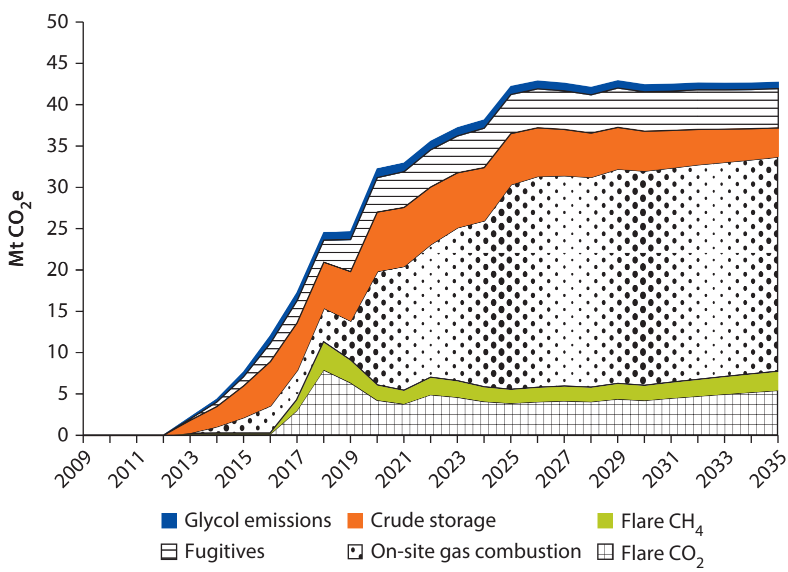
The study team identified a large number of potential mitigation options for each part of the oil and gas processing chain and made estimates of the costs (capital and operating) and emission reductions of implementing these options. To establish a low-carbon scenario emissions forecast, they selected several options, and decided when each would be implemented. For the analysis in this book, an annual budget ceiling for implementing low-carbon options of $3 billion per year (about 5 percent of projected net revenues from oil and gas production) was considered reasonable. From 2016 onward, however, the low-carbon scenario is actually forecast to be self-financing through sale of the gas recovered through low-carbon option implementation.

Engineering capacity was also assumed to limit the low-carbon options that could be implemented annually, for example, no more than 35 flare reduction projects per year were considered feasible. All other parameters that had been used to develop the reference scenario (oil and gas production levels, and so on) were kept unchanged. Within those constraints, mitigation options were chosen at random, rather than selecting the lowest MAC options first, as this is considered to reflect how low-carbon options are likely to be implemented in practice.

Figures 9.7 and 9.8 illustrate the reduction in carbon emissions achievable through implementation of the low-carbon scenario and the resultant emission profile.

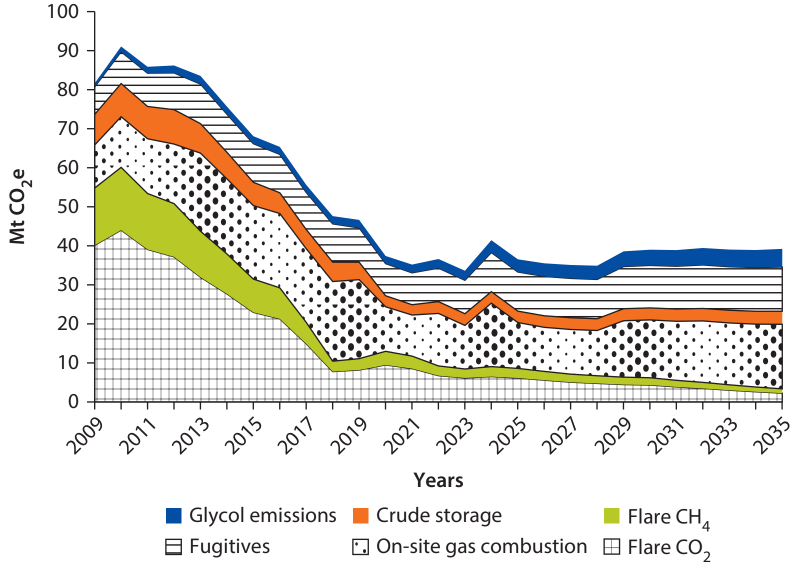
The emission reductions attributed to reducing gas flaring in the low-carbon scenario are significant. However, note that the reference scenario already includes large reductions in flaring over the study period and, without these reductions, the estimated reference scenario emissions would be significantly higher. Reduction in gas flaring is the single most effective emission reduction activity.

**Figure 9.7 Low-Carbon Scenario: Emissions Reductions from Oil and Gas**




*Source:* Calculations based on data sources listed in chapter 5.

**Figure 9.8 Low-Carbon Scenario: Oil and Gas Sector $CO_2$e Emissions by Source**




*Source:* Calculations based on data sources listed in chapter 5.

## Notes

1. The base fields have been extended to represent new or yet-to-be developed fields (see G. Howorth 2012).
2. For example, for carbon capture and storage (CCS), Energy Redefined Ltd. Glasgow, United Kingdomhas models for estimating $CO_2$ storage costs.
3. LPG, methanol, and LNG revenues are netted-back for processing, transportation, and regasification costs.
4. Includes GTL, LNG, and gas processing plants and transportation systems.
5. This is beyond the scope of this book, as its assessment would require detailed knowledge of the geology and reservoir conditions of the fields.

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**CHAPTER 10**

# Gas, LPG, and Electricity Prices

Most carbon mitigation options generate revenues from sale of natural gas, liquefied natural gas (LNG), liquefied petroleum gas (LPG), and/or electricity. Because of inevitable considerable uncertainty about the future prices of these products, the study team supplements the base case price projections (the mid-scenario) with low- and high-price scenarios, summarized in table 10.1. For mid– and low–gas price scenarios, U.S. Department of Energy *Annual Energy Outlook* (AEO) (EIA 2011 projections through 2035 were used, consistent with analysis of low-carbon options for the Nigerian power sector. The high–gas price scenario is based on UK Department of Energy and Climate Change (DECC 2011) high–gas price scenario, which is notably higher than the AEO high-scenario projection.

Natural gas supplied to LNG plants is valued the same as LNG exports to Europe, less $1.67 for marginal production cost, $1.33 for shipping, and $0.37 for regasification, for a total netback reduction of $3.37/MMBtu. For gas sold domestically, the price in 2012 is assumed to be at current low gas prices, with an increase to export parity by 2015 in accordance with the assumptions used in the power sector analysis.

Net revenues for large-scale LPG volumes are estimated, at the gas processing facility (GPF) plant outlet, at $400 per tonne, based on a Rotterdam price of $800 per tonne less shipping and transportation. For small-scale domestic LPG sales near the well-head, net revenue is estimated at $150 per tonne. LPG prices are projected to increase over time indexed to the price of oil, using base, low, and high scenarios.

The revenues from sale of electricity generated from gas used by low-carbon options are estimated to be the same as the generation cost for grid-connected gas turbines used in the analysis of the Nigerian power sector, at $52 per megawatt-hour in 2010, increasing to $63 per megawatt-hour in 2015, as the gas price approaches export parity. Electricity prices in the low and high scenarios are derived from low– and high–gas price scenarios.

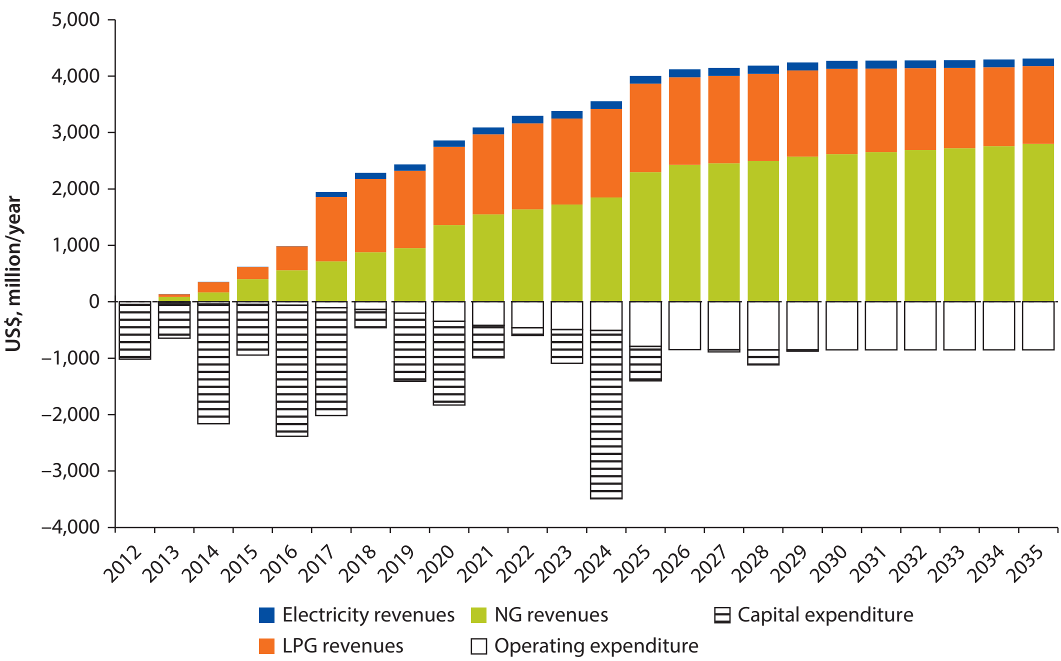
Using base prices (the mid price scenario), figure 10.1 shows the costs and revenues for the low-carbon scenario. The largest capital expenditures occur in

**Table 10.1 Low-, Mid-, and High- Product Price Scenarios, 2012–35**

| *Year* | *2012* | *2015* | *2020* | *2025* | *2030* | *2035* |
|---|---|---|---|---|---|---|
| ***Natural gas ($/MMBtu)*** | | | | | | |
| Low | 4.41 | 4.55 | 4.78 | 5.02 | 5.28 | 5.55 |
| Mid | 4.50 | 4.71 | 5.07 | 5.46 | 5.89 | 6.34 |
| High | 8.34 | 9.23 | 10.71 | 11.45 | 11.45 | 11.45 |
| ***LPG ($/tonne)*** | | | | | | |
| Low | 316 | 315 | 323 | 317 | 335 | 319 |
| Mid | 404 | 427 | 488 | 516 | 531 | 539 |
| High | 532 | 597 | 681 | 732 | 760 | 772 |
| ***Electricity ($/MWh)*** | | | | | | |
| Low | 55 | 60 | 61 | 63 | 65 | 67 |
| Mid | 57 | 63 | 65 | 68 | 71 | 75 |
| High | 87 | 99 | 104 | 104 | 104 | 104 |

*Source:* EIA 2011; DECC 2011.

**Figure 10.1 Revenues and Costs for the Low-Carbon Scenario**




*Source:* Calculations based on data sources listed in chapter 5.

the early years. As the graph shows, the early low-carbon options generate sufficient revenue to fund further implementation after 2016.

As can be seen from the breakdown of the low-carbon scenario revenues in figure 10.1, while gas sales make the greatest contribution to revenues, the extraction and sale of LPG also make a significant contribution. If these estimated LPG revenues cannot be fully realized, the marginal abatement cost (MAC) values for most low-carbon options and the overall economics of the low-carbon scenario would be eroded significantly.

## References

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EIA (Energy Information Administration). 2011. *Annual Energy Outlook 2011*. Washington, DC: EIA, U.S. Department of Energy.

NNPC (Nigerian National Petroleum Corporation). 2013. Petroleum Industry Bill. www.nnpcgroup.com/PublicRelations/PetroleumIndustryBill.aspx.

CHAPTER 11

# Marginal Abatement Costs Curve and Return Value

The marginal abatement cost (MAC) is a useful measure to compare the relative cost of low-carbon and emissions abatement technologies for reducing emissions. The MAC of a low-carbon technology or option is its net cost per unit reduction in emissions, expressed in $/t$CO_2$e, relative to a reference technology. Each MAC is calculated as the ratio of the present value (PV at a 10 percent real discount rate) of the annual stream of net costs to the total undiscounted reduction in emissions within the project period 2009–35. The PV net cost is the present value in 2009 of the annual capital and operating costs less the annual revenue from use or sale of natural gas, liquefied petroleum gas (LPG), and electricity. Table 11.1 shows for each mitigation option, its parent source group, the total carbon savings, and the MAC.

The study analyzed flare reduction options on a cluster basis. That is, combining gas supplies and sharing costs, as this is typically more economical than addressing individual flares. Flaring emissions are expected to incur significant penalties (not included in current calculations) following enactment of the proposed Petroleum Industry Bill, which would make the economics of flare reduction even more attractive. The net cost of implementing the low-carbon options also excludes the impact of any deferral of oil or gas sales that may occur due to the shutdown of the facilities/equipment to implement the options.

In the longer term, use of alternative low-carbon energy sources for on-site power generation would be attractive if this power can be produced at less than $60/MWh (per megawatt-hour). As well as reducing emissions, use of alternative sources for on-site energy frees up gas for sale, thereby reducing the need for investment in other sources of the gas to meet demand.

The study estimated that some 425 Mt $CO_2$e of emissions could be mitigated by implementing low-carbon options that have negative MAC values, that is, those that are economically attractive even in the absence of carbon credits. A real-term discount rate of 10 percent was used when calculating these MAC values, and it is recognized that this may be considered low when evaluating oil

**Table 11.1 Total Emissions Reductions and Marginal Abatement Costs for Mitigation Options**
*10 percent real-term discount rate*

| *LCO ordered* | *Group* | *Carbon savings ($MtCO_2e$)* | *MAC ($\$/tCO_2e$)* |
|---|---|---|---|
| Flare gas to NGL extractor—gas to power | Flaring | 10.42 | (101.10) |
| Flare gas to central GPP—gas to LNG | Flaring | 22.17 | (84.31) |
| Flare gas to central GPP—gas to grid | Flaring | 55.98 | (64.41) |
| Flare gas to GPP—gas to power plants | Flaring | 23.24 | (33.48) |
| CCS at field and reinjection | Gas used for on-site power generation | 25.06 | (12.33) |
| New power drives in on-site power plants | Gas used for on-site power generation | 53.77 | (10.62) |
| Variable speed drives on compressors | Gas used for onsite powergen | 27.13 | (10.40) |
| Replace flare pilot flames with bullet ignition | Flaring | 6.75 | (6.99) |
| Replace rings and rods on compressors | Fugitives | 0.02 | (6.74) |
| Enhanced maintenance—productions facilities | Fugitives | 29.87 | (2.45) |
| Flash tanks on gas dehydrator | Glycol dehydration | 10.82 | (1.14) |
| Glycol recirculator on gas dehydrator | Glycol dehydration | 8.31 | (1.10) |
| Compressor fuel gas modifications | Fugitives | 0.03 | (0.96) |
| Enhanced maintenance—pipeline, meters etc | Fugitives | 0.38 | (0.85) |
| Direct maintenance—compressors | Fugitives | 0.37 | (0.66) |
| CCS of combustion gas, transport | Gas used for on-site power generation | 141.85 | (0.29) |
| Variable speed drive on pumps | Gas used for on-site power generation | 6.88 | (0.05) |
| Compressor seal replacement | Fugitives | 2.98 | (0.02) |
| Retrofit fixed roof with internal floating roof | Crude storage | 77.96 | 0.05 |
| Replace gas with air in control instruments | Fugitives | 9.49 | 0.37 |
| Low-bleed pneumatic control devices | Fugitives | 6.57 | 0.49 |
| Improve flare combustion efficiency | Flaring | 1.91 | 1.06 |
| New floating roof tanks | Crude storage | 52.94 | 1.30 |
| Install optimal production control systems | Gas used for on-site power generation | 4.08 | 4.11 |
| General maintenance system improvement | Fugitives | 37.82 | 5.46 |
| Replace compressors and turbine drive units | Gas used for on-site power generation | 22.86 | 6.02 |
| Directed maintenance—pipeline, meters etc | Fugitives | 0.15 | 7.88 |
| Replace powerplants with LC sources | Gas used for on-site power generation | 86.80 | 11.64 |
| LNG fugitives reduction | Gas used for on-site power generation | 19.20 | 31.77 |

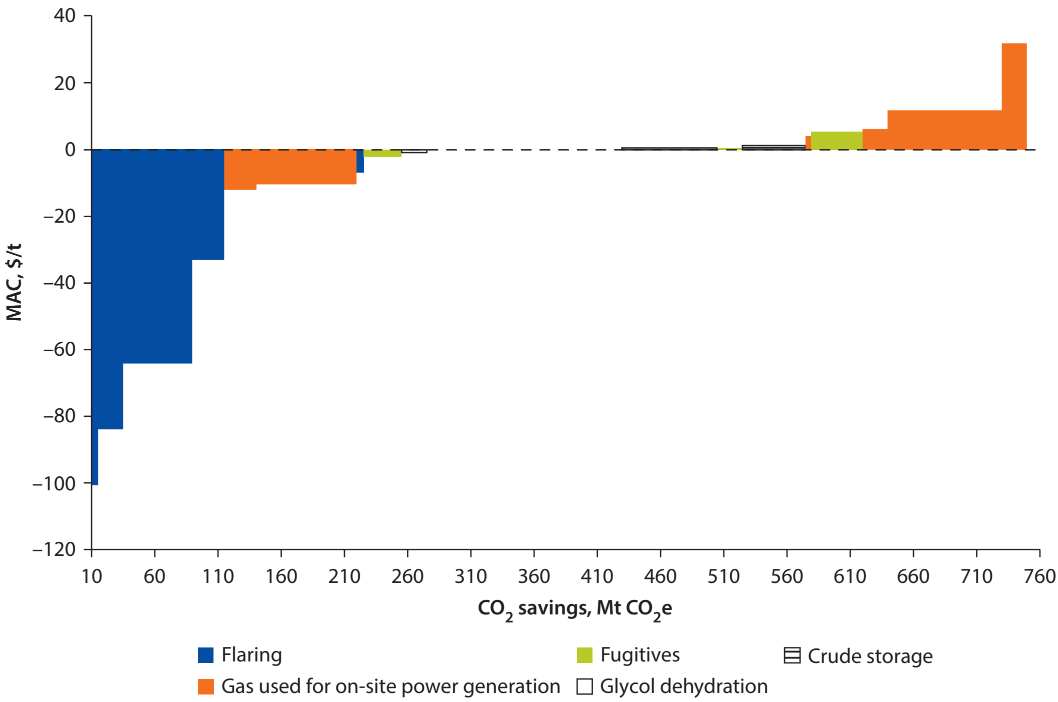
*Source:* Calculations based on data sources listed in chapter 5.

and gas investments. At a discount rate of 15 percent, it is estimated that some 275 Mt $CO_2e$ can still be reduced, again in the absence of carbon credits.

## Calculating the MAC Curve

Figure 11.1 shows the MAC curve for these options. Each colored rectangle identifies a class of low-carbon options. The height of each rectangle identifies its MAC in net present value dollars per tonne of $CO_2e$ emissions (or its depth below the axis shows the NPV return produced per tonne $CO_2e$). The width of each rectangle shows the total emissions savings summed to the horizon date in millions of tonnes $CO_2e$. The groups of options, each depicted by a rectangle, are sequenced from lowest MAC (highest return) on the left to largest on the right.

**Figure 11.1 MAC Curve for Low-Carbon Options in Table 11.1**




*Source:* Calculations based on data sources listed in chapter 5.

The mitigation options at the top of table 11.1 and on the left in figure 11.1 have negative MAC values, meaning that they are expected to generate positive returns on investment, even ignoring the carbon savings. Conversely the options at the bottom of the table (and to the right in the figure have positive MACs, meaning that there is a net cost to mitigate these greenhouse gases (GHG) emissions. Carbon taxes or saleable carbon savings would improve the viability of all the options, and could be sufficient for these high MAC options to be economically viable.

The study estimated that, of the potential 745 Mt $CO_2$e mitigated by implementation of all the low-carbon options in the low-carbon scenario. Approximately 425 Mt $CO_2$e could be mitigated by implementing low-carbon options with negative MAC values.

CHAPTER 12

# Sensitivity Analysis of the Study Results

It is impossible to eliminate the inevitable uncertainties in the assumptions and estimates made in the analysis of the low-carbon mitigation options, but it is possible to estimate how much difference variation in the assumptions would make to key results.

Key estimates and assumptions include the reduction in emissions ($CO_2$ saved), raw/dry gas volumes, liquefied petroleum gas (LPG) produced, electricity produced (MW), capital expenditures (CPX) and operating expenditures (OPX). Changes in the prices of gas, LPG, and electricity are expressed as percent changes from the mid-price scenario to the low- and high-price scenarios for each product.

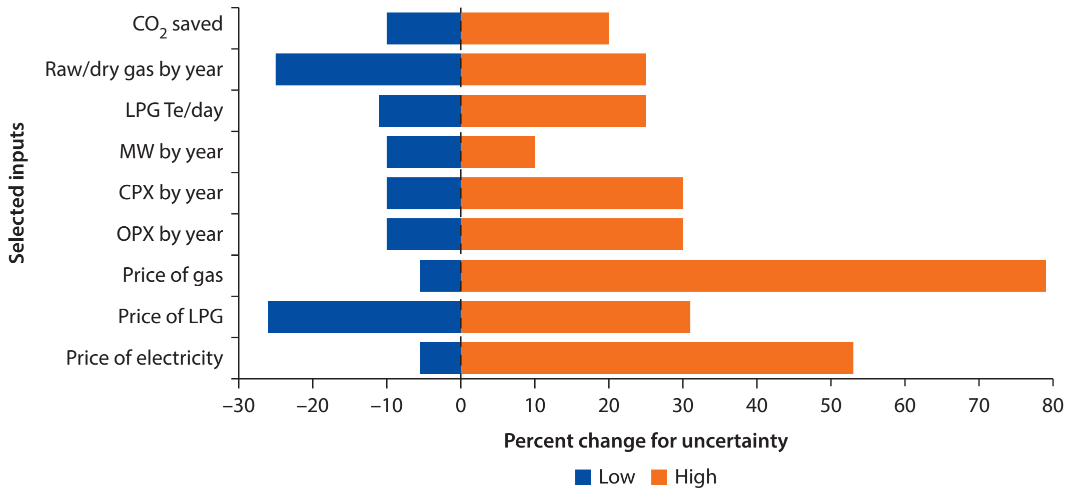
Figure 12.1 shows the estimated low- and high-percentage perturbations (about the average) in the input assumptions used in the analysis, to illustrate the uncertainty in each of these quantities.

The tornado chart in figure 12.2 shows the sensitivities of the present value of the net cost (net cost = CPX + OPX – revenues) resulting from changing each of the input assumptions from its low to high value, holding all other assumptions at their base value. Uncertainty in the price of gas has by far the largest effect, followed by uncertainty in gas volume and the price of LPGs, followed by CPX and the quantity of produced LPG. By comparison the effects of uncertainty in the other variables—operating cost and price/quantity of electricity—are small.

## Sensitivity to Discount Rate

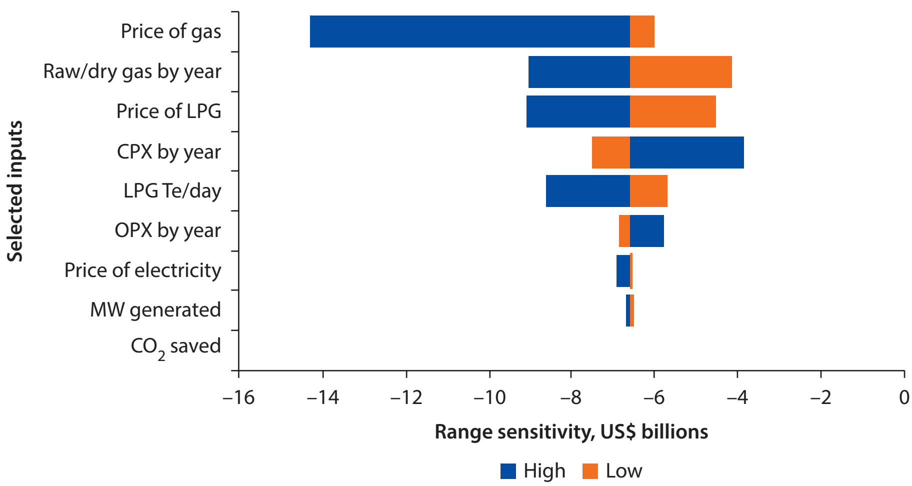
While a real-terms discount rate of 10 percent may be considered appropriate for other sectors, for example the power sector, investment in the oil and gas sector is often considered to carry higher risk, therefore warranting use of a higher discount rate. Therefore the study also evaluated the MAC values for the low-carbon options at a 15 percent real-term discount rate, with the result shown in table 12.1.

**Figure 12.1 Perturbations to Selected Uncertain Assumptions as Percent of Mid Values Used for Range Sensitivity Analysis**




*Source:* Calculations based on data sources listed in chapter 5.

**Figure 12.2 Range Sensitivity of Present Value of Net Cost to Changes in Uncertain Assumptions**



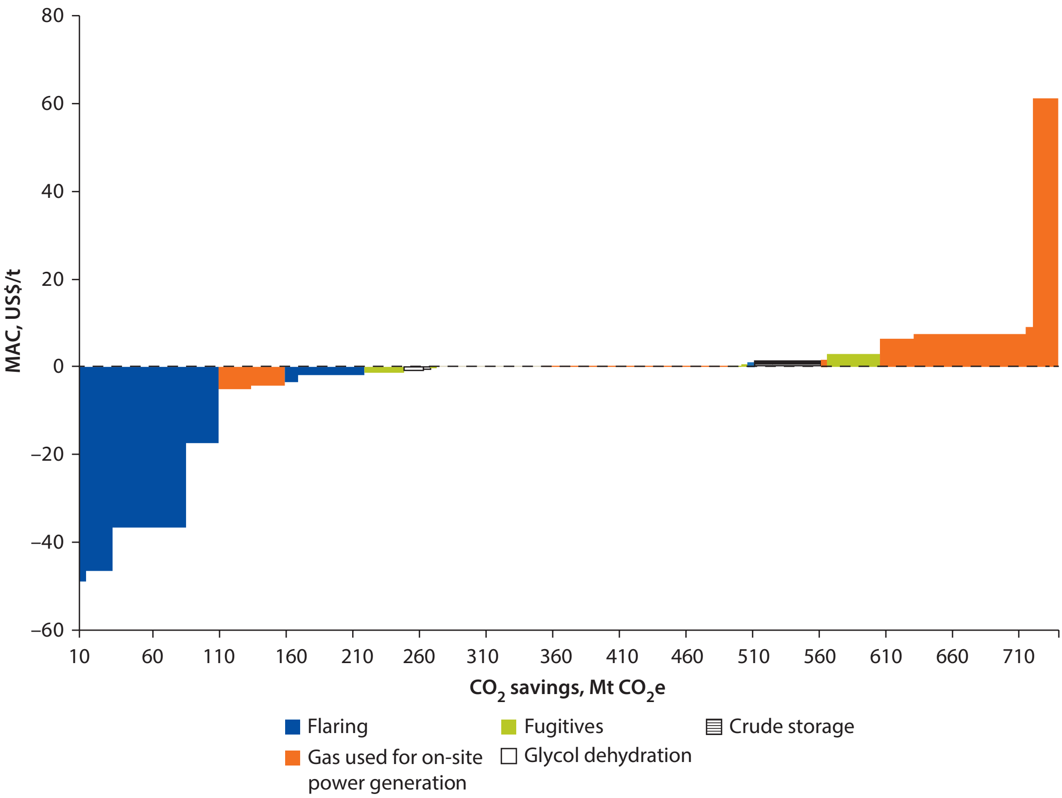

*Source:* Calculations based on data sources listed in chapter 5.
*Note:* Tornado chart (range sensitivity analysis) shows the effect on present value net cost of changing each uncertain input variable from its low to high value, while keeping the other variables at their base values.

**Table 12.1 Total Emissions Reductions and Marginal Abatement Costs (15% real-term discount rate)**

| *LCO ordered* | *Group* | *Carbon savings ($MtCO_2e$)* | *MAC ($/$tCO_2e$)* |
|---|---|---|---|
| Flare gas to NGL extractor—gas to power | Flaring | 10.421 | (49.087) |
| Flare gas to central GPP—gas to LNG | Flaring | 22.175 | (46.501) |
| Flare gas to central GPP—gas to grid | Flaring | 55.976 | (36.666) |
| Flare gas to GPP—gas to power plants | Flaring | 23.241 | (17.344) |
| CCS at field and reinjection | Gas used for on-site power generation | 25.063 | (5.086) |
| Variable speed drives on compressors | Gas used for on-site power generation | 27.133 | (4.281) |
| Replace rings and rods on compressors | Fugitives | 0.024 | (4.110) |
| Replace flare pilot flames with bullet ignition | Flaring | 6.750 | (3.437) |
| New power drives in on-site power plants | Gas used for on-site power generation | 53.774 | (1.992) |
| Enhanced maintenance—productions facilities | Fugitives | 29.871 | (1.466) |
| Flash tanks on gas dehydrator | Glycol dehydration | 10.821 | (0.727) |
| Glycol recirculator on gas dehydrator | Glycol dehydration | 8.308 | (0.688) |
| Compressor fuel gas modifications | Fugitives | 0.029 | (0.570) |
| Enhanced maintenance—pipeline, meters etc | Fugitives | 0.383 | (0.516) |
| Direct maintenance—compressors | Fugitives | 0.370 | (0.382) |
| Compressor seal replacement | Fugitives | 2.982 | (0.014) |
| Retrofit fixed roof with internal floating roof | Crude storage | 77.956 | 0.113 |
| CCS of combustion gas, transport | Gas used for on-site power generation | 141.847 | 0.196 |
| Replace gas with air in control instruments | Fugitives | 9.489 | 0.337 |
| Low bleed pneumatic control devices | Fugitives | 6.570 | 0.445 |
| Improve flare combustion efficiency | Flaring | 1.913 | 0.916 |
| New floating roof tanks | Crude storage | 52.943 | 0.925 |
| Variable speed drive on pumps | Gas used for on-site power generation | 6.880 | 1.503 |
| General maintenance system improvement | Fugitives | 37.816 | 3.028 |
| Directed maintenance—pipeline, meters etc | Fugitives | 0.146 | 4.499 |
| Replace compressors and turbine drive units | Gas used for on-site power generation | 22.857 | 6.419 |
| Replace power plants with LC sources | Gas used for on-site power generation | 86.801 | 7.529 |
| Install optimal production control systems | Gas used for on-site power generation | 4.082 | 9.136 |
| LNG fugitive and combined emissions reduction | Gas used for on-site power generation | 19 | 61.30013 |

*Source:* Calculations based on data sources listed in chapter 5.

**Figure 12.3 MAC Curve for Low-Carbon Options in 12.1**




*Source:* Calculations based on data sources listed in chapter 5.

Comparing table 12.1 with table 11.1 and comparing figure 12.3 with figure 11.1 shows that using a higher discount rate (15 instead of 10 percent) gives higher (that is, less negative) MAC values for all options. This is because the higher discount rate reduces the present value of the cost and revenues, while the discount rate is not applied to the emission savings. However, even when discounted at a 15 percent real-term discount rate, options to mitigate some 275 Mt $CO_2$e of emissions have negative MAC values and could still be economically implemented in the absence of any carbon price.

CHAPTER 13

# Recommendations

This chapter makes recommendations for achieving maximum benefits from a low-carbon plan for Nigeria's oil and gas sector, based on the analysis presented above identifying those options with the highest benefits.

## Recommendations for the Short Term

### *Policy Recommendations for the Federal Government of Nigeria*

- Consider setting up a joint government-industry group to develop a low-carbon strategy and action plan for the oil and gas industry.
- Ensure that Nigerian National Petroleum Corporation's (NNPC's) annual budget includes sufficient funding for implementation of at least the high-priority mitigation options.
- Consider implementing a fast-track budget approval process for mitigation options.
- For many emission estimates, the study relied on realistic assumptions regarding the oil and gas facilities in Nigeria and their condition. In order to develop better and more detailed emission estimates that can form the basis of a detailed plan for their mitigation, it is recommended that Federal Government of Nigeria (FGN) promotes
  - Creation of a sectorwide inventory of emission sources, which in addition to information on current greenhouse gases (GHG) emissions, should include the status of each source—for example, age, condition, emission reduction actions already taken, and identified potential emission reduction options.
  - Application of the facility-specific Tier 1 methodology to establish the current level of emissions. If Tier 1 is considered to be unrealistic to carry out in a reasonable timeframe, at least a Tier 2 estimate could be prepared. (Tier 1 and Tier 2 estimation methodologies are described in the *API Compendium* [API 2009]).

## Recommendations for the Medium Term

### *Actions to be Taken by the Oil And Gas Industry (including NNPC)*

#### *Flaring*

- Address gas flaring reduction as the highest priority action, not only to reduce the direct emissions from the flaring but also to extract maximum benefit from delivering gas.
- Because of the high cost of installing gas gathering and processing facilities at small flare sites, consideration could be given to collecting the small volumes of associated gas (AG) in clusters for processing and export of the dry gas and liquefied petroleum gases (LPGs).

#### *Energy efficiency*

- Consider replacement of older and/or smaller on-site power plants with new equipment.
- Consider use of variable-speed drives on pumps and compressors to improve efficiency.

#### *Other recommendations for reducing emissions*

- Where not already done, consider replacing fixed roof tanks with floating roof tanks with gathering systems for the liberated gas.
- Enhanced and directed inspection and maintenance programs have been very effective in reducing emissions in other oil and gas ventures. Consider implementing such programs in a sequential way in Nigeria.
- Since some flaring will still occur, for example, for safety, consider improving combustion efficiency of remaining flares.

## Recommendations for the Long Term

A number of technologies that may become economically attractive in the longer term include alternative energy sources such as wave power to replace on-site gas/diesel combustion and carbon capture and storage (CCS). It would be desirable that the cost trend for these technologies be monitored so that, when they appear to be viable, their potential for implementation in Nigeria could be considered.

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**APPENDIX F**

# Framework for Estimating Oil and Gas Emissions

The basis of the analytical framework presented in this Annex is the American Petroleum Institute's *Compendium of Greenhouse Gas Emissions Estimation Methodologies for the Oil and Natural Gas Industries* (*API Compendium* 2009). Emissions from oil and natural gas systems are primarily carbon dioxide from combustion and flaring, with some accidentally vented or fugitive emissions of natural gas consisting primarily of methane, with some quantities of non-methane volatile organic compounds (VOCs), carbon dioxide, and carbon monoxide.

For the purpose of this framework, oil and gas systems are divided into five major areas: production of oil and associated gas; production of non-associated gas; natural gas processing; oil and gas transportation; and LNG/GTL facilities.

Following are the equations the study team used to estimate the emissions from each source or type of equipment from each segment of the industry, along with the corresponding emissions factors.

## Framework for Calculating GHG Emissions for Oil Production Facilities

### *Venting Emissions*

The study team found that deliberate venting of associated gas (AG) is not practiced in Nigeria; unused gas is flared. Therefore the analysis assumed that the major sources of greenhouse gases (GHG) venting in this segment comes from the following sources:

#### *Glycol Dehydration Emissions*

Glycol dehydration is used to remove water from gas streams. AGs produced with crude oil that will be used in the market is passed through glycol dehydration on the oilfield even before they are sent to gas processing facilities (GPFs). Methane emissions arise from glycol dehydration because a small amount of $CH_4$

absorbed by the glycol is driven off into the atmosphere during glycol regeneration process. These venting emissions are estimated as:

$$VE_{cop,GD,i,t} = COP_{i,t} * GOR_{i,t} * f_{i,AGP,t} * EF_{GD,i}$$

$$VE_{cop,GD,t} = 25 * VE_{cop,GD,i,t}$$

Where:

$VE_{cop,GD,i,t}$ = Venting emissions of $CH_4$ from glycol dehydration units at oil production facilities under the fiscal arrangement ***i*** in year *t* (tonnes $CH_4$)

$VE_{cop,GD,t}$ = Total Venting Emissions of $CH_4$ from the Glycol Dehydration Units of Crude Oil Production Facilities in the Nigerian Oil Fields under all Production Fiscal Arrangements in year *t* ($tCO_2e$);

*i* = Type of Fiscal Arrangement for Crude Oil Production in the Nigerian Oil and Gas Industry. There are two Fiscal Arrangements; therefore *i* = PSC and JV

$COP_{i,t}$ = Crude Oil Production in Fiscal Production Arrangement *i* fields in year *t* (barrels)

$GOR_{i,t}$ = Gas to Oil Ratio of Crude Oil Production in Fiscal Production Arrangement *i* Fields in Year *t* $\left(\frac{\text{SCF}}{\text{barrel}}\right)$

$f_{i,AGP,t}$ = Fraction of AG Produced at Fields under type *i* that is sent to the glycol unit in year *t* $EF_{GD,i}$

$EF_{GD,i}$ = Emission factor for $CH_4$ for Gas Dehydration Segment of the Oil Field $\left(\frac{\text{tonnes } CH_4}{\text{MMSCF Gas Processed}}\right)$

***Glycol Pumps***

Both electric and gas-assisted pumps are used to circulate glycol in the dehydrator system. This class of vented emissions were modeled as follows:

$$VE_{GTR,GP,t} = 25 * G_{Tr,t} * EF_{GP,GTR}$$

$$G_{Tr,t} = G_{FGPF,t} * (1 - G_{l,t})$$

Where:

$VE_{GTR,GP,t}$ = Venting Emissions of $CH_4$ from the Glycol Pump Units along Gas Transmission Pipeline Facilities in Nigeria in year *t* ($tCO_2e$)

$G_{Tr,t}$ = Volume of gas sent into transmission lines in Nigeria in year *t* (SCF)

$G_{FGPF,t}$ = Total Gas processed at GPFs in Nigeria in year *t* (SCF)

$f_{AG,GPF,t}$ = Fraction of AGs produced in the Nigerian Oil fields that were sent to a GPF in year *t* (fraction)

$$G_{l,t} = \text{Gas loss (fraction) at the GPF (fraction)}$$

$EF_{GP,GPF}$ = Emission factor for $CH_4$ venting from Glycol Pumps of GPF in $\left(\frac{\text{tonnes } CH_4}{\text{SCF Gas Processed}}\right)$

***Acid Gas removal and $CO_2$ Venting From Sour Gas Processing***

The study team assumed that emissions from these sources in crude oil producing fields in Nigeria is negligible because the average country's crude belongs to the class of crude referred to as "sweet crude," with minimal $H_2S$ (hydrogen sulfide) and $CO_2$ content.

***Crude Storage Tank Emissions***

In the reservoir, while under pressure, gas is dissolved in the oil. When the oil is produced and brought to atmospheric conditions, this solution gas is released primarily in the gas–oil separator, but some remains in the oil and is subsequently released in the storage tanks through flashing.

The simple emission factor approach of the *API Compendium* was used to estimate these emissions as follows:

$$VE_{cop,TF,i,t} = COP_{i,t} * f_{i,tanked,t} * EF_{FL,i}$$

$$VE_{cop,TF,t} = 25 * \Sigma_i \, VE_{cop,TF,i,t}$$

Where:

$VE_{cop,TF,i,t}$ = Venting emissions of $CH_4$ from tank flashing from crude oil storage tanks at Crude Oil Production Facilities in Fiscal Production Arrangement Fields in year $t$ (tonnes $CH_4$)

$VE_{cop,TF,t}$ = Total Venting emissions of $CH_4$ from tank flashing from crude oil storage tanks of Crude Oil Production Facilities in Fiscal Production Arrangement in year $t$ ($tCO_2e$)

$f_{i,tanked,t}$ = Fraction of Crude Oil Produced at the Fiscal Arrangement $i$ Fields that is tanked before being sold in year $t$

$EF_{FL}$ = Emission factor for $CH_4$ flashing from crude oil storage tanks $\left(\frac{\text{tonnes } CH_4}{\text{barrel of crude}}\right)$

***Tank Working and Standing Losses***

Oil storage tanks in the production segment and in refineries can produce hydrocarbon emissions through working and standing (breathing) losses. Working loss emissions occur during emptying and filling of these tanks, while standing losses occur during the storage of the liquids and are affected by diurnal temperature changes. Most $CH_4$ emissions from storage tanks occur due to flashing; working and breathing loss emissions are small and, as per the *API Compendium*, tank working and standing losses are assumed to be negligible.

***Other Emissions***

$CH_4$ venting emissions also take place in other oil field operations, but the analysis assumed that they are negligible relative to the ones covered above; they include: (1) Cold Vents, (2) Maintenance and Turnaround Emissions, and (3) Exploratory Drilling and Well Testing Emissions.

***Total Venting Emissions (TVE) during the oil production process was estimated as:***

$$TVE_{COP,t} = VE_{cop,GD,t} + VE_{cop,GP,t} + VE_{cop,TF,t}$$

### *Fugitive Emissions*

According to the *API Compendium* (API 2009) fugitive emissions refer to emissions from equipment leaks, where any pressurized equipment has the potential to leak. These leaks generally occur through valves, flanges, seals, or related equipment. Fugitive emissions also include non-point evaporative sources such as from wastewater treatment, pits, and impoundments. The facility level approach—one of the fugitive GHG emissions estimation methods for which emission factors were presented in the *Compendium*—were used in estimating Crude Oil Fugitive Emissions for the Nigerian Oil and Gas Sector in this book. Applying average facility-level emission factors is the simplest method for estimating $CH_4$ emissions from petroleum operations. According to the *Compendium*, while fugitive $CH_4$ emissions from oil transmission pipelines are negligible, they are significant for onshore and offshore oil production. These are estimated for the Nigerian Crude Oil production according to the following equations:

$$FE_{cop,i,t} = COP_{i,t} * EF_{FE,i}$$

$$FE_{cop,t} = 25 * \sum_i FE_{cop,i,t}$$

Where:

$FE_{cop,i,t}$ = Fugitive emissions of $CH_4$ from Crude Oil Production Facilities in Fiscal Production Type *i* Field in year *t* (tonnes $CH_4$)

$FE_{cop,t}$ = Total Fugitive emissions of $CH_4$ from Crude Oil Production Facilities in the Nigerian Oil Fields under the PSC and the JV Arrangements in year *t* ($tCO_2e$)

$COP_{i,t}$ = Crude Oil Production in Fiscal Production Type i Fields in year *t*

$EF_{FE,i}$ = Emission factor fugitive $CH_4$ emissions from Fiscal Production Type i Fields in year *t* $\left(\frac{\text{tonnes } CH_4}{\text{barrel of oil produced}}\right)$

### *Combustion Emissions*

Combustion emissions include emissions from fuel combustion during the oil production process and emissions from the flaring of AG at the field.

For emissions from fuel combustion, the *API Compendium* assumes complete combustion (that is, 100 percent of the fuel combusts to $CO_2$). This assumption applies to almost all combustion, with the exception of flaring. In oil production, apart from the fuel combusted to derive energy needed to drive drilling equipment during the drilling and completion of producing wells, fuel is also combusted to supply energy to some of the separation processes encountered in the oil, water, and associated natural gas separation processes. Due to lack of specific data for this category of GHG emission in Nigerian fields, the study team developed the following framework to estimate GHG emissions in this work as follows:

***Emissions from Fuel Combustion at Stationary Sources***

Estimates of emissions from combustion of fuels in on-site stationary energy equipment at PSC and JV oil fields have been made as follows:

***For the Combustion of Gas at Fiscal Production Type* i *Fields:***

$$CE_{i,GC,t} = \left( \frac{COP_{i,t} * f_i * f_{gas,i} * \rho_C * 44}{HHV * 12 * 10^3} \right)$$

Where:

$CE_{i,GC,t}$ = GHG emissions from combustion of natural gas at the Crude Oil Fiscal Production Type $i$ Fields in year

$COP_{i,t}$ = Crude Oil Production in Fiscal Production Arrangement $i$ fields in year $t$ (barrels)

$f_i$ = Fuel combusted at Fiscal Production Type $i$ Fields to Produce 1 barrel of oil $\left( \frac{\text{Kcal of fuel}}{\text{barrel of Crude Oil}} \right)$

$f_{gas,i}$ = Fraction of fuel combusted at Fiscal Production Type $i$ Fields that is natural gas (Fraction)

$HHV$ = High heating values of natural gas (Kcals/$m^3$)

$\rho_C$ = Carbon density of natural gas $\left( \frac{\text{Kg of carbon}}{\text{m}^3 \text{ of natural gas}} \right)$

***For the Combustion of diesel fuel at Fiscal Production Type* i *Fields:***

$$CE_{i,DC,t} = \left( \frac{COP_{i,t} * f_i * (1 - f_{gas,i}) * \rho_{Cd} * 44}{HHV * 12 * 10^3} \right)$$

Where:

$CE_{i,DC,t}$ = GHG emissions from combustion of Diesel at Fiscal Production Type $i$ Fields in year $t$ ($tCO_2e$)

$COP_{i,t}$ = Crude Oil Production in Fiscal Production Arrangement $i$ fields in year $t$ (barrels)

$f_{PSC}$ = Fuel combusted at Fiscal Production Type $i$ Fields to Produce 1 barrel of oil $\left( \frac{\text{Kcal of fuel}}{\text{barrel of Crude Oil}} \right)$

$f_{gas,i}$ = Fraction of fuel combusted at Fiscal Production Type $i$ Fields that is gas (fraction)

$HHV$ = High heating values of diesel (Kcals/Kg diesel)

$\rho_{Cd}$ = Carbon density of diesel $\left( \frac{\text{Kg of carbon}}{\text{Kg of diesel}} \right)$

**Total Combustion Emission($TCE_{COP,t}$) from production of oil is estimated as:**

$$TCE_{COP,t} = CE_{PSC,GC,t} + CE_{JV,GC,t} + CE_{PSC,DC,t} + CE_{JV,DC,t}$$

### *Emissions from Flaring of Associated Natural Gas*

Flares are used at oil fields to dispose of AG produced when this gas has no ready market or on-site use. Flares are also used to dispose of gas for safety reasons or when process upsets occur. For flared gas, the following equations were used to calculate the GHG emissions:

$$FLE_{i,CO_{2},t} = COP_{i,t} * GOR_{it} * f_{fflared,i,t} * MV_{i,t} * \sum_{i} (MHC_{i,t} * C_{i,t}) * fCE_{i,t} * MW_{CO_2} \quad (15)$$

$$FLE_{i,CH_{2},t} = COP_{i,t} * GOR_{it} * f_{fflared,i,t} * CH_4Mf_{i,t} * RSDCH_{4i,t} * CH_4MV_{i,t} * MWCH_4$$

**Total Flaring Emissions are given by:**

$$FLE = \sum_{i} FLE_{i,CO_{2},t} + 25 * \sum_{i} FLE_{i,CH_{4},t}$$

Where:

$FLE_t$ = Total Emissions of GHG from the flaring of AG in the Nigeria Oil Fields in year $t$ ($tCO_2e$)

$FLE_{i,CO_{2},t}$ = $CO_2$ Emissions of the flaring of AG at Fiscal Production Type $i$ Fields in Nigeria in year $t$ ($tCO_2e$)

$FLE_{i,CH_{4},t}$ = $CH_4$ Emissions of the flaring of AG at Fiscal Production Type $i$ Fields in Nigeria in year $t$ ($tCH_4$)

$COP_{i,t}$ = Crude Oil Production in Fiscal Production Arrangement $i$ fields in year $t$ (barrels)

$GOR_{i,t}$ = Gas to oil Ratio of AG to Crude Oil at Fiscal Production Type $i$ Fields in year $t$ $\left(\frac{\text{CM}}{\text{Barrel of Crude}}\right)$

$f_{fflared,i,t}$ = Fraction of AG produced in Fiscal Production Type $i$ Fields that is flared in year $t$ (fraction)

$MV_{i,t}$ = Average Molar Volume of AG produced in Fiscal Production Type $i$ Fields in Nigeria in year $t$ $\left(\frac{\text{Moles of Gas}}{\text{volume of AG}}\right)$

$MHC_{i,t}$ = Moles of hydrocarbon per mole of AG produced in Fiscal Production Type $i$ Fields in Nigeria in year $t$ $\left(\frac{\text{moles of hydrocarbon}}{\text{mole of AG}}\right)$

$C_{i,t}$ = Average moles of carbon per mole of HC in Fiscal Producton Type $i$ Field AG in the Nigeria in year $t$ (Moles of C/mole of HC)

$fCE_{i,t}$ = Combustion efficiency (0.98 moles of $CO_2$ formed each mole of carbon combusted)

$MWCO_2$ = Molecular weight of $CO_2$

**Table F.1 Emission Factors for Venting and Fugitive Emissions at Crude Oil Production Facilities**

| *Emission factor type* | *Value to be used* | *Unit* | *For which emission?* | *Specific characteristics* | *Source of data* |
|---|---|---|---|---|---|
| $EF_{GD,PSC}$ | 0.0052869 | tonnes $CH_4$/$10^6$ SCF gas processed | Emissions from Glycol Dehydrator Facilities | Based on a 78.8 mole % $CH_4$ content | Table 5.1, p. 5–3 *API Compendium* |
| $EF_{GD,JV}$ | 0.0052869 | tonnes $CH_4$/$10^6$ SCF gas processed | Emissions from Glycol Dehydrator Facilities | Based on a 78.8 mole % $CH_4$ content | Table 5.1, p. 5–3 *API Compendium* |
| $EF_{GD,PSC}$ | 0.01903 | tonnes $CH_4$/$10^6$ SCF gas processed | Emissions from Glycol Pumps | Based on a 78.8 mole % $CH_4$ content | Table 5.3, p. 5–6 *API Compendium* |
| $EF_{GP,JV}$ | 0.01903 | tonnes $CH_4$/$10^6$ SCF gas processed | Emissions from Glycol Pumps | Based on a 78.8 mole % $CH_4$ content | Table 5.3, p. 5–6 *API Compendium* |
| $EF_{FL,PSC}$ | 0.000886 | tonnes $CH_4$ / bbl of crude | Emissions from flashing of $CH_4$ from Crude Oil Storage Tanks | Factor based on separator $CH_4$ content of 78.8% (vol.) | Table 5–6, p. 5–42 *API Compendium* |
| $EF_{FL,JV}$ | 0.000886 | tonnes $CH_4$/bbl of crude | Emissions from flashing of $CH_4$ from Crude Oil Storage Tanks | Factor based on separator $CH_4$ content of 78.8% (vol.) | Table 5–6, p. 5–42 *API Compendium* |
| $EF_{FE,PSC}$ | 0.00009371 | tonnes $CH_4$/bbl of Crude Produced | Fugitive Emissions from Crude oil Fields | Based on a 78.8 mole % $CH_4$ content | Table 6–1, p. 6–5 *API Compendium* |
| $EF_{FE,JV}$ | 0.0002342 | tonnes $CH_4$/bbl of Crude Produced | Fugitive Emissions from Crude oil Fields | Based on a 78.8 mole % $CH_4$ content | Table 6–1, p. 6–5 *API Compendium* |

*Source:* API 2009.

$CH_4Mf_{i,t}$ = $CH_4$ mole fraction in the AG produced in the Nigerian Fiscal Production Type $i$ Fields in year $t$ (fraction)

$RSDCH_{4i,t}$ = % Residual $CH_4$ uncombusted in the flare of the Nigerian Fiscal Production Type $i$ Fields in year $t$

### *Emission Factors for Crude Oil Production*

The relevant emission factors, obtained from the *API Compendium* are listed in table F.1

## Framework for Calculating GHG Emissions at Non-associated Gas Production Facilities

### *Venting Emissions*

It is assumed that in the Nigerian fields, the major sources of GHG venting in this segment comes from the following sources:

#### *Glycol Dehydration Emissions from NAG Production*

Glycol dehydration is used to remove water from gas streams. The entire NAG produced is passed through glycol dehydration at the field even before they are sent to gas processing facilities. Methane emissions occur when $CH_4$ absorbed by the glycol is driven off into the atmosphere during the glycol regeneration process. These venting emissions are estimated as follows:

$$VE_{NAG,GD,i,t} = NAG_{i,t} * EF_{GD,i}$$

$$VE_{NAG,GD,t} = 25 * \Sigma_i VE_{NAG,GD,i,t}$$

Where:

$VE_{NAG,GD,i,t}$ = Venting emissions of $CH_4$ from the Glycol Dehydration Units of NAG Production Facilities in the Nigerian Gas Fields under the Fiscal Production Type *i* Field in year *t* (tonnes)

$VE_{NAG,GD,JD,t}$ = Venting emissions of $CH_4$ from the Glycol Dehydration Units of NAG Production Facilities in the Nigerian Gas Fields under the JV Arrangements in year *t* (tonnes $CH_4$)

$NAG_{i,t}$ = Non-associated gas production in Fiscal Production Arrangement *i* Fields in year *t* (CM)

$VE_{NAG,GD,t}$ = Total Venting emissions of $CH_4$ from the Glycol Dehydration Units of NAG Production Facilities in the Nigerian Gas Fields under the PSC and the JV Arrangements in year *t* ($tCO_2e$)

$EF_{GD}$ = Emission factor for $CH_4$ for Gas Dehydration Segment of the Gas Field $\left(\frac{\text{tonnes}}{\text{MMSCF Gas Processed}}\right)$

***Glycol Pumps***

Both electric and gas-assisted pumps are used to circulate glycol in the dehydrator system. We have modeled this class of vented emissions in NAG production as follows:

$$VE_{NAG,GP,i,t} = NAG_{i,t} * EF_{GP,i}$$

$$VE_{NAG,GP,t} = 25 * \sum_i VE_{NAG,GP,i,t}$$

Where:

$VE_{NAG,GP,i,t}$ = Venting emissions of $CH_4$ from the Glycol Pumps Units of NAG Production Facilities in the Nigerian Gas Fields under the Fiscal Production Type *i* Field in year *t* (tonnes)

$NAG_{i,t}$ = Non-associated gas production in Fiscal Production Arrangement *i* fields in year *t* (CM)

$VE_{cop,GP,t}$ = Total Venting emissions of $CH_4$ from the Glycol Dehydration Units of NAG Production Facilities in the Nigerian Gas Fields under the PSC and the JV Arrangements in year *t* ($tCO_2e$)

$EF_{GP,i}$ = Emission factor for $CH_4$ for Glycol Pumps in the Fiscal Production Type *i* Gas Field $\left(\frac{\text{tonnes } CH_4}{\text{MMSCF Gas Processed}}\right)$

***Total Venting Emissions at NAG producing fields $EF_{PW,JV}$ is estimated by:***

$$VE_{NAG,t} = VE_{NAG,GD,t} + VE_{NAG,GP,t} + VE_{NAG,PW,t}$$

### *Fugitive Emissions from NAG Production*

According to the *API Compendium*, fugitive emissions from the production of NAG can be significant. They are estimated for the Nigerian NAG production fields according to the following equations:

$$FE_{NAG,i,t} = NAG_{i,t} * EF_{FEG,i}$$

$$FE_{NAG,t} = 25 * \sum_i FE_{NAG,i,t}$$

Where:

$FE_{NAG,i,t}$ = Fugitive emissions of $CH_4$ from NAG Production Facilities in the Nigerian Gas Fields under the Fiscal Production Arrangement Type *i* Fields in year *t* (tonnes $CH_4$)

$NAG_{i,t}$ = Non-associated gas production in Fiscal Production Arrangement *i* Fields in year *t* (CM)

$FE_{NAG,t}$ = Total Fugitive emissions of from NAG Production Facilities in the Nigerian Gas Fields under the PSC and the JV Arrangements in year *t* ($tCO_2e$)

$EF_{FEG,i}$ = Emission for fugitive $CH_4$ emissions from Fiscal Production Type *i* Gas Fields in Nigeria in year *t* $\left(\dfrac{\text{tonnes } CH_4}{\text{barrels of oil produced}}\right)$

### *Combustion Emissions from NAG Production*

GHG emissions during the production of NAG come from the combustion of fuel to supply energy to the facility. For emissions from fuel combustion the approach taken in the *API Compendium* is to assume complete combustion (that is, 100 percent of the fuel combusts to $CO_2$). This assumption applies to almost all combustion, with the exception of flaring. In NAG production, apart from the fuel combusted to derive energy needed to drive drilling equipment during the drilling and completion of producing wells, fuel is also combusted to supply energy to some of the separation processes encountered. The study team developed the following framework to estimate GHG emissions from fuel combustion during the production of NAG as follows:

#### ***Emissions from Fuel Combustion at Stationary Sources***

Estimates of emissions from combustion of fuels in on-site stationary energy equipment at PSC and JV oil fields were made as follows:

***For the Combustion of Gas at the JV and PSC NAG fields:***

$$CE_{i,G,GC,t} = \left(\frac{NAG_{i,t} * f_{i,G} * f_{Ggas,i} * \rho_C * 44}{HHV * 12 * 10^3}\right)$$

Where:

$CE_{i,G,GC,t}$ = GHG emissions from combustion of natural gas at the NAG Fiscal Production Type *i* fields in year *t* ($tCO_2e$)

$NAG_{i,t}$ = Non-associated gas production in Fiscal Production Arrangement *i* fields in year *t* (CM)

$f_{i,G}$ = Fuel combusted at the Fiscal Production Type *i* NAG fields to produce 1 SCF of NAG $\left(\frac{\text{Kcal of fuel}}{\text{SCF of NAG Produced}}\right)$

$f_{Ggas,i}$ = Fraction of fuel combusted at the Fiscal Production Type *i* NAG fields that is natural gas (fraction)

*HHV* = High heating values of natural gas (Kcals/$m^3$)

$\rho_C$ = Carbon density of natural gas $\left(\frac{\text{Kg C}}{\text{m}^3 \text{ of natural gas}}\right)$

***For the Combustion of Diesel Fuel at the JV and PSC Oil Field:***

$$CE_{i,G,DC,t} = \left(\frac{NAG_{i,t} * f_{i,G} * (1 - f_{Ggas,i}) * \rho_C * 44}{HHV * 12 * 10^3}\right)$$

Where:

$CE_{i,G,DC,t}$ = GHG emissions from combustion of Diesel at the NAG Fiscal Production Type *i* fields in year *t* ($tCO_2e$)

$f_{i,G}$ =Specific fuel combusted at the Fiscal Production Type *i* NAG fields to produce 1 SCF of NAG $\left(\frac{\text{Kcal of fuel}}{\text{SCF of NAG Produced}}\right)$

$f_{Ggas}$ = Fraction of fuel combusted at the NAG fields that is natural gas (fraction)

*HHV* = High heating values of diesel (Kcals/Kg diesel)

$\rho_C$ = Carbon density of diesel $\left(\frac{\text{Kg C}}{\text{Kg of diesel}}\right)$

**Total Combustion Emission ($TCE_{NAG,t}$) from production of NAG is estimated as:**

$$TCE_{NAG,t} = \sum_i CE_{i,G,GC,t} + \sum_i CE_{i,G,DC,t}$$

### *Emission Factors for NAG Production*

The relevant emission factors, obtained from the *API Compendium*, are listed in table F.2

## Framework for Calculating GHG Emissions at Natural Gas Processing Facilities

Natural gas produced in the fields (AG and NAG) must be treated at gas processing facilities (GPFs) before they can be used at the various end uses. Such gas processing is not needed for AG that will be flared or that will be used for field pressure enhancement and enhanced crude oil recovery at the field. The following equations and specifications were used to estimate GHG emissions for this segment of the oil and gas industry in Nigeria. The equations are based on a methodological framework described in the *API Compendium*.

**Table F.2 Emission Factors for Venting at NAG Production Facilities**

| *Emission factor type* | *Value to be used* | *Unit* | *For which emission?* | *Specific characteristics* | *Source of data* |
|---|---|---|---|---|---|
| $EF_{GD,PSC}$ | 0.0052869 | tonnes $CH_4/10^6$ SCF gas processed | Emissions from Glycol Dehydrator Facilities | Based on a 78.8 mole % $CH_4$ content | Table 5.1, p. 5–3 *API Compendium* |
| $EF_{GD,JV}$ | 0.0052869 | tonnes $CH_4/10^6$ SCF gas processed | Emissions from Glycol Dehydrator Facilities | Based on a 78.8 mole % $CH_4$ content | Table 5.1, p. 5–3 *API Compendium* |
| $EF_{GP,PSC}$ | 0.01903 | tonnes $CH_4/10^6$ SCF gas processed | Emissions from Glycol Pumps | Based on a 78.8 mole % $CH_4$ content | Table 5.3, p. 5–6 *API Compendium* |
| $EF_{GP,JV}$ | 0.01903 | tonnes $CH_4$/SCF gas processed | Emissions from Glycol Pumps | Based on a 78.8 mole % $CH_4$ content | Table 5.3, p. 5–6 *API Compendium* |
| $EF_{FEG,PSC}$ | 0.01038 | tonnes $CH_4$/SCF of NAG Produced | Fugitive Emissions from NAG PSC Fields | Based on a 78.8 mole % $CH_4$ content | Table 6–1, p. 6–5 *API Compendium* |
| $EF_{FEG,JV}$ | 0.02595 | tonnes $CH_4$/SCF of NAG Produced | Fugitive Emissions from Crude Oil Fields | Based on a 78.8 mole % $CH_4$ content | Table 6–1, p. 6–5 *API Compendium* |

*Source:* API 2009.

## *Venting Emissions from Gas Processing*

The following $CH_4$ venting emission pathway is considered in the natural gas processing segment of the Nigerian Oil and Gas industry:

### *Glycol Dehydration Emissions at GPFs*

Methane venting emissions from glycol dehydrators at Gas Processing Facilities are calculated using the following equations:

$$VE_{GPF,GD,t} = G_{FGPF,t} * EF_{GD,GPF}$$

$$G_{FGPF,t} = \Sigma_i NAG_{i,t} + f_{AG,GPF,t} * \Sigma_i AG_{i,t}$$

Where:

$VE_{GPF,GD,t}$ = Venting emissions of $CH_4$ from the Glycol Dehydration Units of GPFs in Nigeria in year $t$ (tonnes $CH_4$)

$G_{FGPF,t}$ = Total Gas processed at GPFs in Nigeria in year $t$ (SCF)

$f_{AG,GPF,t}$ = Fraction of Associated Gas produced in the Nigerian Oil fields that were sent to a GPF in year $t$ (fraction)

$EF_{GD,GPF}$ = Emission factor for $CH_4$ venting from Gas Dehydration Segment of GPF in $\left(\frac{\text{tonnes } CH_4}{\text{SCF Gas Processed}}\right)$

### *Glycol Pumps*

Vented $CH_4$ emissions from Glycol Pumps in NAG Production are estimated as follows:

$$VE_{GPF,GP,t} = G_{FGPF,t} * EF_{GP,GPF}$$

$$G_{FGPF,t} = \sum_i NAG_{i,t} + f_{AG,GPF,t} * \sum_i AG_{i,t}$$

Where:

$VE_{GPF,GP,t}$ = Venting emissions of $CH_4$ from the Glycol Pumping Units of GPFs in the Nigeria in year *t* (tonnes $CH_4$)

$G_{FGPF,t}$ = Total Gas processed at GPFs in Nigeria in year *t* (SCF)

$f_{AG,GPF,t}$ = Fraction of Associated Gas produced in the Nigerian Oil fields that were sent to a GPF in year *t* (fraction)

$EF_{GP,GPF}$ = Emission factor for $CH_4$ venting from Glycol Pumping Units of GPF in $\left(\frac{\text{tonnes } CH_4}{\text{SCF Gas Processed}}\right)$

***Total venting emissions at the GPF are estimated as:***

$$VE_{GPF,t} = 25 * (VE_{GPF,GD,t} + VE_{GPF,GP,t} + VE_{GPF,PW,t})$$

Where:

$VE_{GPF,t}$ = Total venting emissions at the GPFs in Nigeria in year *t* ($tCO_2e$)

### *Fugitive Emissions at GPFs*

According to the *API Compendium*, fugitive emissions from the processing of natural gas can be significant. They are estimated using the following equations:

$$FE_{GPF,t} = 25 * (G_{FGPF,t} * EF_{FE,GPF})$$

$$G_{FGPF,t} = \sum_i NAG_{i,t} + f_{AG,GPF,t} * \sum_i AG_{i,t}$$

Where:

$FE_{GPF,t}$ = Fugitive emissions of $CH_4$ from GPFs in year *t* ($tCO_2e$)

$G_{FGPF,t}$ = Total natural gas processed at GPFs in Nigeria in year *t*(SCF)

$EF_{FE,GPF}$ = Emission factor for fugitive $CH_4$ emissions from GPFs $\left(\frac{\text{tonnes } CH_4}{\text{SCF of gas processed}}\right)$

### *Combustion Emissions*

GHG emissions during the processing of natural gas at the GPFs come from the combustion of fuel to supply energy to the facility. For emissions from fuel combustion the approach taken in the *API Compendium* is to assume complete combustion (that is, 100 percent of the fuel combusts to $CO_2$). This assumption applies to almost all combustion, with the exception of flaring. The study team developed the following framework to estimate GHG emissions from fuel combustion during the processing of natural gas at the GPFs:

***Emissions from Fuel Combustion at Stationary Sources***

Assuming that all energy required is generated on-site (that is, no importation of electricity from the grid), estimated emissions from combustion of fuels in stationary equipment at GPFs are as follows:

For the Combustion of Gas at GPFs:

$$CE_{g,GPF,t} = \left( \frac{G_{FGPF,t} * f_{GPF} * f_{Ggas} * MW_g * C_g * 44}{HHV * \rho_{mg} * 12 * 10^6} \right)$$

Where:

$CE_{g,GPF,t}$ = GHG emissions from combustion of natural gas at GPFs in Nigeria in year *t* ($tCO_2e$)

$G_{FGPF,t}$ = Total volume of natural gas processed at GPFs in Nigeria in year *t* (SCF)

$f_{GPF}$ = Fuel combusted at the GPFs for each SCF of Gas processed $\left( \frac{\text{Kcal of fuel}}{\text{SCF of gas processed}} \right)$

$f_{Ggas}$ = Fraction of fuel combusted at the GPFs that is natural gas (fraction)

$MW_g$ = Molecular weight of natural gas $\left( \frac{\text{g of natural gas}}{\text{g mole of natural gas}} \right)$

$C_g$ = Weight of carbon per weight of natural gas $\left( \frac{\text{g of carbon}}{\text{100 g of natural gas}} \right)$

*HHV* = High heating values of natural gas ($Kcals/m^3$)

$\rho_{mg}$ = Molar density of natural gas $\left( \frac{\text{Cubic meters of natural gas}}{\text{g mole of natural gas}} \right)$

***For the Combustion of diesel fuel at the GPFs:***

$$CE_{d,GPF,t} = \left( \frac{G_{FGPF,t} * f_{GPF} * (1 - f_{Ggas}) * MW_g * C_g * 44}{HHV * \rho md * 12 * 10^6} \right)$$

Where:

$CE_{d,GPF,t}$ = GHG emissions from combustion of Diesel at the GPFs in year *t* ($tCO_2e$)

$G_{FGPF,t}$ = Total gas processed at the at the GPFs in year *t* ($tCO_2e$)

$f_{GPF}$ = Fuel combusted at the GPFs for each SCF of Gas processed $\left( \frac{\text{Kcal of fuel}}{\text{SCF of gas processed}} \right)$

$f_{Ggas}$ = Fraction of fuel combusted at the GPFs that is natural gas (fraction)

$MW_d$ = Molecular weight of diesel $\left( \frac{\text{g of diesel}}{\text{g mole of diesel}} \right)$

$C_g$ = Weight of carbon per weight of diesel $\left( \frac{\text{g of carbon}}{\text{100 g of diesel}} \right)$

*HHV* = High heating values of diesel (Kcals/Kg diesel)

$\rho_{md}$ = Molar density of diesel $\left( \frac{\text{g of diesel}}{\text{g mole of diesel}} \right)$

**Table F.3 Emission Factors for Venting and Fugitive Emissions at Gas Processing Facilities**

| *Emission factor type* | *Value to be used* | *Unit* | *For which emission?* | *Specific characteristics* | *Source of data* |
|---|---|---|---|---|---|
| $EF_{GD,GPF}$ | 0.0023315 | tonnes $CH_4/10^6$ SCF gas processed | Emissions from Glycol Dehydrator Facilities | Based on a 87 mole % $CH_4$ content | Table 5.1, p. 5–3 *API Compendium* |
| $EF_{Gp,GPF}$ | 0.0034096 | tonnes $CH_4/10^6$ SCF gas processed | Emissions from Glycol Pumps | Based on a 87 mole % $CH_4$ content | Table 5.3, p. 5–6 *API Compendium* |
| $EF_{FE,GPF}$ | 0.02918 | tonnes $CH_4$/SCF of gas processed | Fugitive emissions from GPFs | Based on a 87 mole % $CH_4$ content | Table 6–1, p. 6–5 *API Compendium* |

*Source:* API 2009.

### *Emission Factors for Gas Processing*

Table F.3 provides information on the EFs used for the calculation of emissions from gas processing facilities (GPFs):

## Framework for Calculating GHG Emissions from Gas Transportation

Marketable natural gas produced at the GPF is transported through long distances at high pressures to markets where it is distributed. Due to constant changes in pressure and temperature during this transportation processes, liquids including condensate and water condense out as liquids in the gas. These must be removed to avoid hydrate and other problems in pipelines. Therefore condensed water is removed at intervals along the pipeline route using glycol dehydrating units. $CH_4$ venting occurs at these dehydrators. Fugitive $CH_4$ emissions also occur along the transmission pipelines. Fugitive emissions come from equipment leaks, generally occurring through valves, flanges, seals, or related equipment. Last but not the least is combustion emissions from gas used to fuel the compressors needed to move the gas.

### *Venting Emissions from Glycol Dehydration Plants*

Venting emissions are assumed limited to those from glycol dehydration units.

#### *Glycol Dehydrator Units*

The following equations are used to estimate these emissions:

$$VE_{GTR,GD,t} = 25 * (G_{Tr,t} * EF_{GD,GTR})$$

$$G_{Tr,t} = G_{FGPF,t} * (1 - G_{l,t})$$

Where:

$VE_{GTR,GD,t}$ = Venting emissions of $CH_4$ from the Glycol Dehydration Units along Gas Transmission Pipeline Facilities in Nigeria in year $t$ ($tCO_2e$)

$G_{Tr,t}$ = Volume of gas sent into transmission lines in Nigeria in year $t$ (SCF)

$G_{FGPF,t}$ = Total Gas processed at GPFs in Nigeria in year $t$ (SCF)

$f_{AG,GPF,t}$ = Fraction of AG produced in the Nigerian Oil fields that were sent to a GPF in year $t$ (fraction)

$G_{l,t}$ = Gas loss (fraction) at the GPF (fraction)

$EF_{GD,GPF}$ = Emission factor for $CH_4$ venting from Gas Dehydration Segment of GPF in $\left(\frac{\text{tonnes } CH_4}{\text{SCF Gas Processed}}\right)$

### *Fugitive Emissions from Glycol Dehydration Plants*

Fugitive emissions are calculated as follows:

$$FE_{GT,CH_4,t} = G_{Tr,t} * SPK_{Tr} * EF_{Tr,CH_4}$$

$$FE_{GT,CO_2OX,t} = G_{Tr,t} * SPK_{Tr} * EF_{Tr,CO_2OX}$$

$$FE_{GT,CO_2LKX,t} = G_{Tr,t} * SPK_{Tr} * EF_{Tr,CO_2LKX}$$

**Total fugitive emissions from natural gas transmission lines are calculated as:**

$$FE_{GT,t} = 25 * (FE_{GT,CH_4,t}) + FE_{GT,CO_2OX,t} + FE_{GT,CO_2LKX,t}$$

Where:

$FE_{GT,t}$ = Total Fugitive Emissions from gas transmission line in year *t* ($tCO_2e$)

$FE_{GT,CH_4,t}$ = Fugitive Emissions from pipeline leaks of $CH_4$ from a gas transmission line in year *t* (tonnes $CH_4$)

$FE_{GT,CO_2OX,t}$ = Fugitive Emissions from oxidation of pipeline leaks of $CH_4$ from a gas transmission line in year *t* (tonnes $CH_4$)

$FE_{GT,CO_2LKX,t}$ = Fugitive Emissions from pipeline leaks of $CO_2$ from a gas transmission line in year *t* (tonnes $CH_4$)

$G_{Tr,t}$ = Volume of gas transmitted in transmission lines in year *t* (SCF)

$SPK_{Tr}$ = Specific Pipeline length per SCF transmitted Characteristic of the sector in Nigeria $\left(\frac{\text{Miles}}{\text{SCF}}\right)$

$EF_{Tr,CH_4}$ = Emission factor for methane leakage from transmission pipelines $\left(\frac{\text{tonnes } CH_4}{\text{mile-year}}\right)$

$EF_{Tr,CO_2OX}$ = Emission factor for oxidation of methane leakage from transmission pipelines $\left(\frac{\text{tonnes } CO_2}{\text{mile-year}}\right)$

$EF_{Tr,CO_2LKX}$ = Emission factor for $CO_2$ leakage from transmission pipelines $\left(\frac{\text{tonnes } CO_2}{\text{mile-year}}\right)$

### *Combustion Emissions from Compressors*

Most compressors in the natural gas delivery system use gas from their own lines as fuel. Compressor stations are located approximately every 50 to 60 miles along each pipeline to boost the pressure lost through the friction of the natural gas moving through the pipe. Compressors are fueled directly using gas from the pipeline; however, many are run by electric engines that are also gas-fueled.

Due to lack of data from the Nigerian gas sector, the study team used information from the U.S. gas supply system to build a scenario for the Nigerian system. According to a study conducted in 2008 (INGAA 2008), the pipeline grid in the US moves approximately about 20 trillion cubic feet (TCF) of natural gas annually to consumers. About 3 percent of gas is used by the compressor station to pressurize and move the gas. This analysis assumed that, for the Nigerian case, also 3 percent of gas delivered to consumers in a year is used to pressurize and move the gas to consumers. Assuming 100 percent combustion, emissions of $CO_2$ from the network of pipelines and their appurtenances to move natural gas to end-use consumers are calculated using the following equations:

**For natural gas consumed as fuel at the compressor stations:**

$$CE_{GT,t} = \left( \frac{G_{TD,t} * f_{TDC} * f_{Ggas} * MW_g * C_g * 44}{HHV * \rho_{mg} * 12 * 10^6} \right)$$

$$G_{TD,t} = \sum_i G_{i,t}$$

Where:

$CE_{GT,t}$ = GHG emissions from combustion of natural gas at Compressor Stations in year $t$ ($tCO_2e$)

$G_{TD,t}$ = Total volume of natural gas supplied to end users in year $t$ (SCF)

$G_{i,t}$ = Gas supply to consumer sector $i$ in year $t$ (SCF)

$f_{TDC}$ = Fraction of natural gas supply to consumers that is used as fuel at the Compressor stations (fraction)

$f_{Ggas}$ = Fraction of fuel combusted at the compressor stations as fuel that is natural gas (fraction)

$$MW_g = \text{Molecular weight of natural gas} \left( \frac{\text{g of natural gas}}{\text{g mole of natural gas}} \right)$$

$$C_g = \text{Weight of carbon per weight of natural gas} \left( \frac{\text{g of carbon}}{\text{100 g of natural gas}} \right)$$

$HHV$ = High heating values of natural gas (Kcals/$m^3$)

$$\rho_{mg} = \textit{Molar} \text{ density of natural gas} \left( \frac{\text{Cubic meters of natural gas}}{\text{g mole of natural gas}} \right)$$

## Framework for Calculating GHG Emissions from Oil Transportation

Fugitive emissions from crude oil transmission pipelines are assumed to be negligible. Emissions come from burning of crude oil to fuel the pumps used to ship the oil.

### *Combustion Emissions*

Pump stations are installed at intervals along the pipeline used to ship the oil. It is estimated that 1 percent of the oil transported as fuel is combusted to provide energy to the pumps. The combustion emissions for oil transportation is calculated by the following equation:

$$CE_{c,CPS,t} = \left( \frac{CTR_{RF,t} * f_{PS} * MW_{CR} * C_{CR} * 44}{HHV * \rho_{mCR} * 12 * 10^6} \right)$$

Where:

$CE_{c,CPS,t}$ = GHG emissions from combustion of Diesel at the Crude Pumping Stations in year $t$ ($tCO_2e$)

$CTR_{RF,t}$ = Total Crude Oil transported in pipelines to domestic refineries in year $t$ (barrels)

$f_{PS}$ = Equivalent fraction of the crude combusted as fuel at the Pumping Stations (fraction)

$$MW_{CR} = \text{Molecular weight of Crude} \left( \frac{\text{g of Crude}}{\text{g mole of Crude}} \right)$$

$$C_{CR} = \text{Weight of Carbon per weight of Crude} \left( \frac{\text{g of carbon}}{\text{100 g of Crude}} \right)$$

$HHV$ = High heating values of crude (Kcals/Kg Crude)

$$\rho_{mg} = \text{Molar density of Crude} \left( \frac{\text{g of Crude}}{\text{g mole of Crude}} \right)$$

### *Emission Factors for Oil and Gas Transportation*

Table F.4 provides information on the EFs used for the calculation of emissions from Oil and Gas Transport.

**Table F.4 Emission Factors for Venting and Fugitive Emissions at Oil and Gas Transportation Facilities**

| *Emission factor type* | *Value to be used* | *Unit* | *For which emission?* | *Specific characteristics* | *Source of data* |
|---|---|---|---|---|---|
| $EF_{GD,GTR}$ | 0.001798 | tonnes $CH_4/10^6$ SCF gas processed | Emissions from Glycol Dehydrator Facilities | Based on a 93.4 mole % $CH_4$ content | Table 5.1, p. 5–3 *API Compendium* |
| $EF_{Tr,CH_4}$ | 2.233 | tonnes $CH_4$/Km-year | Fugitive Emissions of $CH_4$ from Gas Transmission lines | Based on a 93.4 mole % $CH_4$ content | Table 6–1, p. 6–5 *API Compendium* |
| $EF_{Tr,C02OX}$ | 0.002139 | tonnes $CO_2$/Km-year | Fugitive Emissions of $CO_2$ from Methane Oxidation in Gas Transmission lines | Based on a 2 mole % $CO_2$ content in gas | Table 6–1, p. 6–5 *API Compendium* |
| $EF_{Tr,C02LKX}$ | 0.1315 | tonnes $CO_2$/Km-year | Fugitive Emissions from $CO_2$ leakage in Gas Transmission lines | Based on a 2 mole % *of* $CO_2$ content in gas | Table 6–1, p. 6–5 *API Compendium* |

*Source:* API 2009.

## Framework for Calculating GHG Emissions from LNG Facilities

GHG emissions in an LNG facility include $CO_2$ emissions from on-site combustion of gas used as fuel to supply the energy requirement of the LNG facility (power and heat) and emissions ($CH_4$ and $CO_2$) from flaring of gas at the LNG facility and fugitive emissions from the LNG facilities (mostly $CH_4$). In the absence of specific data for fugitive emissions at LNG plants in the *API Compendium*, EFs have been assumed to be as for a Gas Processing Facility.

### *Emissions from Combustion of Gas from LNG Facilities*

These emissions are calculated as follows:

$$CE_{LNG,t} = \left( \frac{G_{LNG,t} * f_{F,t} * \rho_g * C_g * 44}{12 * 1000} \right)$$

Where:

$CE_{LNG,t}$ = Emissions of $CO_2$ from the combustion of natural gas used as fuel at LNG facility in year $t$ ($tCO_2e$)

$G_{LNG,t}$ = Total quantity of natural gas supplied to LNG facilities in Nigeria in year $t$ (SCF)

$f_{F,t}$ = Fraction of natural gas supplied to LNG facilities in Nigeria in year $t$ that was used as fuel (%)

$$\rho_g = \text{Density of natural gas} \left( \frac{\text{kg}}{\text{SCF}} \right)$$

$C_g$ = Carbon content of the natural gas supplied to LNG facilities $\left( \frac{\text{kg C}}{\text{Kg Natural Gas}} \right)$

### *Flare Emissions from LNG Facilities*

Flaring occurs during operation of a LNG liquefaction plant, and during loading operations. LNG like all other gas processing facilities routinely flares some of their gas throughput usually for safety reasons. In these flaring operations, $CO_2$ is usually the main GHG emission gas while $CH_4$ is also produced from incomplete combustion at the flares. The emissions from flaring at LNG plants are calculated as follows:

$$CE_{LNGf,C02,t} = G_{LNG,t} * f_{\text{Gflared},t} * \sum_i (MHC_{i,t} * C_{i,t}) / MV_{G,t} * flE_{\text{eff}} * 44 * 1000$$

$$CE_{LNGf,CH_4,t} = 25 * G_{LNG,t} * f_{Gflared,t} * CH_4 Mf_{G,t} * MWCH_4 * \left( \frac{1 - flE_{eff}}{MV_{G,t}} \right) * 1000$$

Where:

$CE_{LNGf,CO_2,t}$ = Emissions of $CO_2$ from flaring of gas at LNG facilities in year $t$ ($tCO_2e$)

$CE_{LNGf,CH_4,t}$ = Emissions of $CH_4$ from flaring of gas at LNG facilities in year $t$ ($tCO_2e$)

$f_{Gflared,t}$ = Fraction of the gas supplied to the LNG facility that is flared

$MV_{G,t}$ = Molar Volume of the Gas $\left(\frac{\text{Moles of natural Gas}}{\text{Volume of natural gas}}\right)$

$MHC_{i,t}$ = Mole fraction of Hydrocarbon type $i$ in the gas

$C_{i,t}$ = Number of Carbon Atoms in Hydrocarbon type $i$ in the gas

$flE_{eff}$ = Flare efiiciency (fraction)

$GWP_{CH_4}$ = Global Warming Potential of $CH_4$

$CH_4Mf_{G,t}$ = Mole Fraction of $CH_4$ in gas supplied to the LNG Facilities in year $t$

$MWCH_4$ = Molecular Weight of $CH_4$(16)

### *Fugitive Emissions from LNG Facilities*

Fugitive emissions at LNG facilities are estimated using the same emission factor as the one used for such emissions at Gas Processing Facilities (GPFs). The equation used for this estimation is:

$$CE_{fgLNG,t} = 25 * G_{LNG,t} * EF_{FE,LNG}$$

Where:

$CE_{fgLNG,t}$ = fugitive emissions of $CH_4$ from LNG facilities operating in Nigeria in year $t$ ($tCO_2e$)

$EF_{FE,LNG}$ = Emission Factor for Fugitive Emissions from LNG Facilities $\left(\frac{tCH_4}{\text{Volume of Gas processed}}\right)$

## Framework for Calculating GHG Emissions from GTL Plants

Similar assumptions for emissions at LNG facilities were made concerning GHG emissions at GTL facilities. For example, the significant types of emissions sources in this segment of the oil and gas sector are assumed to be: Emissions from on-site combustion of gas used as fuel at the GTL facilities, emissions from flaring at the GTL facilities, and fugitive emissions at the GTL facilities.

The relevant equations used for this segment of the industry in this book are as follows:

### *Emissions from Combustion of Gas in GTL Plants*

This $CO_2$ emission is calculated as:

$$CE_{GTL,t} = \left(\frac{G_{GTL,t} * f_{FG,t} * \rho_g * C_g * 44}{12*100}\right)$$

Where:

$CE_{GTL,t}$ = Emissions of $CO_2$ from the combustion of natural gas used as fuel at GTL facility in year *t* ($tCO_2e$)

$G_{GTL,t}$ = Total quantity of natural gas supplied to GTL facilities in Nigeria in year *t* (SCF)

$f_{FG,t}$ = Fraction of natural gas supplied to GTL facilities in Nigeria in year t that was used as fuel (%)

$$\rho_g = \text{Density of natural gas}\left(\frac{\text{Kg}}{\text{SCF}}\right)$$

$C_g$ = Carbon content of the natural gas supplied to GTL facilities $\left(\frac{\text{Kg C}}{\text{Kg Natural Gas}}\right)$

### *Flare Emissions from GTL Plants*

GTL plants, like all other gas processing facilities, routinely flare some of their gas throughput, usually for safety reasons. In these flaring operations, $CO_2$ is usually the main GHG emission gas while $CH_4$ is also produced from incomplete combustion at the flares. The emissions from flaring at GTL plants are calculated as follows:

$$CE_{GTLf,\text{C02},t} = G_{GTL,t} * f_{\text{Gflared},t} * \sum_i (MHC_{i,t} * C_{i,t})/MV_{G,t} * flE_{eff} * 44 * 1000$$

$$CE_{GTLf,CH_4,t} = 25 * G_{GTL,t} * f_{Gflared,t} * CH_4 Mf_{G,t} * MWCH_4 * \left(\frac{1 - flE_{eff}}{MV_{G,t}}\right) * 1000$$

Where:

$CE_{LNGf,CO_2,t}$ = Emissions of $CO_2$ from flaring of gas at GTL facilities in year *t* ($tCO_2e$)

$CE_{LNGf,CH_4,t}$ = Emissions of $CH_4$ from flaring of gas at GTL facilities in year *t* ($tCO_2e$)

$f_{Gflared,t}$ = Fraction of the gas supplied to the GTL facility that is flared

$$MV_{G,t} = \text{Molar Volume of the Gas}\left(\frac{\text{Moles of natural Gas}}{\text{Volume of natural gas}}\right)$$

$MHC_{i,t}$ = Mole fraction of Hydrocarbon type *i* in the gas

$C_{i,t}$ = Number of Carbon Atoms in Hydrocarbon type *i* in gas

$flE_{eff}$ = Flare efficiency (fraction)

$CH_4Mf_{G,t}$ = Mole Fraction of $CH_4$ in gas supplied to the GTL Facilities in year *t*

$MWCH_4$ = Molecular Weight of $CH_4$(16)

### *Fugitive Emissions from GTL plants*

Fugitive emissions at GTL facilities are estimated using the same emission factor the as was used for such emissions at Gas Processing Facilities (GPFs). The equation used for this estimation is:

$$CE_{fgGTL,t} = 25 * G_{GTL,t} * EF_{FE,GTL}$$

Where:

$CE_{fgGTL,t}$ = Fugitive Emissions of $CH_4$ from GTL Facilities operating in Nigeria in year $t$ ($tCO_2e$)

$EF_{FE,GTL}$ = Emission Factor for Fugitive Emissions from GTL Facilities $\left(\frac{t,CH_4}{\text{Volume of Gas processed}}\right)$

## Appendix References

API (American Petroleum Institute). 2009. *Compendium of Greenhouse Gas Emissions Estimation Methodologies for the Oil and Gas Industry*. Washington, DC: API.

INGAA (Interstate Natural Gas Association of America). 2005. *Greenhouse Gas Emission Estimation Guidelines for Natural Gas Transmission and Storage*, Vol. 1. Washington, DC: INGAA. http://www.ingaa.org/cms/33/1060/6435/5485.aspx.

PART 3

# Power Sector

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# Abbreviations

| | |
|---|---|
| AEO | *Annual Energy Outlook*, U.S. Department of Energy |
| AMAC | Analytica Marginal Abatement Cost model |
| BAU | business-as-usual |
| CAGR | compound annual growth rate |
| CCA | Climate Change Assessment Program, World Bank |
| CBN | Central Bank of Nigeria |
| CCGT | Combined-cycle gas turbine |
| CCS | carbon capture and storage |
| CDM | Clean Development Mechanism |
| CER | Certified Emissions Reduction |
| CFL | compact fluorescent lamp |
| $CO_2$ | carbon dioxide |
| $CO_2e$ | carbon dioxide equivalent emissions |
| CSP | concentrating solar (thermal) power |
| DLC | delayed low-carbon scenario |
| DNI | direct normal irradiance |
| ECN | Energy Commission of Nigeria |
| ECOWAS | Economic Community of West African States |
| EE | energy efficiency |
| EFFECT | Energy Forecasting Framework and Emissions Consensus Tool |
| EIA | Energy Information Agency, U.S. Department of Energy |
| ESCO | energy service companies and cooperatives |
| ESMAP | Energy Sector Management Assistance Program, World Bank |
| ESPRA | Electric Power Sector Reform Act, 2005 |
| FGN | Federal Government of Nigeria |
| FIT | feed-in tariff |
| FME | Federal Ministry of the Environment |
| FMP | Federal Ministry of Power |
| FMST | Federal Ministry of Science and Technology |

| | |
|---|---|
| GDP | gross domestic product |
| GHG | greenhouse gases |
| GJ | gigajoule |
| GW | gigawatt |
| IEA | International Energy Agency |
| IFC | International Finance Corporation |
| IPCC | Intergovernmental Panel on Climate Change |
| IPP | independent power producer |
| ISCC | integrated solar combined cycle |
| kWh | kilowatt-hour |
| l | liter |
| LCOE | levelized cost of electricity |
| LDC | load duration curve |
| LFGE | landfill gas to energy |
| MAC | marginal abatement cost |
| MDA | ministries, departments, and agencies |
| MJ | megaJoule |
| MMBtu | million British thermal units |
| MMSCF | million standard cubic feet (of gas) |
| MPR | Ministry of Petroleum Resources |
| MRV | monitoring, reporting and verification |
| MSMEs | micro, small, and medium enterprises |
| Mt | million metric tonnes |
| Mt $CO_2e$ | million metric tons of carbon dioxide equivalent emissions |
| MW | megawatt |
| MYTO | Multi-Year Tariff Order |
| NAEC | Nigerian Atomic Energy Agency |
| NAMA | Nationally Appropriate Mitigation Action |
| NEP | National Energy Policy |
| NERC | Nigerian Electricity Regulatory Commission |
| NESREA | National Environmental Standards and Regulation Agency |
| NGO | nongovernmental organization |
| NPIRD | National Policy on Integrated Rural Development |
| NPV | net present value |
| NREL | *National Renewable Energy Laboratory* |
| NSSP | Nigeria Strategy Support Program |
| O&M | Operation and Maintenance |
| PACP | Presidential Action Committee on Power |
| PHCN | Power Holding Company of Nigeria, plc |

| | |
|---|---|
| PPA | power purchase agreements |
| PTFP | Presidential Task Force on Power |
| PV | Photovoltaic |
| PV-W-D | PV-wind-diesel |
| REA | Rural Electrification Agency of Nigeria |
| REC | Renewable Energy Certificate |
| R&D | research and development |
| RPS | renewable portfolio standards |
| SCGT | Single-cycle gas turbine |
| SHP | small hydropower |
| SSA | Sub-Saharan Africa |
| T&D | transmission and distribution |
| TCN | Transmission Company of Nigeria |
| TWh | terawatts per hour |
| UN | United Nations |
| UNDP | United Nations Development Programme |
| UNDP-GEF | United Nations Development Programme–Global Environment Facility |
| UNFCCC | United Nations Framework Convention on Climate Change |
| USD | United States dollars |
| Wp | watts-peak |

# Executive Summary

As part of a broader, multisector analysis of low-carbon development opportunities in Nigeria, this part of the book evaluates how the country can expand power generation and broaden access to electricity while at the same time reducing the associated carbon footprint.

Nigeria's power grid faces many challenges, including insufficient capacity to meet demand, shortages of gas for power generation, and inefficient, limited coverage transmission and distribution. These problems result in unreliable grid supply and frequent load shedding. Partly for these reasons, an estimated 50 percent of electrical energy is currently produced off-grid by diesel and gasoline generators. Nigeria has developed a comprehensive and ambitious plan to address these challenges in the "Roadmap for Power Sector Reform" (FGN 2010). The study on which this volume is based builds on these shorter-term power sector priorities and the economic growth targets envisaged by Vision 20: 2020, with projections through 2035. It identifies a reference scenario where long-term growth objectives are achieved through a power sector development model largely based on conventional generation technologies, mostly gas turbine and some hydropower.

However, this study also develops an alternative, a *low-carbon scenario* (table ES 3.1) that would enable Nigeria to achieve the same long-term development objectives, at lower overall cost—of 7 percent less in terms of NPV (net present value)—through a more diversified mix of generation sources with a more balanced supply across regions. As a cobenefit, the low-carbon scenario would also reduce greenhouse gas (GHG) emissions by 43 percent, from 4,335 down to 2,475 Mt $CO_2$e (million tonnes of carbon dioxide equivalent) through 2035.

Such an alternative low-carbon paradigm presents a number of implementation challenges in terms of information needs, technologies, institutions, regulations, and financial barriers. But it deserves consideration by policy makers, since—under a range of plausible scenarios on future power generation costs—it can save Nigeria significant costs in the long run, although with a higher up-front capital expenditure.

As Nigeria has Africa's highest population, substantial revenues from oil and gas, and a wide diversity of energy resources, it has the potential to become a continental leader in the energy technologies of the future. Growth prospects for

**Table ES 3.1 Reference and Low-Carbon Scenarios: Values for Development of Power Sector to 2035**

| | *Generation in 2035* | *Net present value of generation costs (US$ billions)* | | | *Cumulative emissions* | *% diversity of energy source* |
|---|---|---|---|---|---|---|
| *Scenarios* | *TWh* | *Capital and O&M* | *Fuel* | *Total* | *Mt $CO_2e$* | *Complement of Gini index*[a] |
| Reference | 620 | 52 | 127 | 178 | 4,335 | 17 |
| Low carbon | 525 | 71 | 94 | 166 | 2,475 | 34 |

*Source:* Calculations based on data sources listed in chapter 14 references.
a. The Gini index is often used to measure income inequality. In complement form, it is useful as a measure of the diversity of a portfolio of generation technologies. A perfectly diverse portfolio with equal generation from every technology would have a complement Gini index of 100 percent. An index of 0 percent implies a totally concentrated portfolio, with all generation from a single technology.

grid-based solar power are significant, including photovoltaics (PV) and concentrating solar thermal power (CSP). According to the EIA's *Annual Energy Outlook* (EIA 2011), solar power generation will grow 10 percent per year worldwide over the next 20 years, but 24 percent per year in Africa. By investing early enough in renewable energy, Nigeria has the opportunity to become a leader in a quickly expanding market and could perhaps establish itself as a regional hub for technology development and deployment in the rest of Africa.

## The Reference Scenario: Growing Power Demand

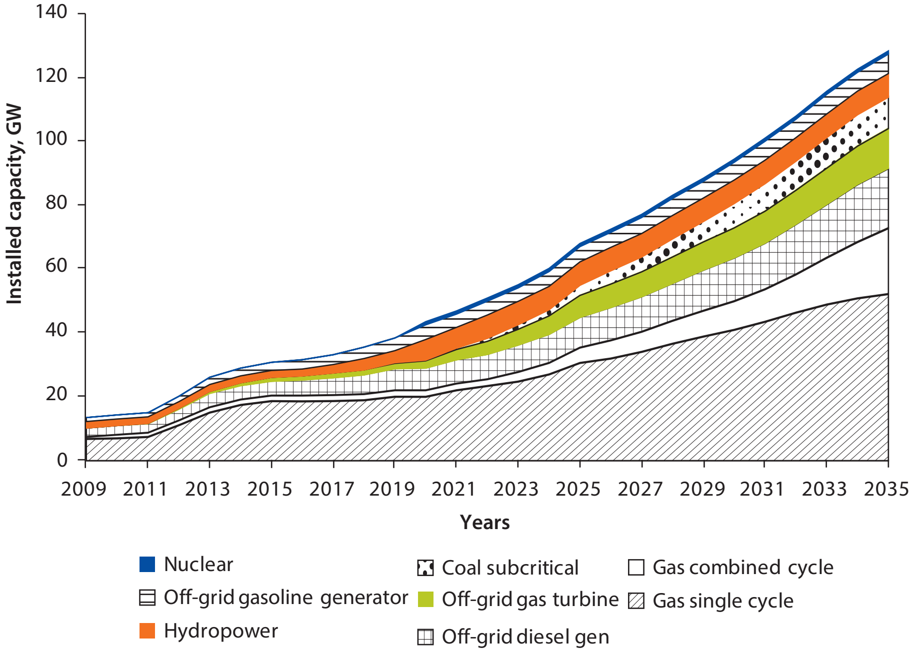
Nigeria's demand for power is poised to grow sixfold over this decade, with a declining but still significant share of off-grid supply and a rapid expansion of gas-powered generation capacity. Due to the inadequacies of the grid, Nigerians generated an estimated 50 percent of their electricity off-grid in 2009, mostly from diesel and gasoline generators. As grid capacity and reliability improve, the percentage of power generated off-grid is projected to decline to 30 percent by 2035. But, with the rapid expansion of demand, the absolute amount of off-grid generation is projected to increase by a factor of 10 over this time.

To define the reference scenario, the study team applied gross domestic product (GDP) growth rates consistent with Vision 20: 2020 (although in a slightly more conservative version) to income elasticities of power demand derived from international experience. Using an income elasticity of 1.46 and a rate of population growth of 2.4 percent on average for 2011–35, it is estimated that by 2035 Nigeria's electricity demand will be in the range of 620 Terawatt hours (TWh) per year.

## Expanded, Lower Cost Generation

The reference scenario meets projected demand with a dramatic increase in capacity, rising to 30 gigawatts in 2015, 68 gigawatts by 2025, and 128 gigawatts in 2035. It adds generating capacity following a technology mix similar to that

**Figure ES 3.1 Generation Capacity Mix in the Reference Scenario**




*Source:* Calculations based on data sources listed in chapter 14 references.

in use today (figure ES 3.1). Grid-connected generation is primarily from single-cycle gas turbines (SCGT), with a modest increase in the proportion of combined-cycle gas turbines (CCGT), which have lower levelized costs of electricity (LCOE) at expected higher gas prices. It expands hydropower subject to limits on viable sites. It also includes 1 gigawatt nuclear and 10 gigawatts subcritical coal generation, following existing Federal Government of Nigeria (FGN) plans. New off-grid capacity largely follows the existing mix of gasoline and diesel generators; it adds some off-grid gas turbine capacity, which is lower cost but only practical in those limited areas of the Niger Delta where natural gas is available. The cost of electricity from diesel and gasoline generators is high, estimated in this study as US$0.25 and $0.42/kWh, respectively, compared to about $0.07/kWh from grid-connected single-cycle gas turbines where gas is available.

The reference scenario is projected to reduce generation costs (capital, O&M (operation and maintenance), plus fuel) by 21 percent by 2035—compared to a business-as-usual (BAU) scenario that generates the same quantity of energy in 2035 using the same technology mix as today—from $84 down to $62 billion/year. This savings is mostly due to reducing off-grid generation, with its high proportion of diesel and gasoline generators that are inefficient and expensive, from 50 percent to 30 percent of total generation. Note that the projected economic growth rate of 9 percent per year through 2025 is extremely ambitious and unlikely to be compatible with the BAU assumption that off-grid generation continues at 50 percent of total generation through 2035, given its high costs. These numbers are included here simply as an illustration of the reduction in emissions and costs of the reference scenario compared to a hypothetical BAU scenario.

## A More Energy-Efficient Alternative Model

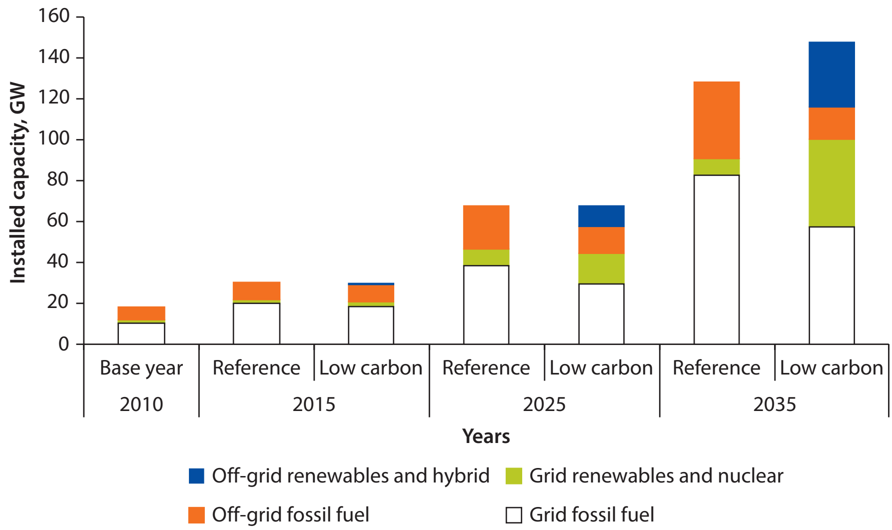
Energy efficiency is a key element of any low-carbon scenario. Given the limitations of existing Nigerian data on consumption patterns across sectors and end uses (such as lighting and appliances), the study combines information from Nigeria with comparison countries such as India to estimate that total electricity demand could be reduced by 14 percent in 2020 and 15 percent by 2035 by means of energy efficiency measures, including more efficient lighting, with transmission and distribution losses reduced from about 20 percent today down to 10 percent.

Lighting is a particularly interesting area for energy efficiency savings. Replacing incandescent light bulbs with compact fluorescent lamps (CFLs) and other high-efficiency lights, such as tube fluorescent lights and LEDs, makes better use of limited capacity (adding "Negawatts," that is, a reduction in demand). Peak demand in Nigeria typically occurs in early evening, coinciding with peak lighting demand. Where there are constraints on capital, deploying CFLs at about US$50 capital cost per kilowatt reduction in peak demand requires far less capital than adding new generators. These cost about $400 per kilowatt for diesel generators, $800 per kilowatt for SCGT, or $4,000 per kilowatt for off-grid photovoltaic (PV) (ESMAP 2007); that is, new generation costs 8, 16, or 80 times higher, respectively, than CFLs per Negawatt. Installing new CFLs or other lights is also generally much faster to implement than adding new generation capacity, especially for grid-connected generation.

## A Diversified Technology Mix

Taking into account the priority of a rapid short-term expansion of gas-powered generation (as laid out in the *Power Roadmap* (FGN 2010) this study defines a mix of technologies that can be deployed in the medium to long run to meet the projected growth in power sector demand. The study team first characterizes the physical potential of renewable energy, which is well defined for hydro, but less so for wind. The potential for solar PV and CSP is so large that they are likely to be limited more by available investment capital than suitable sites. Then criteria such as cost minimization, balancing intermittent solar and wind with dispatchable gas and hydro, and geographical balance of generation sources were used to develop the technology mix for the low-carbon scenario portrayed in figure ES 3.2 for comparison to the reference scenario.

**Figure ES 3.2 Generation Capacity Mix in the Reference and Low-Carbon Scenarios**




*Source:* Calculations based on data sources listed in chapter 14 references.
*Note:* Grid fossil fuel includes gas and coal-fired generators. Grid renewables include hydropower, biomass, concentrating and PV solar, and wind turbines. Off-grid fossil includes gasoline, diesel, and gas turbines. Off-grid renewables include small hydropower, PV solar, and hybrid systems.

## Comparing Scenarios

Over time, the alternative low-carbon scenario develops a more diverse portfolio of technologies than the reference scenario. Grid-connected technologies still include a substantial amount of gas, but with a larger proportion of CCGT, because their greater efficiency results in a lower cost of generation than single cycle turbines, and somewhat lower emissions. A diversified technology mix provides robustness in the face of uncertainties in fuel prices, the cost and availability of renewables, and the effect of increasing variability of rainfall on hydropower.

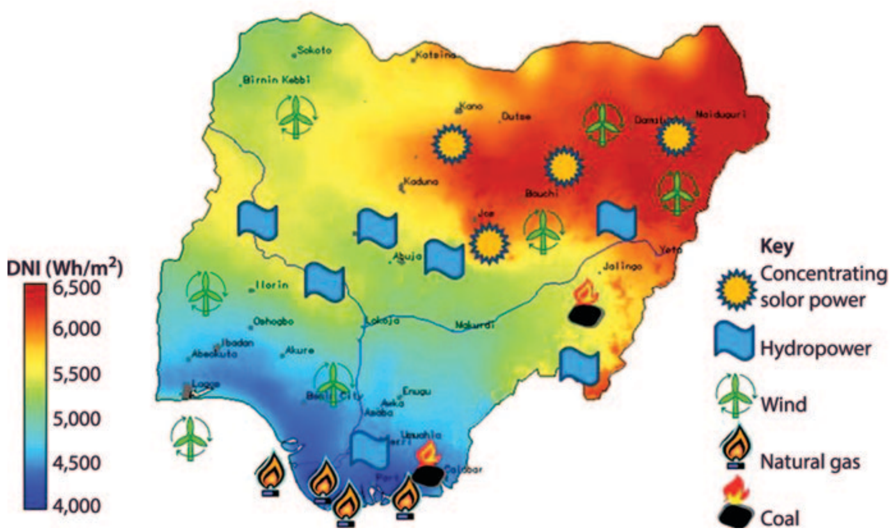
In 2015, the low-carbon scenario adds 100 megawatts each of PV and concentrating solar power (CSP), 200 megawatts of wind, and 300 megawatts of biomass power. These are intended as demonstration projects to evaluate their technical and economic viability in Nigeria and to build local expertise to enable rapid adoption of these renewable energy sources as soon as they become economic. The scenario projects further addition of these grid-connected renewable technologies by 2025 reaching 10 gigawatts each for PV, CSP, and wind by 2035, reflecting the anticipated reduction in costs to reach "grid parity" and below during that time. It includes a more aggressive expansion of hydropower, which provides low-carbon electricity and is also dispatchable to balance the intermittency of solar and wind power.

Off-grid capacity, as described earlier, includes a more rapid addition of PV and hybrid, reaching 16 gigawatts and 11 gigawatts, respectively, by 2035. Off-grid PV and hybrid systems are today near competitive with diesel generators, with levelized cost of electricity in the region of $0.25 per kilowatt-hour for diesel, off-grid PV, and hybrid systems. Costs of PV modules are decreasing rapidly, where the price of diesel is likely to increase. Off-grid generation is currently mostly for backup or replacement of unreliable grid power. Expanding off-grid generation in rural villages and towns away from the grid will supply pumping, irrigation, and public lighting, followed by residential applications and light industry associated with food and agriculture. The low-carbon scenario projects similar total capacity to the reference scenario up to 2025. It needs a higher total of 147 gigawatts in 2035 compared to 128 gigawatts for the reference scenario to compensate for the lower-capacity factors of solar, wind, and hybrid systems.

An important feature of the low-carbon scenario is that it entails a significant degree of diversification of energy sources across the national territory, with grid generation near load centers in key regions of the country. The map (ES 3.1) indicates the regions in Nigeria with high potential for selected energy resources; most of the country is suitable for PV. Oil and gas are concentrated in the South and offshore, hydropower in central and southern Nigeria, coal deposits in the South and East, direct solar radiance for concentrating solar power (CSP) in the Northeast (orange areas), good PV potential in most areas, and promising wind sites in the North and offshore.

Geographically distributed sources of power—connected to load centers and to each other by an adequate grid—can ensure sharing of benefits in all regions

**Map ES 3.1 Diversification of Energy Sources in Low-Carbon Scenario**




*Source:* PVGIS © European Communities, 2001–2012, HelioClim-1 © MINES ParisTech, Centre Energetique et Procedes, 2001–2008, amended and reproduced by the World Bank study team with permission.
*Note:* Map color represents Direct Normal Irradiation (DNI), a measure of solar intensity relevant to concentrating solar power (CSP). The map provides a stylized illustration of the distribution across Nigeria of sources of energy. Oil and gas are concentrated in the South and offshore; hydropower in central and southern Nigeria; coal deposits in the South and East; direct solar radiance for CSP in the Northeast (orange areas); good photovoltaic (PV) potential is found in most areas; and promising wind sites in the North and offshore.

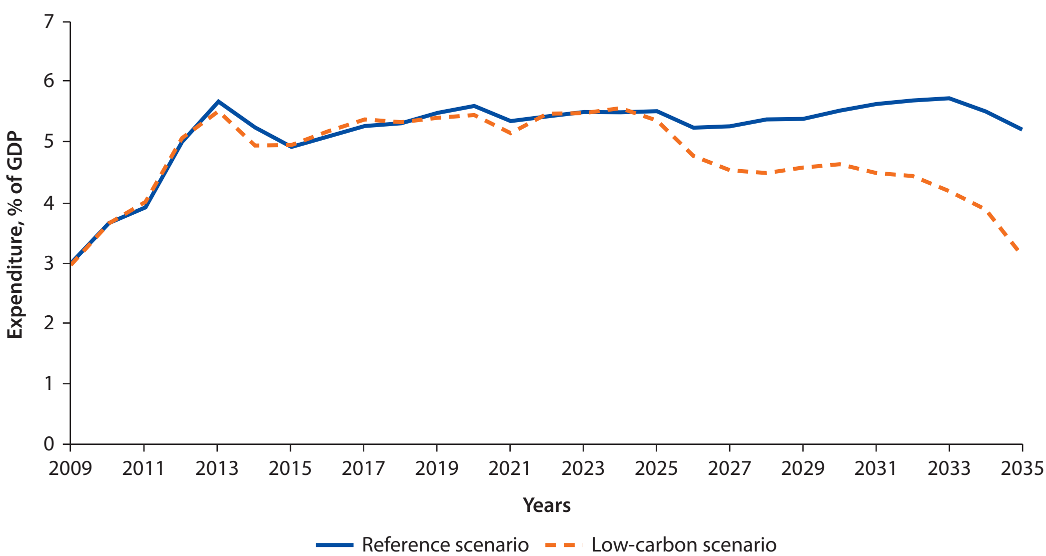
of the country. A diverse portfolio of resources provides flexibility and balances intermittent solar and wind with dispatchable gas, hydro, and, possibly, coal and nuclear.

## Lower Costs in the Long Term

While long-term projections of costs of different generation technologies remain uncertain, there is increasing consensus that the current gap in LCOE separating renewable from thermal generation will continue to decline over time. Assuming that the prices of natural gas and diesel will move in the next few years towards export parity and import parity, respectively; that global fossil fuel prices will gradually increase over the long term as projected by the US DOE; and that the LCOE of renewables will decline as projected in the international literature (EIA 2011) as a result of learning curve effects and economies of scale, the analysis estimates total expenditure on generation of electricity over time for the two scenarios, as shown in figure ES 3.3.

Total expenditure for the reference scenario increases rapidly from 3.7 percent up to 6.0 percent of GDP by 2013, reflecting the ambitious expansion and consequent capital expenditures planned in the *Power Roadmap* (FGN 2010). Expenditures stay between 5 and 6 percent percentage of GDP for the rest of the simulation, reflecting similar rates of growth for GDP and power expenditures. Expenditures for the low-carbon scenario remain close to the reference scenario until 2025, after which they decline below the reference scenario, reaching 3.1 percent of GDP in 2035. This reflects savings from energy

**Figure ES 3.3 Total Generation Expenditure for Reference and Low-Carbon Scenarios**



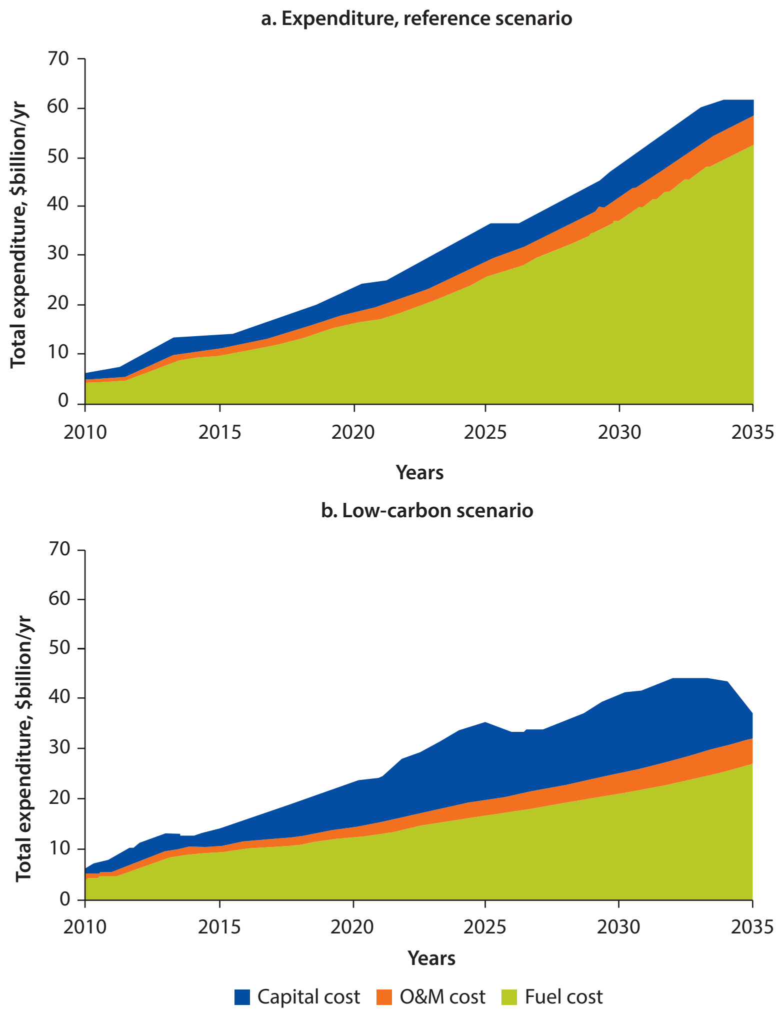

*Source:* Calculations based on data sources listed in chapter 14 references.

efficiency programs and, in later years, from the lower fuel costs of renewable power, especially off-grid.

## Higher Up-front Costs

Figure ES 3.4 breaks down the total costs for the two scenarios by capital, O&M, and fuel costs. It reveals that (1) capital costs are significantly larger for the low-carbon scenario, as expected since the renewables have higher capital cost, and (2) its higher capital costs are outweighed by its much lower fuel cost, resulting in noticeably lower total costs after 2025. Although the total annual costs of the low-carbon scenario are almost the same or lower each year, its

**Figure ES 3.4 Total Capital, O&M, and Fuel Costs for Reference and Low-Carbon Scenarios**




*Source:* World Bank data.

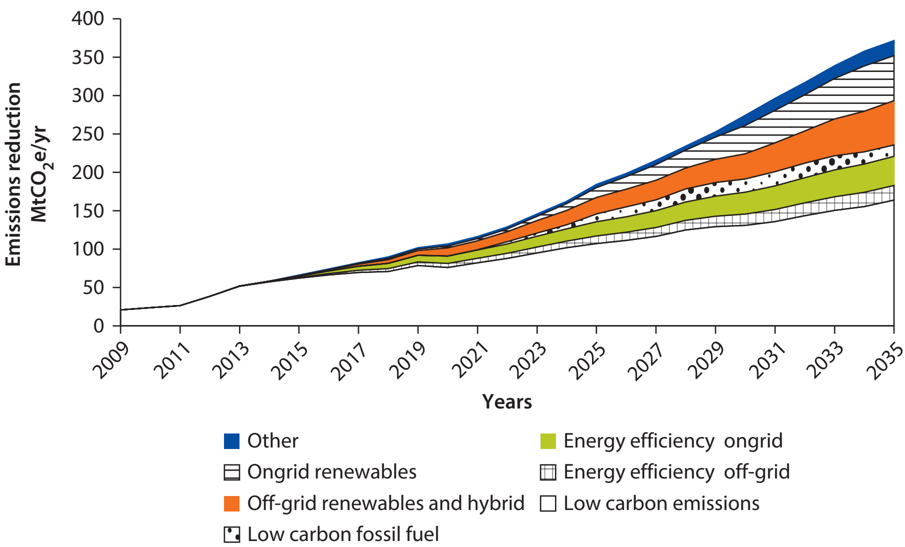
higher capital costs could create financing challenges for particular power generating organizations, whether large-scale grid utilities or small off-grid microgrids, if there are constraints on available capital—even if they reduce costs in the long run.

## The Cobenefits of Carbon Emissions Reduction

The wedge chart in figure ES 3.5 shows the reduction in emissions resulting from the low-carbon scenario: The topmost line shows the emissions from the reference scenario, reaching 372 $MtCO_2e$/yr (million tonnes carbon dioxide equivalent per year) in 2035.

The top edge of the bottom area shows the emissions from the low-carbon scenario, reaching 164 $MtCO_2e$/yr in 2035. This is a reduction of 56 percent in annual emissions in 2035, or a reduction of 43 percent in cumulative emissions. The two top wedges represent the emissions avoided by energy efficiency for ongrid and off-grid lighting, respectively, followed by other (nonlighting) energy efficiency options. These include (moving top to bottom) savings in emissions from combined cycle (CCGT) relative to SCGT (SCGT) and emission reduction obtained through the adoption of grid-based wind, PV, and CSP generation. The largest contributors are

**Figure ES 3.5 Projected Annual Emissions Reductions in Low-Carbon Scenario, with Energy Efficiency**




*Source:* Calculations based on data sources listed in chapter 14 references.
*Note:* Wedges for energy efficiency for grid and off-grid include lighting and other sources of efficiency. Low-carbon fossil fuel includes gas-combined cycle replacing single-cycle gas turbines and adding carbon capture and storage (CCS) to coal. Off-grid renewables include small hydropower, PV solar, and hybrid systems. Grid renewables include hydropower, biomass, concentrating and PV solar, and wind turbines. Other includes nuclear, biomass power, and transmission and distribution loss reduction.

off-grid PV and hybrid PV-wind-diesel, which replace diesel and gasoline generators.

## Uncertain Future Costs of Fossil Fuel and Renewables

Inevitably uncertain are the future domestic and export prices of fossil fuels, including oil, diesel, and natural gas. Also uncertain are the future capital cost of renewables—for example, whether solar PV will continue its recent rapid decline. The study team based the low-carbon scenario on the LCOE by technology, using recent projections adapted from a variety of credible international sources, including IEA (2011), EIA (2011), and DECC (2011). A sensitivity analysis explored a "*delayed low-carbon* scenario" in which adoption of renewables is delayed by 5–10 years due to lower fuel prices and/or slower learning curves for renewables. This delayed LC scenario reduces cumulative emissions through 2035 by 40 percent relative to the reference scenario, compared to a 43 percent reduction due to the original low-carbon scenario. It costs about the same as the original low-carbon scenario, assuming costs favor fossil (low fossil prices and slow renewable learning). Both the original and delayed low-carbon scenarios cost less than the reference scenario for all three cost cases, implying that the conclusions are qualitatively robust to these uncertainties.

## Recommendations for Short-Term Low-Carbon Progress (2012–15)

Nigeria has the opportunity to forge a new kind of low-carbon development path in the way it uses and produces energy that could make it a leader in Africa. As well as being the most populous country in Africa, it is blessed with a wide variety of indigenous sources of energy—oil, gas, coal, hydro, wind, solar, and biomass—distributed around the country and offshore. The current state of Nigeria's electric power sector is, admittedly, challenging. But the FGN has already put in place an aggressive plan (FGN 2010) to rectify this situation by rapid expansion of the grid and generation capacity by a factor of 6–40 gigawatts by 2020. The first priority must be to implement that *roadmap*—essential for economic growth.

A low-carbon plan for Nigeria can build on the existing roadmap, which will itself start to reduce carbon emissions by substituting gas turbine generators for inefficient, high-carbon off-grid diesel and gasoline generators. A low-carbon plan should expand the roadmap to promote renewable technologies that are economically competitive. It should develop a portfolio with a regionally balanced diversity of energy resources. It should integrate plans for grid and off-grid power, and create the flexibility to take advantage of new opportunities, such as low-cost renewables, as they become available.

The primary focus of recommendations in this volume is on short-term actions that can make an immediate contribution to improving availability of power and establish a foundation for successful medium- and longer-term strategies to expand access to power with low-carbon technologies. Following are the recommended actions.

## Improve Energy Data

Better data in several areas are urgently needed so that plans can be based on actual conditions in Nigeria rather than estimates adapted from other countries. Key actions to be taken include the following:

- **Survey off-grid generation.** Better data are much needed on the quantity, capacity, and energy produced from captive generators of all types—fueled by gasoline, diesel, and gas. It should quantify categories of off-grid generation for residential, commercial, industrial, and institutional sectors in urban and rural areas around the country.
- **Survey power consumption.** Better data on the types of consumption by appliances, such as lighting, refrigerators, and so on for the residential and public sectors are being obtained by the Energy Commission of Nigeria (ECN) in partnership with United Nations Development Programme–Global Environment Facility (UNDP-GEF, as mentioned in UNDP 2011). It would be helpful to expand this to commercial and industrial sectors in urban and rural areas, for both ongrid and off-grid generations.
- **Measure wind resources.** A high-resolution wind atlas is urgently needed to quantify wind potential (on-shore and off-shore) and identify the most promising sites for wind farms.
- **Empower sharing of energy data.** FGN could significantly facilitate planning and analysis by all stakeholders by building on existing facilities, for example, at ECN, to provide a comprehensive online resource for sharing data, projections, and reports related to energy.

## Promote Demand-Side Energy Efficiency

Improvements in energy efficiency are usually the lowest cost options for reducing carbon emissions, since they pay for themselves in reduced energy costs, often in only months. They enable limited existing or new grid capacity to provide the benefits of lighting, cooling, and so on to more consumers. They are a valuable complement to the expansion of generation capacity. Energy efficiency should be first priority for a low-carbon development plan. Key elements might include the following:

- **Promote compact fluorescent lights (CFLs)** and other energy-efficient lights as part of a national program, and consider phasing out sales of incandescent lamps.
- **Establish efficiency standards** for common appliances, including refrigerators and air-conditioners, with phase-out of sales of less efficient appliances. Because most appliances in Nigeria are imported, a “top runner” program like that in

Japan in which the most efficient model on the market is used to set future efficiency standards would also make sense.

- **Develop energy literacy** campaigns and education programs for schools, communities, and religious organizations on the value of using efficient appliances for the individual consumer and community levels.
- **Create incentives** for utility companies and electricity retailers to promote energy efficiency to their customers instead of maximizing power usage.
- **Accelerate deployment of smart consumer meters** to encourage conservation, enhance collection of payment from consumers, and support time-of-day metering to encourage shifting load from peak.

### Expand Grid-Connected Capacity

The Federal Ministry of Power's (FMP) immediate focus for the for grid-connected capacity is to refurbish existing gas turbines and hydropower generators, as well as build new ones to expand grid capacity. Additional elements to be considered in the intermediate term as part of an integrated low-carbon plan are as follows:

- **Deploy barge-mounted gas turbines** for rapid low-cost installation of much-needed capacity in coastal areas. Barges can be moved or sold when better lower-carbon options become available.
- **Promote investment in combined-cycle gas turbines (CCGT)**, which are lower in levelized generation cost and emissions than existing single-cycle gas turbines (SCGT), by adjustment of tariffs and tax or duty exemptions, for example, by amending the new tariffs laid out in the 2011 Multi-Year Tariff Order (MYTO).
- **Actively develop large-scale renewable energy projects.** Hydropower could be an immediate priority, and a goal might be to have major hydro projects ready for construction within two years, with full feasibility studies completed (resettlement and environmental and social impact assessments). FMP might also prepare full feasibility studies for large-scale demonstration projects for grid-connected PV, CSP, and wind of about 100 MW each, also ready for construction within two years.

### Adopt a Leapfrog Strategy for Off-grid Power

The planned expansion of electrical power coupled with the fact that an estimated 50 percent of electrical energy is currently generated off-grid actually suggests an opportunity: Nigeria could leapfrog traditional development pathways for electricity based entirely on grid-connected fossil-fuel capacity. Instead, it could move to develop a power system in which distributed generation and renewable resources play a major role. This strategy takes inspiration from telecommunications: Nigeria—like many emerging economies—expanded telephone access a hundredfold between 2001 and 2011 by adopting mobile technology, leapfrogging the landline infrastructure used in developed economies.

More specifically, the following actions could be considered:

- **Deploy off-grid natural gas turbine**s to replace diesel generators where gas is available. They can provide power at significantly lower cost as well as lower carbon emissions.
- **Use solar PV for water pumping and irrigation**. These are important applications in many areas and are economically highly competitive with generators.
- **Encourage local independent power producers (IPPs)** and companies that are currently distributing gasoline, diesel, and off-grid generators to expand their business to include PV and hybrid systems.

## Develop Policies to Level the Playing Field for Low-Carbon Technologies

Even as low-carbon technologies become economically competitive, there remain institutional, regulatory, and financial obstacles to reaping their full benefits. FGN has an important role to play in creating institutions, policies, and programs to remove these obstacles. Key elements include the following:

- **Let fuel revert to global market prices.** Artificially low domestic prices for gasoline and natural gas have created market distortions, shortages, and burdens on the national budget. They unfairly disadvantage other sources of energy. FGN has already taken action to allow gas prices to increase toward export parity. In early 2012, FGN announced plans to eliminate the substantial subsidy on gasoline, with substantial reduction in subsidy now in place.
- **Let electricity tariffs reflect costs.** In 2011, Nigeria's Multi-Year Tariff Order (MYTO 2011) established the principle of cost recovery so that prices would fully reflect all costs by 2013.
- **Develop a policy framework to promote off-grid renewables.** The Nigerian Electricity Regulatory Commission's (NERC) recently announced feed-in tariffs (FITs) are a good starting point. FGN might expand these policies to promote renewable and hybrid options, including net-zero FITs, tax and duty exceptions, and light-touch regulation for renewable facilities under 10 MW. In tailoring policies for Nigeria, it will be valuable to learn from what has and has not worked elsewhere (World Bank 2011).
- **Develop human resources.** Successful development and implementation of a low-carbon plan will require a growing corps of Nigerian scientists, engineers, analysts, technicians, and project developers with expertise in key technologies. Early demonstration projects for renewables are an excellent way to develop local expertise.
- **Expand financing options.** Although some off-grid applications of renewables are already competitive in terms of LCOE, their up-front capital costs remain higher than those of diesel generators. Low-interest loans and microcredit,

energy service companies and cooperatives (ESCOs), use of Clean Development Mechanism (CDM) offsets and other sources of international financing can all play a role in accelerating adoption for capital-poor consumers, microgrids, and small power utilities. The expected rapid adoption in Nigeria of mobile phone payment and banking should provide more practical payment options for consumer financing electrical power on and off the grid, given the low acceptance of conventional checks and credit cards.

## Recommendations for Medium-Term Low-Carbon Progress (2015–20)

Key recommendations for medium-term progress on a low-carbon development include further expansion of grid capacity as well as off-grid generation and the development of a comprehensive energy systems plan to coordinate longer-term development.

### Further Expansion of Grid Capacity

- **Expand hydropower wherever practicable.** Its dispatchability complements other renewables.
- **Expand combined-cycle gas generation**, which offers lower emissions and lower LCOE than SCGT.
- **Implement demonstration project**s for grid-connected PV, CSP, and wind of around 100 MW, based on the feasibility studies completed by 2015. These will enable Nigeria to gain experience and develop national expertise ready for rapid further expansion as these technologies become more economic.
- **Consider siting of renewable generation** when expanding the grid to enable future integration and supply balancing of renewable and fossil sources.

### Expand Off-grid Power

- **Use solar PV** with batteries and hybrid PV-wind-diesel. These technologies are already economically competitive for many off-grid applications, and will become substantially more competitive over time.
- **Develop small hydropower applications** wherever available as a low-cost and low-emissions dispatchable complement to PV and hybrid.

### Develop a Comprehensive Energy Systems Plan

**A comprehensive systems analysis** with spatially disaggregated engineering of generation plants, load centers, and transmission networks is needed to develop detailed longer-range plans, both for reference and low-carbon options. Such a study should examine tradeoffs involved in alternative portfolio technology mixes, and geographic distribution of generation plant. Such an analysis will require much more comprehensive data than currently available and was beyond the scope of this study.

**Integrate off-grid generation and microgrid development** in energy planning as an essential complement to the national grid, along with smart-grid technology to support eventual integration into the national grid. Only an integrated analysis can examine cost and benefit tradeoffs between expanding off-grid generation against expanding the grid network.

**Integrate gas pipelines and CSP** in longer-term plans to enable future development of integrated solar combined-cycle (ISCC) plants where and when it becomes economically attractive.

## Recommendations for Long-Term Low-Carbon Progress (2020–35)

The suggested short- and medium-term actions could establish a sound foundation for longer-range development of Nigeria's future electric power systems. Given the large uncertainties in long-range economic growth, fuel costs, and reductions in cost of renewable technologies, it does not make sense to make specific long-range recommendations. The low-carbon scenario is intended to indicate one possible future, not a specific suggestion about what should happen. Longer-term decisions should be based on the evolving situation and information, about the relative costs and the practicality of energy resources and technologies available when those decisions must be made. Effective short- and medium-term decisions can create the capacity and flexibility to avoid future risks and take opportunities as and when they appear.

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CHAPTER 14

# Introduction

As the second-largest economy and most populous country in Africa today, Nigeria has well-recognized economic potential. However, numerous constraints relating to energy are impeding its development and have so far precluded Nigeria from realizing that potential. These constraints include insufficient electrical power and infrastructure, as well as difficulties with the supply of natural gas from which to generate power.

To address these constraints, the Federal Government of Nigeria (FGN) has developed an ambitious plan for its socio-economic development by 2020, known as the *Vision 20: 2020 Plan* (FGN 2010a). Vision 2020 is intended to lay the groundwork for Nigeria to become one of the 20 largest economies in the world by the year 2020, with a gross domestic product (GDP) target of US$900 billion and a GDP per capita of US$4000 per year. This plan includes a rapid expansion of the Nigerian energy sector with particular emphasis on the synergies between power, oil and gas. It also recognizes the importance of some low-carbon development options. For instance, replacing captive back-up diesel generators with grid power generated from natural gas will reduce both the cost of electricity and carbon emissions.

## Objectives

This analysis is part of the World Bank Climate Change Assessment (CCA) program in Nigeria. It focuses on the power sector to evaluate the potential for increased adoption of low-carbon development pathways through 2035. It seeks to assess opportunities and challenges arising from a lower-carbon pathway for Nigeria's economy compared to growth and development objectives laid out in government strategies.

The key objectives of this study are as follows:

- **Step 1: Build the reference scenario.** Develop a reference scenario based on historical trends and a growth trajectory consistent with government plans for how the Nigerian power sector might evolve. Evaluate its greenhouse gas (GHG) and economic implications.

- **Step 2: Develop an alternative low-carbon scenario.** Identify "no-regrets" low-carbon interventions for the power sector to achieve the same development goals with substantially reduced GHG emissions.
- **Step 3: Build local capacity for low-carbon planning.** Work closely with key personnel in relevant institutions in Nigeria to build local capacity for low-carbon planning.

## Purpose of Power Sector Scenarios

This study described in this volume presents a reference scenario and low-carbon scenario that project possible futures for the power sector of Nigeria through 2035. These scenarios provide a basis for evaluating a wide range of options in terms of planning, public policy, economic costs, and emissions.

The *reference scenario* provides a counterfactual—a reasonable trajectory for growth and structural change of the economy based on existing trends and adopted government policies. The reference scenario ignores any special attempts to reduce emissions of carbon dioxide and other greenhouse gases (GHGs). The *low-carbon scenario* is designed to explore an alternative future in which Nigeria seeks to reduce its GHG emissions relative to the reference scenario without impairing its economic growth.

These scenarios are not intended as *predictions* about what *will* happen. That would be impossible, given the unavoidable uncertainties about future economic growth in Nigeria; future prices of oil, gas, and other commodities; and progress in reducing the costs of technologies for renewable energy and energy efficiency. Neither are these scenarios *prescriptions* about what *should* happen: The choices and policies that Nigeria adopts should be made by the Nigerian government and people in the light of the evolving situation.

Rather these scenarios present *possibilities*—projections of what *could* be achieved. They provide a coherent sequence of events and decisions designed to be consistent with available evidence, current plans and policies, and the laws of physics and economics. They are intended to stimulate thinking and debate about possible futures so as to assist stakeholders in making their choices. In particular, they provide a long-term perspective and context for recommendations for near-term options intended to help Nigeria develop the capacity and flexibility to take advantage of low-carbon options if and when they prove desirable.

## Study Sources and Assumptions

The study builds on a wide variety of existing literature and planning reports. Wherever possible, it is based on information and assumptions from key documents developed by FGN such as the *Vision 20: 2020 Report* (FGN 2010a) and the *Roadmap for Power Sector Reform* (FGN 2010b) in building the draft reference scenario. The other sources for the data on which projections were built for this sector are listed at the end of this chapter.

The basic assumptions for this sector study were developed in consultation with stakeholders, domain experts, and Nigerian government representatives, drawing on the World Bank's extensive knowledge of Nigerian institutions. Drafts of the original study report were presented for discussion and review in a series of three workshops and meetings in Abuja. This consultative process enabled significant stakeholder engagement, a key factor to successfully reflect the complex realities and aspirations for the future of Nigeria's energy systems. The assistance and feedback from the many participants in this process is gratefully acknowledged.

## Scope and Limitations

The study focuses on low-carbon options for the power sector of the Nigerian economy for two major scenarios with projections through 2035, with some minor variations for sensitivity analysis. The analysis is based on data generously provided by Nigerian government sources and other stakeholders in Nigeria and elsewhere. The study team did not have the resources to conduct new surveys or otherwise obtain additional primary data. Where data were not available on critical quantities, estimates were based on professional judgment by the team, supplemented by comparisons with other countries. The team is also most grateful to stakeholders that reviewed and discussed estimates in two series of workshops and bilateral meetings held in Abuja, resulting in several improvements.

The study did not seek to provide a comprehensive low-carbon plan for Nigeria's power sector. That would be beyond the resources available. Rather it provides a specific set of projections for a low-carbon scenario and analysis of its effects and costs. It concludes with a set of recommendations for key elements to be considered for inclusion in such a plan when FGN decides to develop one.

## Organization of Power Sector Study

The rest of this volume is structured as follows:

- Chapter 15 introduces the general framework for analysis and provides macroeconomic projections of Nigeria's population and GDP, used as a basis for those scenarios.
- Chapter 16 presents and analyzes the reference scenario, starting with a projection of energy demand, with a breakdown by grid and off-grid categories. It describes existing and planned generation facilities and projects a technology mix for future power generation and consequent GHG emissions through 2035.
- Chapter 17 presents a low-carbon scenario, including potential contributions from energy efficiency, and the physical potential of low-carbon technologies. It projects a mix of low-carbon technologies that might meet electricity demand. On this basis, it projects total generation and emissions, with analysis

of emissions reduction by technology. It includes analysis of marginal abatement costs (MACs) by technology option.

- Chapter 18 provides a sensitivity analysis to evaluate the effects of delayed cost reductions for solar technologies and fossil fuels with a delayed low-carbon scenario that adds renewable generation later.
- Chapter 19 discusses challenges and opportunities for low-carbon development and offers near-term and mid-term recommendations for Nigeria to develop a comprehensive low-carbon plan based on this analysis.
- Finally, a series of appendixes provide more detailed background data, estimates, and assumptions used in the analyses.

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**CHAPTER 15**

# General Framework

Over the last two decades, Nigeria has grappled with severe electricity shortages and unreliability of the supply that have prevented the country from realizing its full potential for economic growth. Causes include delays in expansion of the grid, difficulties with obtaining an adequate supply of natural gas, and the high economic and environmental cost of off-grid gas and diesel generators. Domestic reserves of crude oil have been vital to the development of the country, but Nigeria's exclusive reliance on fossil fuels has become an environmental issue. Large hydropower plants are also being threatened by diminishing flows in the Niger River. Before 1999, for 20 years, Nigeria witnessed no new investment in electricity infrastructure development. During this period, no new plants were built and existing ones were poorly maintained. The result was that installed capacity fell from 5,600 megawatts to 1,750 megawatts in 2001, while demand was estimated at 6,000 megawatts (Sambo 2008). Assessment of actual demand growth is challenging when it so limited by supply, but it is clear that the inadequacy, unreliability, and limited availability of grid supply has significantly suppressed apparent demand. For the study, demand was estimated by comparing Nigeria to countries with similar per capita gross domestic product (GDP).

It is no surprise then that electricity consumers have demanded of the government significant improvement in service levels. In response to this demand, the Federal Government of Nigeria (FGN) has set forth an aggressive trajectory as part of the Vision 2020 plan for the country's socioeconomic development over the current decade. This plan broadly defines the strategic policy direction for Nigeria to achieve its development goals. In the reelection of President Goodluck Jonathan in April 2011, a key plank of his campaign platform was to improve the availability and reliability of the electricity supply. The *Roadmap for Power Sector Reform* (FGN 2010b) provides a plan to expand sixfold the generation capacity with associated gas supply and transmission and distribution infrastructure by 2020.

As part of this process, the FGN and the World Bank in 2009 agreed to carry out a Climate Change Assessment (CCA) for Nigeria to assess the impact of climate change on the country's growth trajectory, a critical component of which is the analysis of low-carbon options in the energy sectors. Accordingly, the study developed a low-carbon plan for the power sector.

There are strong interdependencies between the power sector and oil and gas sector that were not accounted for in setting the Vision 2020 goals. For instance, plans for building gas turbine power plants require the availability of natural gas. The study takes an integrated modeling approach that links the availability of gas supply from the oil and gas sector with the expansion of natural gas-fired thermal plants in the power sector.

## An Integrated Modeling Framework

The analysis and comparison of the reference and low-carbon scenarios for the power sector use EFFECT (Energy Forecasting Framework and Emissions Consensus Toolkit, World Bank 2013), a spreadsheet-based model developed by the World Bank. EFFECT takes existing and planned capacity additions to the power grid and adds additional renewable and fossil capacity according to specified targets to meet projected demand for electricity. Based on the characteristics of each technology, it projects the total emissions over time for each scenario.

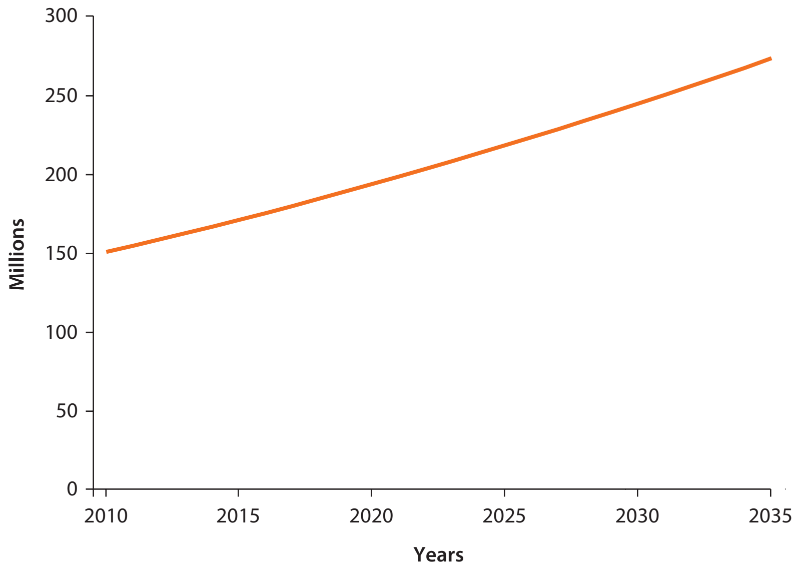
The study team built new modules for analysis of elements incompletely represented in EFFECT. These include projections of future costs of fuel and renewable energy technologies over time; projections of demand by grid and off-grid categories; analysis of the effects of energy efficiency programs, by grid and off-grid categories and residential, commercial, and industry sector; estimation of current and future costs of each fuel and technology, including capital, O&M, and fuel costs; and an automated analysis of marginal abatement cost (MAC) curves. These modules were developed as AMAC (Analytica Marginal Abatement Cost) using the Analytica modeling software.[1]

AMAC takes the projected capacity additions from EFFECT and projects the total reduction in emissions due to each technology, including energy efficiency programs. It uses emissions reduction and abatement costs for each technology, grid and off-grid, from EFFECT to generate MAC curves. It also estimates the total cost of electricity generation and cost per kWh for each scenario, summing over the capital, O&M, and fuel costs for each generation technology. AMAC provides a series of sensitivity analyses to explore the effect of changes in assumptions about off-grid generation, an alternative delayed low-carbon scenario, and alternative scenarios for future costs of fossil fuels and photovoltaics (PV). AMAC works directly with EFFECT as an extension, providing additional input data and reading results directly from the spreadsheet.

## Population Growth

Key assumptions in developing the scenarios are projections of Nigeria's population and gross domestic product (GDP) through the modeling horizon of 2035. Together, these drive the domestic demand for power. Nigeria is the most populous country in Africa. In 2011 the population was about 155 million,

**Figure 15.1 Nigeria Population Projection**
*Millions*




*Source:* UN 2010; Energy Commission of Nigeria.

about one-sixth of the entire continent. The population projection based on UN World Population Prospects (UN 2010) assumes growth rates of 2.53 percent (2010–15), 2.51 percent (2015–20), 2.39 percent (2020–25), 2.30 percent (2025–30), and 2.21 percent (2030–20). The growth rate for years 2012–15 was modified to be about 3.2 percent based on feedback from the Energy Commission of Nigeria (ECN) at a stakeholder workshop held by the World Bank in October 2011. These assumptions result in an estimated population of 274 million by 2035, with the projected growth depicted in figure 15.1.

## GDP Growth

The Nigeria Vision 2020 plan assumes 13 percent annual GDP growth through 2020 (FGN 2010a). It is widely recognized that the GDP annual growth target set forth within the Vision 2020 document is aggressive. The reference scenario assumes a *high growth* GDP scenario, with 9 percent growth through 2025, followed by a 6 percent growth rate through 2035, as shown in table 15.1.

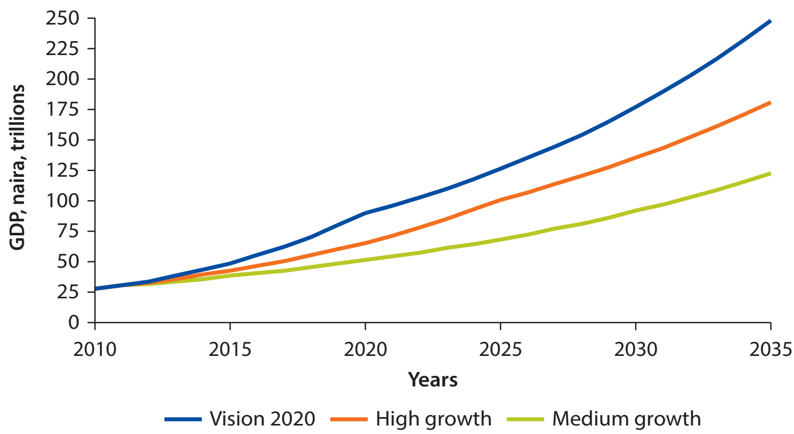
These high growth assumptions achieve the same GDP target as Vision 2020, but 5 years later in 2025. Figure 15.2 shows these three GDP growth scenarios. The reference scenario for the present study is based on the high growth projection. Figure 15.3 shows the GDP per capita used to project demand in Nigeria using this assumption.

**Table 15.1 GDP Compound Annual Growth Rate Assumptions by Scenario, %**

| *Scenarios* | *2010* | *2015* | *2020* | *2025* | *2030* | *2035* |
|---|---|---|---|---|---|---|
| Vision 2020 (modified) | 8.2 | 13 | 13 | 7 | 7 | 7 |
| High growth | 8.2 | 9 | 9 | 9 | 6 | 6 |
| Medium growth | 8.2 | 6 | 6 | 6 | 6 | 6 |

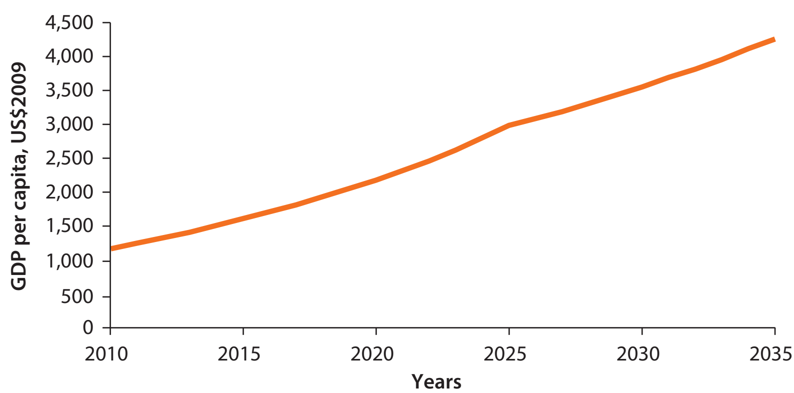
*Source:* FGN 2010a.

**Figure 15.2 Three Scenarios for GDP Growth**




*Source:* FGN 2010b.

**Figure 15.3 Projected GDP Growth Per Capita (US$2009), High Growth Scenario**




*Source:* This study, using assumptions on GDP and population described in the text.

## Note

1. Analytica and the Analytica Marginal Abatement Cost (AMAC) model are available from the authors at Lumina Decision Systems, www.Lumina.com.

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**CHAPTER 16**

# Reference Scenario

The power sector in Nigeria is beset by problems, resulting in a large gap between supply and demand for electrical power, and widespread disruptions and unreliability of supply. This inability to satisfy consumer demands has a variety of causes, ranging from a poorly maintained and aging power infrastructure to unreliable supplies of natural gas, the main fuel for grid-connected thermal power plants. These problems have been exacerbated in recent years by problems with the gas-supply infrastructure and low tariffs for gas and electricity, which have discouraged investment to expand capacity.

The urgent need to find a solution to the problems of the power sector has prompted the FGN to promote several planning studies of the power sector to clarify the sources of these problems and develop sustainable solutions, including the following:

- Presidential Advisory Committee Report on Nigeria's Electricity Sector, 2006 ("PAC Report") (FGN 2006);
- The Nigerian Energy Demand and Power Planning Study for the period 2000–30, conducted by the Energy Commission of Nigeria ("ECN Planning Study") (ECN 2008);
- Nigeria Vision 20: 2020 Energy Report, Medium Term Implementation Plan (2010–13) coordinated by the National Planning Commission ("Vision 2020-Energy"); (FGN 2010); and
- National Load Demand Study, conducted by Omega Systems and Tractabel Engineering ("Load Demand Study") (OS/TE 2009).

An important outcome of three of these studies (PAC Report, Vision 2020-Energy, and Load Demand Study) was to identify 19 key challenges facing the Nigerian power industry including, among which are the following: inadequate power generation capacity; inadequate transmission and distribution network; obsolete and inefficient transmission and distribution equipment; low access to electricity grid; industry regulation; industry and market structure; insufficient gas for power generation; billing and revenue collection; and inappropriate electricity pricing.

In 2010, in an effort to tackle these problems more aggressively, President Goodluck Jonathan established two multiagency bodies for power sector development:

- Presidential Action Committee on Power (PACP), headed by the President
- Presidential Task Force on Power (PTFP), headed by the Presidential Adviser on Power, Bart Nnaji, subsequently Minister of Power.

The PACP report, *Roadmap for Power Sector Reform* (FGN 2010b), together with the Vision 2020-Energy Report (FGN 2010a) contains what can be considered the most authoritative government plan for the development of the Nigerian power sector. The President in his foreword to the Roadmap emphasized his administration's goal to pursue a sectorwide reform. In particular, the government has committed billions of naira in recent years to improve the performance of the Nigerian power sector and has elevated the political commitment to reforming the sector extensively.

## Electricity Demand

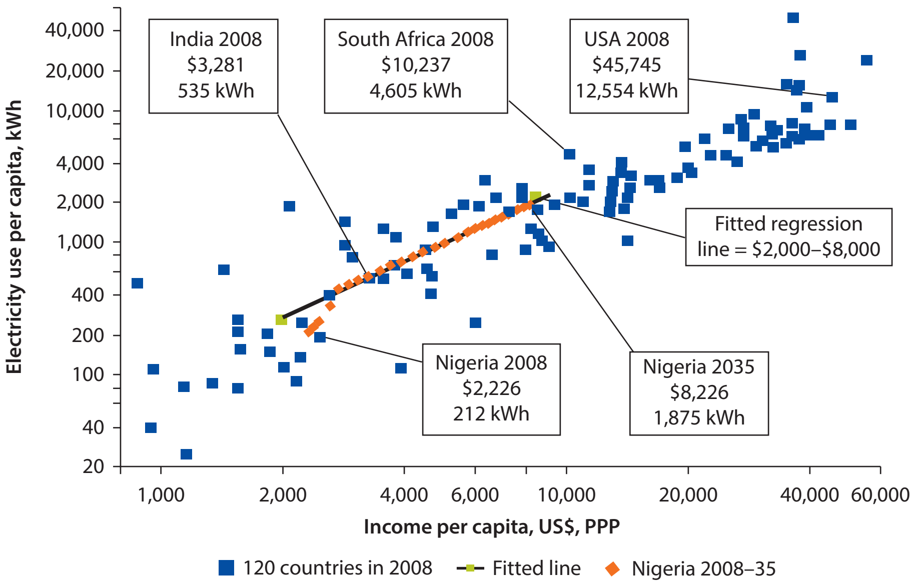
Electricity demand is a key driver to project future capacity, generation, and emissions for the reference and low-carbon scenarios. The planning studies listed in the last section project wide differences in demand, making it difficult to create a consensus reference scenario. Currently, the Nigerian power grid does not provide the capacity and reliability to meet existing demand resulting in an estimated 50 percent of the electricity consumed in the base year being generated off-grid, mostly by captive diesel and gasoline generators. Thus it is likely that many citizens have no access to the grid and cannot afford off-grid power. This situation of insufficient and unreliable supply, limited grid coverage, and high cost of off-grid generation results in suppressed demand.

These conditions make it challenging to estimate what the consumption in Nigeria would be were adequate power supplies available at reasonable cost based only on purely Nigerian data. Therefore, this study bases its demand projections on a comparison of electricity consumption with other countries of comparable income level. Specifically, it uses cross-country estimates of the effect of per-capita income on electricity consumption along with a projection of Nigeria's per-capita income through 2035.

### *Effect of Income on Electricity Demand*

A key question in projecting the demand for electric power is how per-capita demand for power will increase with per-capita income—that is, the elasticity of electricity demand to income. The blue points in figure 16.1 plot per-capita electricity consumption (kWh/year) against per-capita income (US$ per year in Purchasing Power Parity (PPP) in 2009 dollars) on log scales for both axes for 120 countries in 2008 (IEA 2009; World Bank 2011). A few of these countries for illustration in figure 16.1. These numbers represent grid-based power, since good estimates of off-grid generation are not available.

**Figure 16.1 Annual Per-Capita Electricity Use vs. Per-Capita Income for 120 Countries, 2008; Nigeria Projections, 2008–35**




*Source:* Income and population, World Bank 2011; electricity use, IEA 2009; GDP per capita in purchasing power parity (PPP). For Nigeria, electricity per capita 2008–14, FGN 2010; 2015–35, from this study.
*Note:* Orange diamonds are annual projections of usage and income for Nigeria to 2035. The green trend line is fitted to countries with incomes $2,000–8,500, excluding outliers.

A regression line (a straight line in log-log space) was fitted to those countries with incomes in the range $2,000 –8,500,[1] the range of per-capita income projected for Nigeria (green line). The slope of this line indicates an elasticity of 1.46, which implies, for example, that a doubling of income would lead to a 146 percent increase in per-capita energy demand. The relationship between electricity usage and income appears to be less steep (lower elasticity) for higher-income countries, suggesting an S-shaped curve.

The red diamonds project the trajectory of Nigeria's per-capita electricity consumption and income, increasing from 2008 to 2035. Nigeria's base year consumption, estimated at 222 kWh per capita, is well below the trend line of 300 kilowatt-hour per capita at the same income of $2,226 per capita (PPP). This is consistent with significantly suppressed demand due to insufficient supply. The rapid increase in electricity usage projected through 2015 reflects FGN's aggressive plan for expanding gas supply, capacity and availability of gas turbines, and the grid capacity, as described in Vision 2020. The projection after 2015 follows the green trend line. This results in a per-capita consumption of 1,875 kilowatt-hour per capita in 2035 at an income of $8,226 (US$2009 at PPP) consistent with the high growth projection for GDP. This assumes that Nigeria's total electricity consumption, grid and off-grid, approximates the grid-only consumption for the other countries. However, most other countries have a much smaller percentage of off-grid generation, so the difference in total consumption at a given income level will be similarly small.

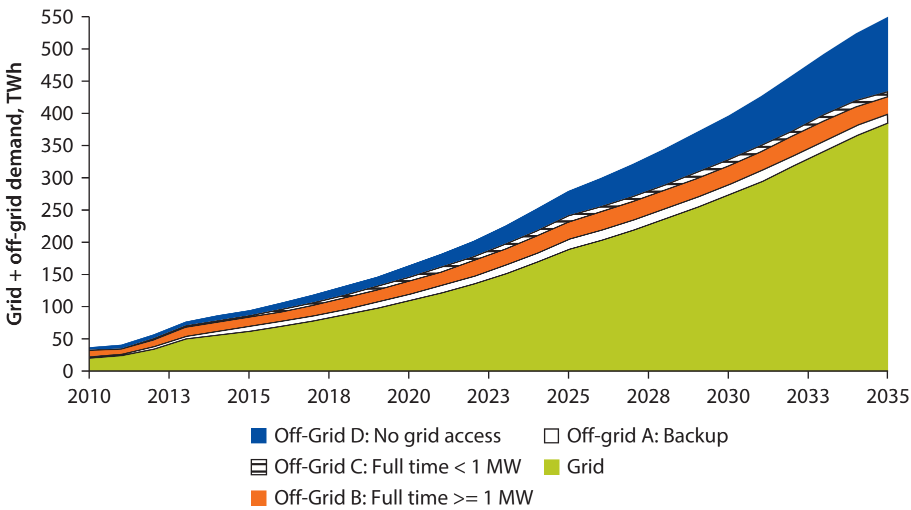
### *Electricity Demand for Grid and Off-grid*

Grid demand for electricity is estimated as the product of the projected population (figure 15.1) and electricity use per capita for the projected income per capita (figure 16.1), with the result shown as the top line in figure 16.2. Total demand (generated by grid plus four categories of off-grid sources) grows by a factor of 5.0 by 2020 and a factor of 16.8 by 2035 relative to 2009.

Because current grid supplies cannot meet the power demand, there is widespread generation of local or captive power. Table 16.1 lists the five categories of generation shown in figure 16.2.

**Figure 16.2 Projected Power Consumption from Grid and Off-grid Sources in Reference Scenario**

*Terawatts per hour per year*




*Source:* Federal Ministry of Power; Power Holding Company of Nigeria (PHCN); Off-grid D projections, UN 2010.
*Note:* Categories defined in table 16.1.

**Table 16.1 Source Categories of Electricity Supply in Nigeria**

| *Supply source* | *Description* |
|---|---|
| Grid-supply | Generation from the power grid |
| Off-grid A: Backup | Off-grid generation used only when on grid power is unavailable |
| Off-grid B: Full time ≥ 1 MW | Off-grid generation is used full time even though there is grid access, with generators greater than or equal to 1 MW (which require government registration). |
| Off-grid C: Full time < 1 MW | Off-grid generation is used full time even though there is grid access, with generators less than 1 MW (not needing government registration). |
| Off-grid D: No grid access | Generation in rural locations with no grid access |

*Source:* Power Holding Company of Nigeria.

The study estimates that about 50 percent of energy is generated off-grid in the base year, coming down to 30 percent by 2035. Base year estimates of off-grid generation are based on data and estimates developed with ECN and the Ministry of Power, summarized in appendix H. As grid supplies increase in quantity and reliability, the study projects that off-grid generation for customers who use off-grid generation even though they have access to the grid (that is, categories A, B, and C) will decline as a percentage of energy used as grid supplies increase in quantity and reliability. However, the energy used by those with no grid access, mainly in rural areas (category D) is projected to increase over time in percentage and absolute terms as demand increases faster than the grid availability. This projection is based on projected growth in population and per-capita income in rural areas using UN forecasts for total population and urban/rural split (UN 2010), along with projected income ratios between urban and rural populations.

Given the inevitable uncertainty in estimating off-grid generation, it is important to explore the effects on results if these estimates are inaccurate. See box 16.1 for a sensitivity analysis for this important issue.

Some of this off-grid generation is met by small-scale gasoline and diesel generators used by residential, commercial, or industrial consumers. But, it is

**Box 16.1 Estimating Off-grid Generation: A Sensitivity Analysis**

Estimating existing off-grid power capacity and generation is challenging. Generators of 1 megawatts or greater must be registered with Ministry of Power, but there is little data on the capacity of smaller off-grid generators, and still less on the actual energy they generate, beyond some local surveys (World Bank 2008). It is yet more challenging to project future off-grid generation. This situation is similar in other developing countries, and is perhaps why studies of power systems have usually ignored off-grid generation. Given the large contribution of off-grid generation in Nigeria, which is unlikely to disappear entirely within 25 years, ignoring it would seriously compromise the practical value of this study. Consequently, the study team chose to include estimates of off-grid generation, while recognizing their inevitable uncertainty.

The effects of this uncertainty can be examined using a sensitivity analysis: What if 2009 off-grid generation were 40 percent less or 40 percent more than the current estimate? Assume the same percent change in off-grid generation relative to the base case through 2035, and the same off-grid generation mix over time as described below for each scenario. This plus or minus 40 percent change in off-grid generation would change the cumulative total emissions through 2035 by plus or minus 14.9 percent for the reference scenario and plus or minus 15.6 percent for the low-carbon scenarios, respectively. It would change the percent reduction in total emissions from the reference to low-carbon scenario from 42.9 percent up to 43.4 percent or down to 42.6 percent due to the higher carbon-intensity of off-grid generation relative to grid-based generation in both scenarios. In other words, a large change in assumptions of off-grid generation has a significant effect on overall emissions but a minimal effect on the percent reduction in emissions in shifting from reference to low-carbon scenario.

anticipated that off-grid supply will be increasingly provided by microgrids—that is, local grids in residential or industrial areas with their own generation and distribution, not connected to the national grid.

The Rural Electrification Program was initiated in 1981 to expand access to electricity. It extended electricity to 94 percent of the 774 local government headquarters. However, growth in demand outstripped supply, and more Nigerians were without access to electricity in 2009 than in 1981. Less than one-fifth of rural households currently have access to electricity. Fuel wood accounts for more than 85 percent of domestic cooking fuel and over 50 percent of energy consumption in rural households, according to NPIRD (National Policy on Integrated Rural Development) and NEP (National Energy Policy).

The Rural Electrification Agency (REA) was established to promote rural electrification under the 2005 Electric Power Sector Reform Act (ESPRA), but suspended by the Ministry of Power in 2009 due to allegations of corruption. The Ministry of Power has restarted REA after two years of suspension. Funding for REA is included in the 2012 budget with the intention of resuming the 1946 projects originally initiated by REA.

FGN plans in the Roadmap (FGN 2010b) call for extensive expansion of transmission capacity to existing grid load centers, but limited expansion of transmission and distribution to new areas. It is likely that the grid coverage will be further expanded by 2035 under auspices of the reestablished REA. But, given the magnitude of generation and transmission capacity expansion required just to meet the unmet and growing demand in existing areas (projected as a factor of 6 by 2020, and 10 by 2035), it seems unlikely that Nigeria will achieve substantial coverage of rural areas by 2035.

A full spatial and financial analysis of potential grid accessibility as a function of grid investment was beyond the scope of this study. However, the projected GDP growth including villages and towns in rural areas will require electricity for irrigation, pumping, lighting, residential use, and light industry associated with food and agriculture. Accordingly, the projections of energy consumption for category D (off-grid) include a significant increase from 12 percent in 2009 to 21 percent in 2035 of total electricity, or a factor of 30 in kWh.

### *Transmission and Distribution (T&D) Losses*

The increased generation from 2012 to 2035 will require a corresponding expansion of transmission capacity. Without adequate investment, transmission could become the weakest link in the electrical supply chain. According to the Roadmap, given the firm investment committed by the FGN, it is unlikely that more than a 10 percent increase in the capacity of the 330 kilovolt network was achieved by the end of 2011. This would bring its capacity to transmit power from generation centers to only about 5,000 megawatts. The *Roadmap* therefore proposed increased investment to ensure an increase to 6,555 megawatts for the 330 kilovolt network and 7,488 megawatts for the 132 kilovolt network by the end of 2011. This infrastructure, coupled with the policy of delivering power to the closest load centers, should minimize stranded generation and better meet demand.

**Table 16.2 Reference Scenario for T&D Losses (%)**

| | *2010* | *2015* | *2020* | *2025* | *2030* | *2035* |
|---|---|---|---|---|---|---|
| Reference scenario | 20 | 19 | 16 | 13 | 12 | 12 |

*Source:* MYTO 2011 (data for 2009–12); long-term projections based on discussion with stakeholders at the Energy Commission of Nigeria (ECN).

A related objective is to reduce losses from transmission and distribution. These losses averaged about 20 percent in 2009 (MYTO 2011). As a result of significant investment planned for the period to 2013, the reference scenario projects that technical losses will reduce down to about 19 percent by the end of 2015, 16 percent by 2020, and gradually stabilize at about 12 percent by 2025 and thereafter. Table 16.2 summarizes these assumptions.

Vision 2020 identifies firmly planned investment by the FGN to strengthen and increase the capacity of the transmission and distribution infrastructure during 2011–13. It specifies a total of 314 billion Nigerian naira (US$ 2.1 billion) earmarked for this investment, with a significant portion already released. It projected a reduction in transmission and distribution (T&D) losses resulting in savings of about 148 megawatts in 2010, 1,481 megawatts in 2011, and 1,787 megawatts in 2012, or a total of 3,396 megawatts. This implies an average of about naira 92.5 million per 1 megawatts in losses saved. The reference scenario for investment assumes a constant cost of 92.5 million naira per megawatts per year for improvements in T&D from 2009 to 2035.

## Load Duration Curve

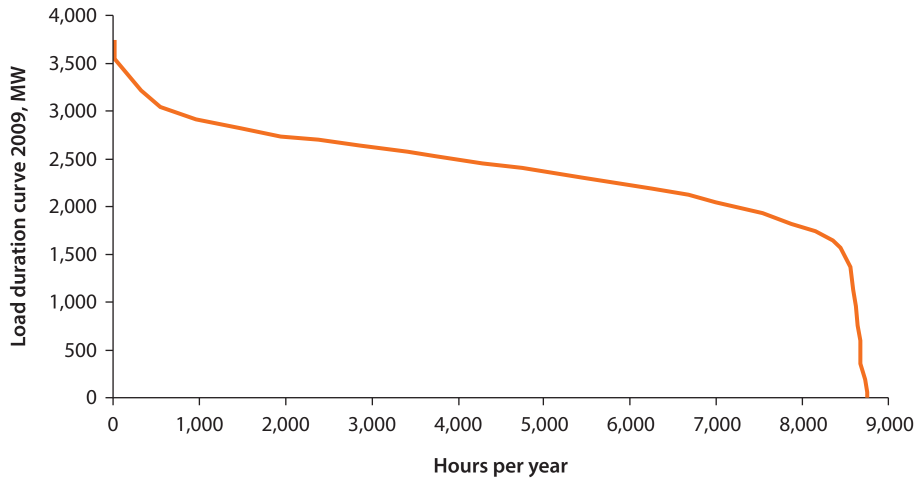
Based on the hourly electricity generation data provided by the Transmission Company of Nigeria (TCN) in Osogbo, in 2009 the Nigerian grid transmitted 20,838 gigawatt hour. These data were used to develop a load duration curve (LDC) for 2009 as shown in figure 16.3. The load factor of 2009 was about 64.5 percent, which was low due to plant downtime. Vision 2020 projects that a system load factor of 75 percent could be attained by 2020. The analysis assumes load factors of 64.54 percent (2011–15), 73.73 percent (2016–20), 75.38 percent (2021–25), and 77 percent (2026–35), based on discussion with Nigerian stakeholders and a comparison with international estimates.

Appendix G table G.2 shows LDC area and load factors for India, Thailand, and Malaysia. The GDP per capita (PPP) range listed for these countries in select years falls in these ranges for GDP per capita between 2009 and 2035, lending further credence to these assumptions. Appendix G table G.3 shows the resulting load duration curve used in this analysis.

## Existing and Planned Generating Capacities

Existing generation capacity in Nigeria is about 26 percent hydropower and the rest are gas turbines: 56 percent single-cycle gas turbine (SCGT) and 18 percent combined-cycle gas turbine (CCGT). As shown in table 16.3, nameplate capacity

**Figure 16.3 Hourly Load Duration Curve (LDC), 2009**




*Source:* Calculations based on data provided by the National Control Center, PHCN Oshogbo.

**Table 16.3 Summary of Nameplate and Actually Available Capacity for Existing Plant and Planned Additions to 2022**

| | *Type* | *Nameplate capacity (MW)* | *Available capacity (MW)* |
|---|---|---|---|
| Existing plants to 2010 | Hydro | 2,230 | 1,108 |
| | SCGT | 6,150 | 2,286 |
| | CCGT | 1,100 | 769 |
| | **Total** | **9,480** | **4,164** |
| Planned additions 2011–22 | Hydro | 3,550 | 2,286 |
| | SCGT | 6,921 | 5,506 |
| | CCGT | 960 | 778 |
| | **Total** | **11,431** | **8,571** |
| Total | Hydro | 5,780 | 3,395 |
| | SCGT | 13,071 | 7,793 |
| | CCGT | 2,060 | 1,547 |
| | **Total** | **20,911** | **12,735** |

*Source:* Summarized from appendix I: Grid Power Supplies.
*Note:* SCGT = single-cycle gas turbine; CCGT = combined-cycle gas turbine.

totals about 9.5 gigawatts, but only about 4.2 gigawatts is actually available because of inadequate maintenance or gas supplies, or, for hydropower, low river flows. These numbers are increasing rapidly as units are refurbished and new capacity comes online. About 11.4 gigawatts nameplate capacity is planned over the next decade, most of it by 2014.

## Power Generation Technologies for Reference Scenario

The reference scenario projects the rapid addition of new generation capacity to meet current suppressed demand and the subsequent anticipated rapid growth in demand. It starts with the planned additions summarized in table 16.3. It then assumes that future capacity additions will follow a technology and fuel mix that does not change substantially from the existing mix of natural gas, hydropower, and diesel, except for the addition of 10 gigawatts coal and 1 gigawatt of nuclear power by 2035, following FGN plans. Before the full technology mix for the reference scenario is outlined, the current status of each type of electricity generation fuel and technology is described as follows.

### *Natural Gas*

Nigeria's abundant natural gas supplies make this the current dominant source for generating electricity. Most existing generation uses single-cycle gas turbines (SCGT). In recent years, power generation has been limited by an insufficient availability of natural gas because of difficulties with transportation from gas production wells in the Niger Delta and offshore and because foreign sales, including liquefied natural gas (LNG), have offered higher prices than the domestic low price. FGN has made it a top priority to remove these bottlenecks with new policies allowing gas prices to increase approaching global market prices to encourage greater supply.

To date, few combined-cycle gas turbines (CCGT) have been installed in Nigeria because of their higher capital cost, even though their greater efficiency will lead to lower levelized cost of electricity (LCOE), especially as gas prices have increased. The LCOE accounts for changing fuel prices over time (computed as the present value of fuel costs over plant lifetime) resulting in lower costs for CCGTs than SCGTs, as explained in the section, "Costs of Grid-Connected Technologies." Based on existing FGN plans, such as Vision 2020 and stakeholder consultations, the reference scenario adopts a slightly greater proportion of CCGT, resulting in their constituting up to 28 percent of gas capacity by 2035.

### *Hydropower*

Nigeria has significant hydropower potential, offering power at relatively low cost and almost zero emissions. It currently has 2.2 gigawatts installed, although about half of that needs maintenance and is not available for generation. The reference scenario follows FGN plans and feedback from stakeholders calling for rapidly bringing all hydropower capacity back online. It projects increasing hydropower up to 7.2 gigawatts by 2035.

### *Coal*

Nigeria has significant reserves of coal. Its coal industry, developed in the colonial period, centered in Enugu, produced over half a million tons per year in the 1950s and 1960s. It declined precipitously due a combination of the discovery of oil and the Nigerian Civil War (1967–70), during which Enugu was the capital of the secessionist state, Biafra. The coal industry has yet to recover substantially. However, there are now plans in early stages to develop coal mines with electricity generation at the mine mouth. Based on consultations with members of FGN and stakeholders, the reference scenario projects 10 GW of coal generation being brought on stream between 2020 and 2035, using subcritical combustion technology.

### Nuclear Energy

In recent years, FGN has developed plans for its first nuclear power plant. The Nigerian Atomic Energy Agency (NAEC) has provided a roadmap calling for 1 gigawatt of nuclear power by 2020. Based on this policy decision to pursue nuclear power, FGN is inviting a first bid for construction, which is unlikely to begin before 2020 (Lewis 2010). Accordingly, 1 gigawatt of nuclear power is included in the reference scenario in 2025.

### Off-grid Diesel, Gasoline, and Gas Turbine Generators

Currently, off-grid generation is comparable to grid generation, as shown in figure 16.2. Diesel generators are responsible for most off-grid generation, with some small gasoline-fueled generators. The reference scenario projects some addition of gas turbines, which are more efficient and cleaner than diesel, resulting in over one third of total off-grid capacity by 2035. The study assumes a 5.5 megawatts off-grid gas turbine. Expansion of such off-grid gas turbines will be limited by the coverage of the gas existing and planned pipeline distribution network mostly to regions in the Niger Delta and South Coast. Diesel and gasoline are more easily transportable by rail and road to rural areas where gas is not available.

## Technology Mix for the Reference Scenario

The reference scenario, shown in table 16.4, projects a mix of generation technologies largely following the existing mix, but expanding capacity almost sixfold by 2035 to meet projected demand. The reference scenario is

**Table 16.4 Projected New Generation Capacity by Technology for the Reference Scenario**

| | *Projected capacity in GW* | | | |
|---|---|---|---|---|
| *Reference scenario* | *2010* | *2015* | *2025* | *2035* |
| ***Grid technologies*** | | | | |
| SCGT (SCGT) | 6.5 | 18.0 | 30.0 | 52.0 |
| Combined-cycle gas turbine (CCGT) | 1.1 | 2.0 | 5.0 | 21.0 |
| Hydropower | 1.9 | 2.1 | 7.2 | 7.2 |
| Coal subcritical | 0 | 0 | 3.5 | 10.0 |
| Nuclear | 0 | 0 | 1.0 | 1.0 |
| Subtotal[a] | 9.5 | 22.1 | 46.7 | 91.2 |
| ***Off-grid technologies*** | | | | |
| Diesel generators | 3.0 | 4.6 | 9.6 | 19.0 |
| Gasoline generators | 1.3 | 2.6 | 5.0 | 6.0 |
| Gas turbines | 0 | 1.3 | 7.0 | 13.0 |
| Subtotal | 4.3 | 8.5 | 21.6 | 38.0 |
| Total | 13.8 | 30.6 | 68.3 | 129.2 |

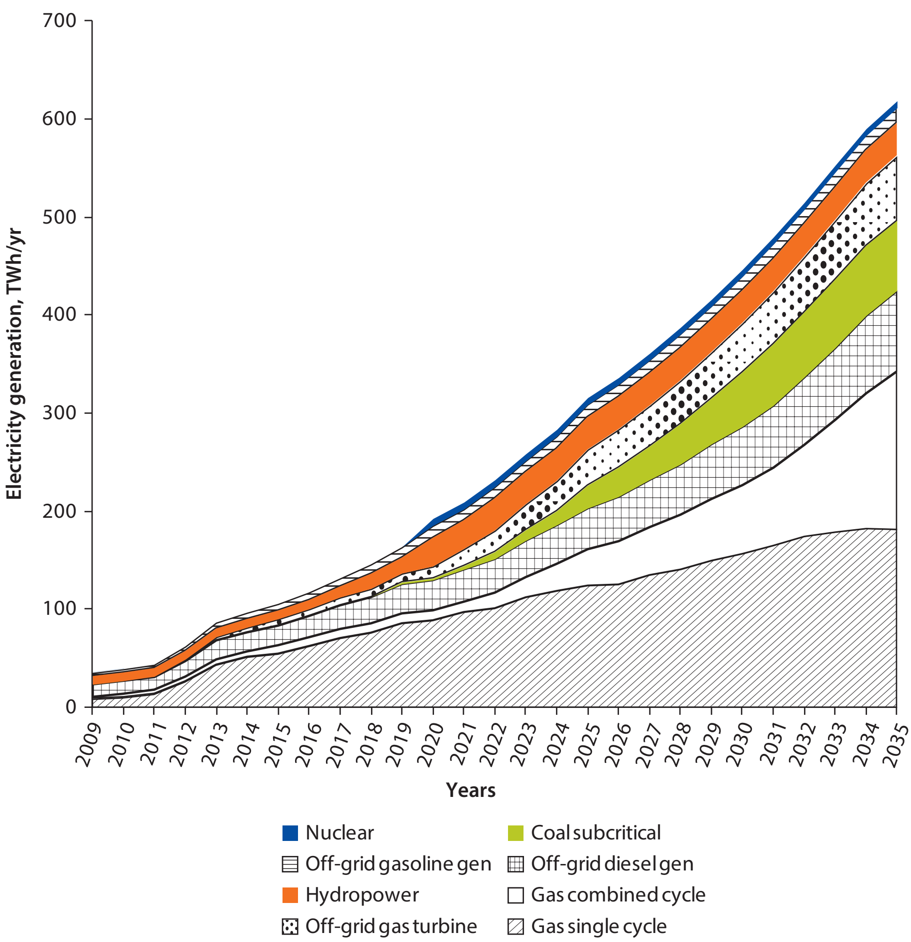
*Source:* Calculations based on data sources listed in chapter 14 references.
a. Less than half of the 2010 installed capacity was actually utilized due to lack of fuel, inadequate maintenance, and other problems.

based in the near term on capacity additions already under development or planned, as described earlier. The mid- and longer-term estimates are based on extensive discussions with stakeholders, with limited data on hydropower and coal potential. The main changes in the grid technology mix over time are a modest increase of CCGT to 28 percent of total gas turbines, expansion of hydropower to 7.2 gigawatts by 2025, and the addition of 10 gigawatts of subcritical coal and 1 gigawatt nuclear to reflect recent government plans. Off-grid, there is some addition of gas turbines to supplement diesel and gasoline generators.

Figure 16.4 shows the electricity generated by year for the reference scenario by technology.

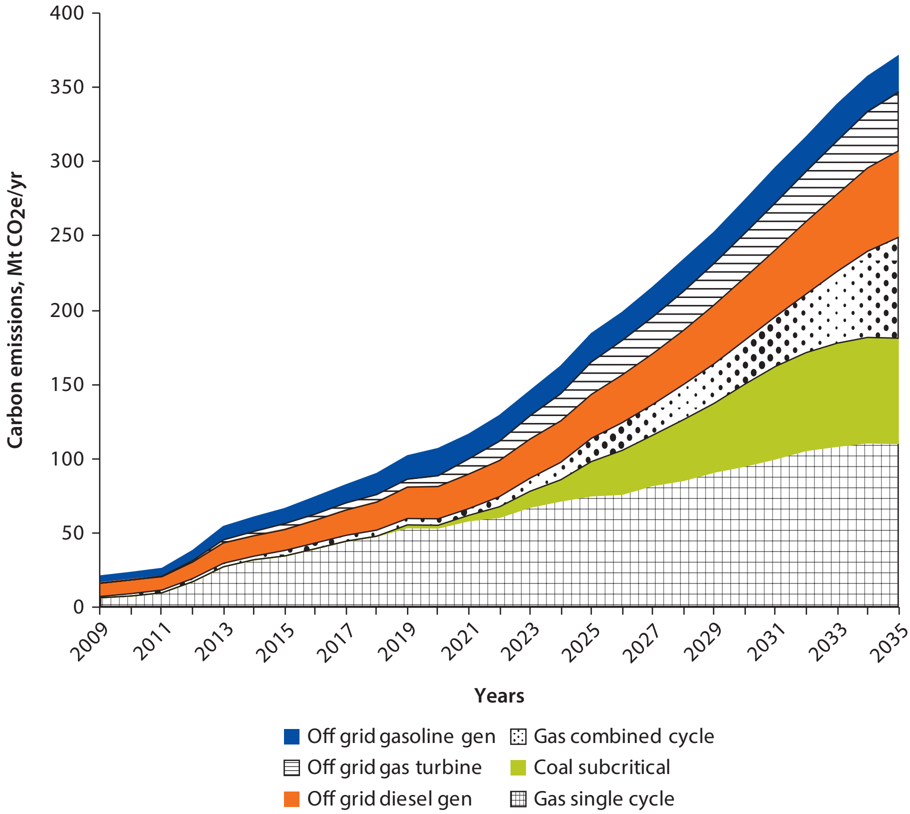
Figure 16.5 shows the corresponding emissions of GHGs for each technology.

**Figure 16.4 Projected Annual Electricity Generation from Reference Scenario by Technology**




*Source:* Calculations based on data sources listed in chapter 14 references.

**Figure 16.5 Projected Emissions, by Generation Technology for Reference Scenario**




*Source:* Calculations based on data sources listed in chapter 14 references.

The average carbon intensity in the reference scenario changes little over time. The increase in emissions from coal is approximately counterbalanced by the lower-carbon intensity from additional hydro, larger proportion of CCGT, and off-grid gas.

## Note

1. Outliers were trimmed, including Angola and the Republic of Congo, with very low electricity use relative to average income, which, like Nigeria, may have a large suppressed demand.

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CHAPTER 17

# Low-Carbon Scenario

The primary goal of the study was to develop practical options for Nigeria to meet its projected growth in demand for electrical power by 2035 without a similar expansion in its greenhouse gases (GHG) emissions. As Nigeria adds generating capacity, it has the opportunity to select from a variety of renewable and other low-carbon technologies, including improvements in energy efficiency to moderate the growth in demand. This chapter examines a variety of low-carbon options and develops a revised technology mix that incorporates greater energy efficiency and more low-carbon generation options to lower overall emissions. The selection and mix of technologies is based on the resource potential, feasibility, and economics of each technology with the goal of developing a portfolio that is balanced among energy resources and also across the geographic regions of Nigeria.

This chapter will provide the following: (1) describe the methodology used to select the low-carbon technologies and develop the low-carbon generation mix used in the scenario; (2) evaluate the potential for improved energy efficiency; (3) evaluate options for improving power transmission and distribution; (4) assess the physical potential for each renewable technology; (5) estimate the cost of generation of each technology (6) develop the low-carbon generation mix based on the assessed resource availability, costs, and other requirements to meet projected demand and estimates its emissions; (7) evaluate the marginal abatement cost (MAC) for this section of technologies; and (8) compare the scenarios in terms of cost of generation.

## Methodology for Developing the Low-Carbon Scenario

The low-carbon scenario, like the reference scenario, starts from the existing and planned generating capacity, based on existing long-term national plans such as the Roadmap (FGN 2010b) and Vision 20: 2020 (FGN 2010a), supplemented by valuable discussions with FGN stakeholders. However, it then modifies addition of new capacity with a variety of low-carbon options, and it reduces projected demand with energy efficiency programs. The study team identified and screened these low-carbon options, based on the methodology outlined in

**Figure 17.1 Steps for Selecting Low-Carbon Options**

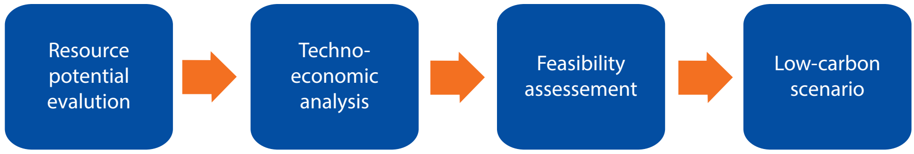



figure 17.1. The team then developed a range of low-carbon scenarios in consultation with stakeholders, and evaluated them using the Energy Forecasting Framework and Emissions Consensus Tool (EFFECT) and Analytical Marginal Abatement Cost model (AMAC) models described earlier to select the primary low-carbon scenario.

### *Resource Potential Evaluation*

The first step involved assessing the physical and technical resource potential of each candidate of all the low-carbon options that were relevant for Nigeria. The potentials for these options were characterized, for both grid and off-grid technologies, including concentrating solar power (CSP), photovoltaics (PV), wind, PV-hybrid systems, hydropower, biomass, and supercritical coal with carbon capture and storage (CCS). In the case of solar and wind, the team assessed the size of the physical resource available in Nigeria, as described below for each technology.

### *Techno-Economic Analysis*

The second criterion for selecting low-carbon interventions is that they should be economically competitive with the reference technology options. To this end, the study team developed projections of future fuel costs and future costs of renewables, and then used these to estimate the projected levelized costs of electricity (LCOE) for each grid and off-grid technology. The LCOE offers a convenient summary measure of overall competitiveness of different generation technologies, representing the present value of the total cost of building and operating a generation plant over an assumed financial life, converted to equal annual payments and expressed in real dollars. For most renewable energy technologies, a common barrier to implementation is the up-front capital cost. To address this in the context of the modeling horizon, the study also accounted for likely improvements resulting from "learning curves"—that is, cost reductions due to future R&D, global deployment, and manufacturing economies of scale. This allowed for the simulation of likely future scenarios in exploring when and how certain technologies would become financially viable.

### *Feasibility Assessment*

A critical aspect of developing the low-carbon scenario is determining the feasibility of implementing the technology options. Numerous sociopolitical and institutional barriers would need to be addressed to fully assess the potential of adopting these interventions in Nigeria. This process required discussions with sectoral experts, public and private sector stakeholders, and members of civil society. In particular, the feasibility assessment entailed identifying potential barriers to implementation—financial, political, or institutional—indicating specific measures and policies to address those barriers. Finally, the low-carbon interventions were subject to thorough review by World Bank staff to ensure that measures were viable, from both political and market perspectives, but also that they satisfy the overall sustainability objectives of the study.

## Promoting Energy Efficiency

Improvements in energy efficiency are usually the most cost-effective options for reducing carbon emissions, so they are discussed before low-carbon generating technologies are evaluated. The "costs" of energy efficiency are often negative—that is, efficiency improvements pay for themselves within a few years or months, even ignoring the benefits of reduced emissions. The advantages of energy efficiency programs are yet more dramatic when electricity is expensive, for example from off-grid generators, or when the grid is capacity constrained—both true in Nigeria.

This section estimates potential energy savings from energy efficiency improvements in the residential, industrial, and commercial sectors. (The latter includes government and education.) Possible programs to improve energy efficiency include promoting compact fluorescent lamps (CFLs) and light-emitting diodes (LEDs); banning sales of inefficient incandescent lights; clear labeling to help consumers understand the cost savings from efficient equipment; and setting efficiency standards for refrigerators, air-conditioning, and other appliances. For the industrial sector, similar programs can promote more energy-efficient industrial equipment, including electric motors, chillers, and heaters. The Energy Commission of Nigeria (ECN) in partnership with the United Nations Development Programme (UNDP) initiated a four-year program to promote energy efficiency in the residential and public sectors in Nigeria (UNDP 2011).

### *The Example of CFLs*

An example of energy efficiency promotion is a program to replace incandescent bulbs by compact fluorescent lamps (CFLs). A recent initiative by ECN and UNDP plans to install 1 million CFLs (including half a million donated by the Government of Cuba) in private and public sector buildings (UNDP 2011). A 14-W CFL gives the same illumination as a 60-W incandescent bulb. Electric light bulb prices in Nigeria were about US$2.33 for CFLs and $0.33 for incandescents in 2011. Since CFLs last seven to ten times longer than incandescent lights, their capital cost is the same or less per hour of illumination. Assuming a light is used three hours per day, each CFL saves about 50 kilowatt-hour per year. Using power from the grid at $0.08 per kilowatt-hour, each CFL would save $4.00 per year. Using off-grid power from diesel generators at $0.25 per kilowatt-hour, the savings from a CFL would be $12.50 per year.

Energy efficiency programs provide “negawatts”—that is, they can reduce the demand for new generating capacity with its associated large capital costs. Assuming lighting is used at peak load, typically 17:00–21:00 hours (5:00–9:00 p.m.) in Nigeria, each CFL can reduce peak demand by 46 Watts per bulb compared to an incandescent (60 Watts minus 14 Watts). The CFL up-front capital cost is about $51 per kilowatts ($2.33/46 watts × 1,000 kilowatts per watt). In comparison, the capital cost of new generation capacity is $408 per kilowatts for diesel generators, or $816 per kilowatts for single-cycle gas turbine (SCGT), a factor of 8 or 16 times larger, respectively. These comparisons ignore the additional capital cost savings on infrastructure to deliver gas or diesel and to expand the grid. Where the need for power is urgent, as it is in Nigeria, it is dramatically easier and faster to purchase and install CFLs than to acquire, install, and operate new generating capacity, whether diesel generators, gas turbines, or renewables. Energy efficiency programs cannot eliminate the need for expanding capacity entirely, but they could noticeably reduce the amount of new capacity needed and the consequent demand for capital. More immediately, replacing 60-watt incandescent bulbs by 14-watt CFLs allows the same limited amount of electrical power to provide the benefits of lighting to over four times as many people.

### *Solar Lamps to Replace Fuel-Based Lighting*

Kerosene lanterns, candles, and other fuel-based lighting are widely used off the grid. Solar lights, which combine a PV panel, battery, and lamp, provide lighting that is more convenient, safer, and at a lower LCOE than fuel-based lights. Lighting Africa (LightingAfrica.org), supported by International Finance Corporation (IFC) of the World Bank Group, is promoting such systems. It has approved 25 commercial off-grid lighting systems as meeting its quality standards. Its partners have sold over 500,000 such lights in Africa in the last two years, benefiting approximately 2.5 million people. Solar lights are mentioned here as a lighting technology that reduces carbon emissions by substituting solar energy for kerosene and other fuels. They do not normally reduce use of electricity directly, but they significantly lower the barrier to entry for low-carbon off-grid electricity generation.

### *Total Potential Savings from Efficient Lighting*

The calculations for bulb replacement show that efficient lighting could produce large savings in energy, costs, and GHG emissions. In order to estimate the total potential for such savings in Nigeria, these factors must be known: percentage of electricity used for lighting, percentage of lighting already uses CFLs or other efficient lighting, and whether and how much a program to promote efficient lighting would accelerate adoption. Unfortunately, little data are available on these, although the current ECN/UNDP program (UNDP 2011) plans to collect some relevant data.

The proportion of electricity used for lighting tends to be high in early-stage economies and grow smaller as per-capita consumption of electricity increases.

ECN (2010) estimated that 48 percent of power was used for lighting in Nigeria in 2009. This is high compared to estimates for other countries—such as 10–15 percent in South Africa (Henderson 1997) and 13–29 percent in India (Mills 2002), but comparable with estimates for other Economic Community of West African States (ECOWAS) countries including Benin (41.9 percent), Burkina Faso (52.4 percent), Mali (31.8 percent), and Senegal (36.1 percent) (de Gouvello, Dayo, and Thioye 2008).

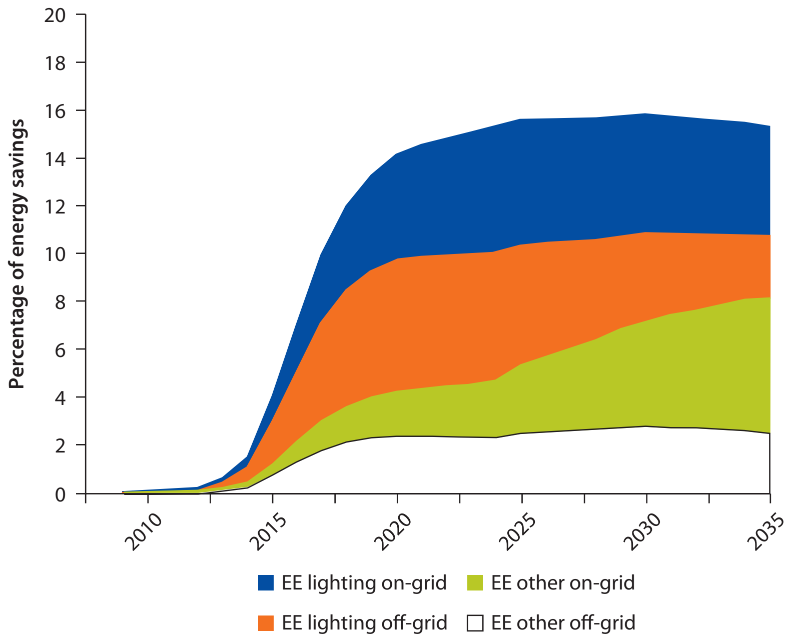
The present study assumes, more conservatively, that Nigeria uses 32 percent of power for lighting in 2010, decreasing to 23 percent by 2035. It assumes that the percentage of lighting currently provided by CFLs and other high-efficiency lamps is 20, 50, and 70 percent of lights in residential, commercial, and industrial sectors, respectively, increasing to 40, 70, and 90 percent, respectively, in 2035 in the reference scenario. The low-carbon scenario assumes a lighting efficiency program, including an eventual ban on incandescent lamps, which replaces 50 percent of the remaining incandescent lights by 2016, increasing to 98 percent by 2020. Such a lighting program would decrease total electricity demand by 9.9 percent in 2020, including 4.4 percent on grid and 5.5 percent off-grid.

### *Estimating the Potential of Energy Efficiency in Nigeria*

To estimate the full potential of energy efficiency programs, it is important to know what fraction of electricity each type of appliance uses. The initiative by ECN in partnership with United Nations Development Programme–Global Environment Facility (UNDP-GEF) plans to survey the quantity, type, and energy rating of lighting, refrigeration, air conditioning, entertainment, and other appliances for a sample of 300 residential and 50 public buildings (UNDP 2011). Since these data are not yet available, this analysis draws on a study of the potential of energy efficiency in India (Government of India 2008; World Bank 2008a), which projects a reduction in demand by 2031 of 23 percent in residential use, and about 10 percent each in commercial and industry applications. This estimate for residential energy efficiency savings is consistent with projected savings potential from energy efficiency programs for Latin America in 2020, which range from 20 percent to 40 percent, including Mexico, Brazil, and Argentina (UNDP 2000). The largest residential energy savings come from improvements in lighting, refrigerators, televisions, air conditioning, and fans (in sequence). The study ignores any rebound effect in which the use of more efficient devices might lead to installing more devices (for example, more lights) and so reduce the overall energy savings, although it increases consumer welfare.

The estimate of savings from energy efficiency programs in Nigeria adapts the World Bank projections for India. It uses similar percentage energy savings, delayed by four years to reflect a program starting in 2012 (where India's programs were planned to started in 2008), and extending the horizon year from 2031 to 2035. In the first decade, the savings in lighting alone as described above would exceed the projections for India, so the energy savings from lighting were reduced so that not more than 60 percent is due to lighting. The resulting projection estimates that energy efficiency programs could reduce total electricity

**Figure 17.2 Potential Energy Savings from EE Programs in the Low-Carbon Option**
*% of reference case energy demand*




*Source:* Calculations based on data sources listed in chapter 14 references.
*Note:* EE lighting, on- and off-grid, represent savings from substituting CFLs for incandescent lights (beyond those included in the reference scenario). EE other, on- and off-grid, represent energy efficiency programs excluding lighting.

demand over 15 percent from the reference scenario by 2025 (figure 17.2). It should be noted that Nigeria has a larger proportion of expensive off-grid generation that may accelerate adoption of energy efficiency. So, the potential savings in Nigeria could be somewhat larger. On the other hand, these projections for both countries ignore the rebound effect that could reduce overall savings.

### *Conclusions on Energy Efficiency*

In summary, EE programs could be a highly cost-effective complement to expanding the grid capacity, reducing the need to expand generating capacity by about 15 percent. These programs could include promotion of CFLs and other efficient lighting with a phase-out of sales of incandescent lamps, high-efficiency standards for new refrigerators, air conditioners, and other appliances, as well as for electric motors and other industrial equipment. The capital costs of more efficient equipment are dramatically lower per watt than adding new generating capacity. While EE improvements in energy efficiency will not eliminate the need for rapid expansion of generation capacity, they can moderate the rate of growth and reduce the need for load shedding, given a constrained supply. They can also accelerate access to the benefits of electricity by allowing a limited energy supply to be shared among more consumers.

**Table 17.1 Planned Reduction in Electricity T&D Losses**
*Percent of generation*

| | *2010* | *2015* | *2020* | *2025* | *2035* |
|---|---|---|---|---|---|
| Reference | 20 | 19 | 16 | 13 | 12 |
| Low-carbon scenario | 20 | 19 | 15 | 12 | 8 |

***Sources:*** MYTO 2011 (data for 2009–2012); long-term projections based on discussion with stakeholders at ECN.

## Improving T&D Loss Reduction

The reference scenario assumes that transmission and distribution (T&D) losses will reduce electricity loss from 20 percent in 2010 to 12 percent by 2035, as shown in table 17.1. The low-carbon scenario assumes a somewhat more aggressive reduction in T&D losses to 8 percent losses by 2035, consistent with international best practice. For comparison, in 2003 some representative developing countries reported the T&D losses above 10 percent: Indonesia (10 percent), India (26 percent), Vietnam (14 percent), and the Philippines (13 percent). Others were less than 10 percent: Thailand (6 percent), Malaysia (5 percent), and China (6 percent). Industrialized countries reported 7 percent in the United States and 5 percent in Japan (Wijaya 2009). Thus the low-carbon scenario assumes that Nigeria could reach a level comparable to other advanced developing countries by 2035.

Some of the major actions in grid T&D loss reduction could include improvements in existing grid infrastructure, the introduction of distributed grid systems and smart grid technology, and reduction of losses in existing grids.

## Power Generation Potential of Renewable Technologies

This section describes renewable generation technology options to reduce carbon emissions and estimates the physical limits of their potential contribution in Nigeria.

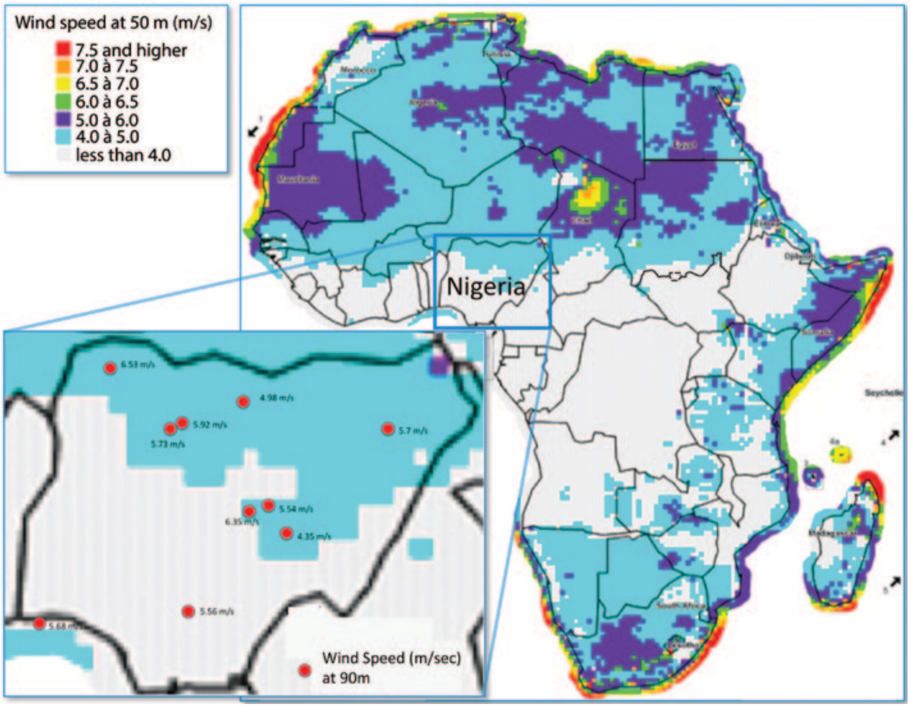
### *Potential for Large Hydropower*

According to the Energy Commission of Nigeria (ECN), Nigeria has a great potential for hydropower (Zarma 2006). Currently, large hydropower accounts for over 20 percent of the total installed commercial electric power capacity. Hydropower is almost ideal because it generates power at low cost and almost zero-carbon emissions and is easily “dispatchable”—that is, capable of load following to compensate for variability in demand and the intermittency of supply from other renewables. The low-carbon scenario makes use of the maximum potential for large-scale hydropower estimated by ECN at 11.2 GW by 2025, compared to the reference scenario’s 7.2 gigawatts hydropower.

### *Wind Energy Potential*

The potential for wind power has yet to be well characterized for much of Africa, and for Nigeria in particular. The *Africa Wind Atlas* prepared by the African

**Map 17.1 Average Wind-Speed Simulation at 50-Meter High**




*Sources:* ADB 2004; FMST 2005.
*Note:* Map shows average wind speed as simulated on mesoscale (50-kilometer grid) model from *Africa Wind Atlas*. An expanded view of Nigeria is overlaid with the average wind speed at 90 meter at 10 locations (red dots), extrapolated from FMST measurements.

Development Bank (ADB 2004) gives average wind speed on a coarse mesoscale 50-kilometer grid based on a simulation model rather than direct measurement. The atlas estimates average wind speeds of 4 to 5 meters per second at 50 meters in Northern and West central Nigeria (map 17.1). In 2005, the Federal Ministry of Science and Technology (FMST) commissioned Lahmeyer International (FMST 2005) to assess wind resources in ten locations in Nigeria. They found average wind speeds of 3.6 to 5.4 meters per second at 30 meters or 40 meters above ground. Table 17.2 extrapolates from these wind speeds to a height of 80 meters, more relevant for utility-scale wind farms in Nigeria. These results are roughly consistent with the mesoscale *Africa Wind Atlas*, except for Ninth Mile Corner (Enugu), in the inset on map 17.1.

Areas with annual average wind speeds above 6.5 meters per second at 80-meter height are generally considered as suitable for wind development (Vaughan 2011). By that criterion, only Sokoto (6.53 meters per second) is suitable. However, the data are insufficient to determine whether other locations might not be economically feasible. A high-resolution wind assessment would likely find additional locations with suitable wind speeds even within broader areas with an average of 5 meters per second. In Kano State, where Lahmeyer

**Table 17.2 Wind Speed at 30, 40, and 80 Meters Above Ground for Sites in FMST (2005)**

| | | *Height above ground* | | |
|---|---|---|---|---|
| | | *Measured* | | *Estimated* |
| *No.* | *Location (local government)* | *30 m* | *40 m* | *80 m* |
| 1 | Badaga (Sokoto) | 5.37 | – | 6.53 |
| 2 | Jose Airport, Kassa (Plateau) | 5.22 | – | 6.35 |
| 3 | Kano, Funtua (Katsina) | 4.87 | – | 5.92 |
| 4 | Gembu, Mambila Plateau (Katsina) | – | 4.99 | 5.73 |
| 5 | Malduguri, Mainok (Borno) | 4.68 | – | 5.70 |
| 6 | Lagos, Lekki Beach (Lagos) | 4.67 | – | 5.68 |
| 7 | Ninth Mile Corner (Enugu) | 4.57 | – | 5.56 |
| 8 | Pankshin Hotel (Plateau) | – | 4.83 | 5.54 |
| 9 | Gumei, Garki (Jigawa) | 4.09 | – | 4.98 |
| 10 | Ibi Meteorological (Plateau/Taraba) | 3.58 | – | 4.35 |

*Source:* FMST 2005.

made a single-point measurement of 4.9 meters per second (extrapolated to 5.9 meters per second at 80 meters), a 30 megawatts wind project is already under construction (Sievert 2011). Thus it is plausible that Nigeria does have significant economic wind potential, especially in the North and East. However, it is essential to develop a high-resolution wind atlas to estimate the size of the resources with greater certainty.

The estimate of Nigeria's wind power potential for each state uses a standard methodology (NREL 2011b) based on estimates from the Africa Wind Atlas. The key steps are as follows:

1. Estimate the percent of each state with wind above 4 meters per second at 50 meters according to the Africa Wind Atlas.
2. Estimate wind turbine capacity in megawatt assuming 5 $MW/km^2$ (NREL 2011b) if 1 percent of the suitable land was used.
3. Estimate energy generated in gigawatt hour per year assuming a 30 percent average capacity factor.

Table 17.3 shows the results for each state in Nigeria that has a significant percentage of its area with average wind speed above 4 meters per second according to the Atlas. For each state, it shows the land area percent above 4 meters per second. It is assumed that 1 percent of this area is suitable for wind development, and this number is used to estimate the corresponding installed capacity and annual generation assuming a 30 percent capacity factor. National wind resource assessments typically assume exploitation between 1 percent and 2 percent of the suitable area. For example, a recent estimate of wind resource in India used 1 percent to estimate its wind potential at 48 gigawatts (Construction Update 2011).

In summary, table 17.3 estimates that Nigeria has a physical potential for about 19 gigawatts of wind capacity, producing about 50 gigawatt hour per years,

**Table 17.3 Estimates of Potential Area Suitable for Wind Energy for Nigerian States**

| *Local government* | *Land area (km$^2$)* | *% with avg. wind speed > 4 m/s* | *1% of suitable area (km$^2$)* | *Installed capacity (MW)* | *Annual generation (MWh)* |
|---|---|---|---|---|---|
| Adamawa | 37,957 | 45% | 170 | 854 | 2,244 |
| Bauchi | 48,197 | 50% | 240 | 1,204 | 3,166 |
| Borno | 72,767 | 100% | 727 | 3,638 | 9,561 |
| Gombe | 17,428 | 100% | 174 | 871 | 2,290 |
| Jigawa | 23,415 | 100% | 234 | 1,170 | 3,076 |
| Kaduna | 44,217 | 60% | 265 | 1,326 | 3,486 |
| Kano | 20,389 | 90% | 183 | 917 | 2,411 |
| Katsina | 23,822 | 100% | 238 | 1,191 | 3,130 |
| Kebbi | 36,320 | 25% | 90 | 454 | 1,193 |
| Plateau | 26,539 | 90% | 238 | 1,194 | 3,138 |
| Sokoto | 32,146 | 90% | 289 | 1,446 | 3,801 |
| Taraba | 59,180 | 40% | 236 | 1,183 | 3,110 |
| Yobe | 44,880 | 100% | 448 | 2,244 | 5,897 |
| Zamfara | 33,667 | 80% | 269 | 1346 | 3,539 |
| **Total** | | | **3,808** | **19,043** | **50,046** |

*Source:* ADB 2004.
*Note:* Areas with wind speed above 4 meters per second, with capacity and annual energy generated, assuming just 1 percent of land is used at 30 percent capacity factor.

mostly in the North and West-Central regions. Expanding the fraction of suitable land developed from 1 percent to 2 percent would of course double these quantities. However, more extensive measurements of wind speed are urgent needed to identify the most promising areas for wind development. This would improve estimates of both physical and economic potentials, given that power increases with the cube of the wind speed.

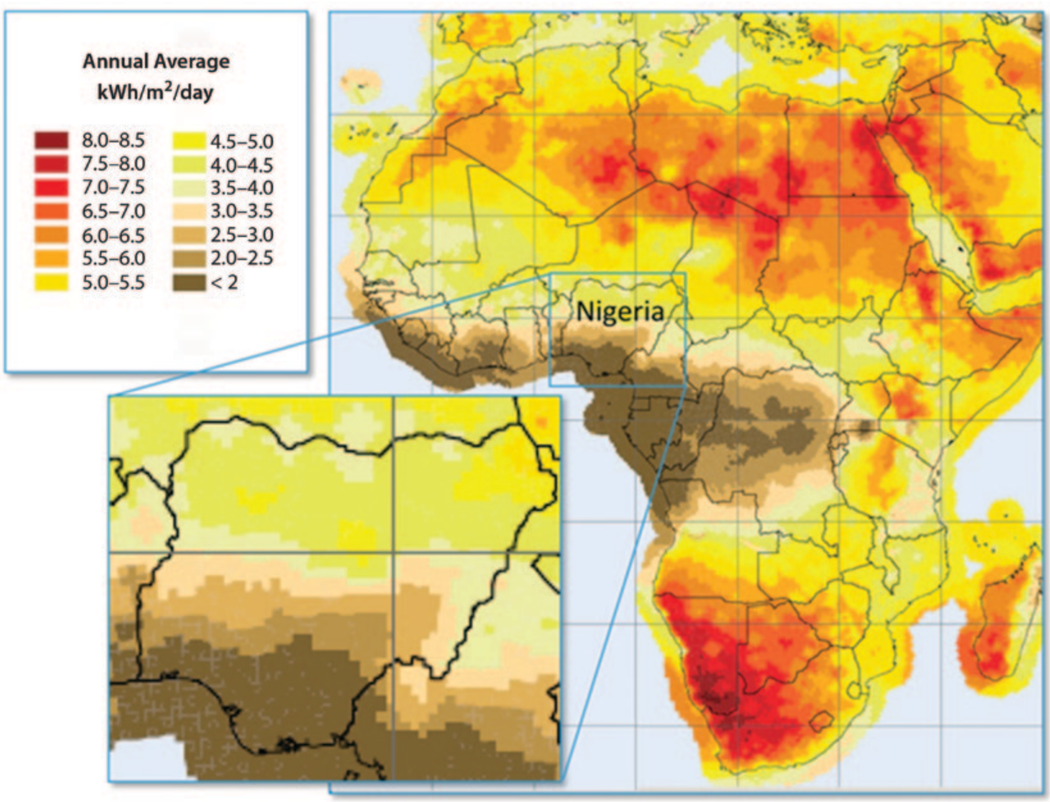
### Concentrating Solar Power Potential

Concentrating solar power (CSP) technologies use mirrors to focus solar radiation to produce heat, which is then used to produce steam to drive turbines to generate power. There are two main kinds of CSPs: Parabolic trough mirrors concentrate the sun's energy onto pipes carrying a thermal fluid; power tower technologies use large fields of steerable mirrors to concentrate solar energy onto a central receiver on a tower. Some tower designs use molten salt as a medium to transfer heat. The hot fluid can be stored in insulated tanks so that a CSP plant can continue to generate power when the sun is not shining. Thus, CSP with thermal storage has the advantage over PV that it can generate power over 24 hours. Recent hybrid integrated solar combined-cycle (ISCC) plants use natural gas as a thermal source when the sun is absent. Both heat sources use the same combined-cycle turbine generator, reducing the total cost to provide solar and back-up fossil power. ISCC with gas would require extending gas pipelines to the areas in North Nigeria most suited for CSP, already part of the FGN's plans for gas infrastructure.

In 2011, there were about 1.2 gigawatts of CSP plants operating and 17.5 gigawatts under development worldwide. The three countries with most CSP under development were the United States, Spain, and China, with 8.7 gigawatts, 4.5 gigawatts, and 2.5 gigawatts respectively (Wang 2011). The International Energy Agency (IEA 2010a) suggests that CSP is a cost-effective technology to lower $CO_2$ emissions and generate electricity at competitive costs in areas with suitable levels of solar radiation. IEA's 2011 *World Energy Outlook* projects 226 gigawatts worldwide by 2030, including 21 gigawatts in India and 30 gigawatts in Africa (IEA 2011). As CSP costs come down the learning curve, the technology will become more economical at lower levels of solar radiation, although the dramatic reduction in PV module prices from 2009 to 2012 has led to some projects switching from CSP to PV.

Nigeria's potential for solar power, both CSP and PV, is better characterized than its wind potential, since it is possible to get good estimates of insolation from satellite observations (see map 17.2). Since CSP technologies use mirrors to reflect the solar energy onto heat absorbers, they require direct solar radiation, usually measured as direct normal irradiance (DNI). CSP developers typically

**Map 17.2 Annual Direct Normal Solar Radiation for CSP for Africa and Nigeria**




*Source:* NREL and UNDP 2005.

look for a minimum DNI of 1,500 (Fluri 2009) to 2,100 (IEA 2010a) kWh/m$^2$/year (4.1 to 5.8 kWh/m$^2$/day) for commercial viability. The Northern, and especially Northeastern, regions of Nigeria are most suitable for CSP projects, with DNI 1,500–2,000 kWh/m$^2$/year (4.1 to 5.5 kWh/m$^2$/day), which is similar to Spain, one of the largest CSP developers. At lower DNI levels, PV has an edge over CSP, since it uses both direct and diffuse solar energy when there is cloud cover, common in Southern Nigeria.

The fourteen states in the northern half of Nigeria comprise an area of 534,000 km$^2$. About 75 percent of this area has DNI greater than 4.1 kWh/m$^2$/day suitable for CSP. Of this area about 71 percent of the land is flat enough to be suitable to build CSP, with slope less than 3 percent, resulting in a total eligible area of 285,000 km$^2$. Assuming that CSP was built on 2 percent of this area with CSP, an energy density of 50 MW/km$^2$ (NREL 2008, 2011a) would imply a potential capacity of 285 GW. At a 30 percent capacity factor this could generate 750 TWh/year. (See appendix K for the underlying analysis at the state level.) These numbers are far greater than the plausible demand in Nigeria, implying that the potential of CSP will be limited by demand and capital availability rather than the physical resource limitations of sun or land in the north part of the country.

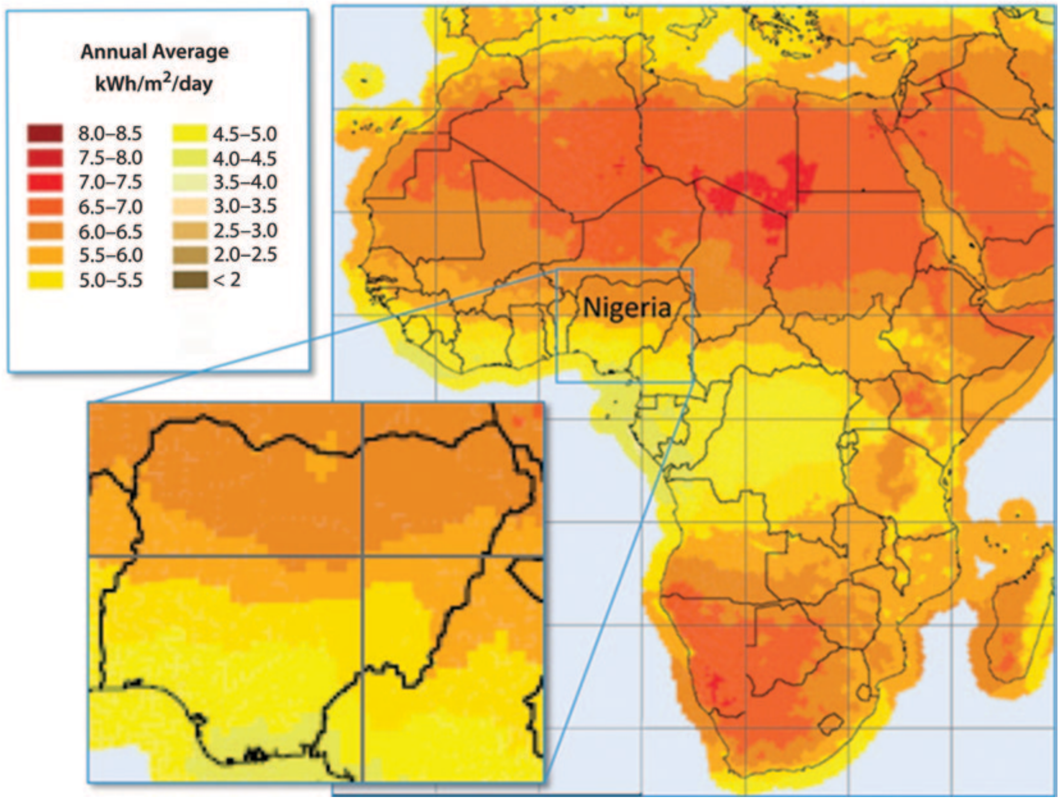
Three African countries, Morocco, Egypt, and Algeria, are developing integrated solar combined cycle (ISCC) CSP plants with parabolic trough collectors, with capacities of 20 megawatts, 20 megawatts, and 35 megawatts, respectively (NREL 2011a). South Africa has also incorporated solar thermal plants in its renewable energy roadmap. As the cost of CSP continues to comes down due to technology innovation, learning, and economies of scale (as described in the section "Costs of Grid-Connected Technologies"), CSP global installed capacity is expected to increase significantly after 2020 (IEA 2010a). The IEA projects that India alone is expected to have about 21 gigawatts of CSP by 2035 (IEA 2011). An installation of 10 gigawatts CSP through 2035 in the northern states of Nigeria is consistent with these plans and projections.

### *Solar Photovoltaics Potential*

PV panels can use both direct radiation and diffuse raditation from haze or light clouds, common in Nigeria, especially in the South. Map 17.3 shows insolation levels for Nigeria using the solar radiation flat plate tilted at latitude at a 40-kilometer resolution (NREL and UNDP 2005), suitable for fixed-axis PV systems. Using this metric, solar radiation in Nigeria averages about 5.5 kwh/m$^2$/day. Levels are higher in the North, with a range of 5.5 to 6.5 kWh/m$^2$/day, but also adequate for PV in the South with a range of 4.0 to 5.5 kWh/m$^2$/day.

Covering 1 percent of the land area of Nigeria with an installed capacity of 1,046 gigawatts would produce about 1,833 terawatt hour per year of energy. (This calculation assumes a total land area of 911,521 km$^2$, average 10 percent PV conversion efficiency, and 20 percent capacity factor.) This simple calculation makes clear that the potential for PV in Nigeria, like CSP, is limited not by the physical resource potential, but rather by energy needs and capital availability.

**Map 17.3 Insolation Levels in Africa and Nigeria for Photovoltaics**




*Sources:* NREL and UNDP 2005.
*Note:* Insolation levels determined using average annual flat plate tilted at latitude at a 40-kilometer resolution.

**Table 17.4 Potential Energy Contribution from Waste-to-Power, Biomass, and Small Hydropower**

| | *2015* | | *2025* | | *2035* | |
|---|---|---|---|---|---|---|
| *Technology* | *GW* | *GWh/y* | *GW* | *GWh/y* | *GW* | *GWh/y* |
| Waste-to-power | 0 | 0 | 0.01 | 87 | 0.04 | 350 |
| Biomass | 0.25 | 1,643 | 1.0 | 6,570 | 2.00 | 13,140 |
| Small hydro[a] | 0.10 | 526 | 3.0 | 15,770 | 3.40 | 17,870 |

*Source:* Estimates based on data from UNIDO 2011 and USEPA 2010; see also appendix M.
a. This calculation assumes 60 percent system efficiency.

## *Potential for Waste-To-Power, Biomass, and Small Hydropower*

A wide variety of other sources of power are available, ongrid and especially off-grid, including using municipal waste to generate methane or to gasify to generate power, combusting biomass directly to make power, and small-scale (micro- or pico-) hydropower. Their potential is summarized in table 17.4, and details can be found in appendix L. These technologies are promising and advantageous where local conditions are suitable, and are well worth pursuing. However, their total potential is relatively modest compared to the overall demand for power, so this book does not assess them in more detail.

## The Costs of Power Generation by Technology

Generation cost is a major driver in the choice of technology in developing a low-carbon scenario, and its accurate assessment of it is essential in screening low-carbon options for economic feasibility. This section discusses projections for future costs of fossil fuels, the fossil generation technologies that use them, and the renewable technologies that do not. It concludes with projections of the future cost of power from grid-connected and off-grid technologies.

### *Fossil Fuel Price Projections*

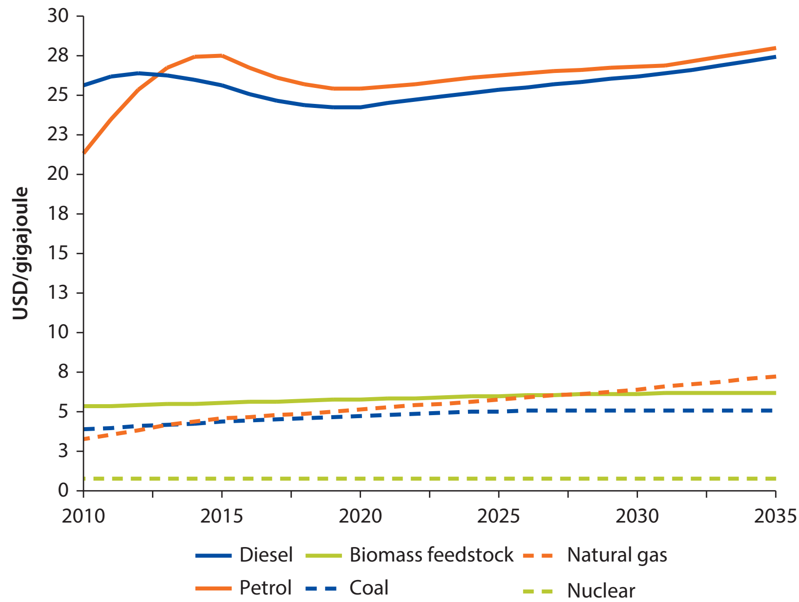
The prices of fossil fuels, especially natural gas, diesel, gasoline, and coal, are key factors in determining the competitiveness of conventional generation technologies. In Nigeria the diesel market is relatively open: most diesel is imported and prices are close to global market prices. Natural gas has long been regulated and gasoline subsidized resulting in prices much lower than global market prices. Recent FGN policies aim to reduce the regulation of gas and reduce or eliminate the subsidy for gasoline. Thus, the projections assume that gas and gasoline will approach global market prices by 2015. Even if they do not, it may be argued that government policy makers should use global market prices when comparing the economic competitiveness of power-generation technologies: Global market prices better reflect the opportunity cost of these fuels to Nigeria, given that most diesel and gasoline are imported and unused natural gas is sold on the global market.

Figure 17.3 shows projected fuel prices for natural gas, diesel, gasoline, coal, and nuclear fuel in US$/gigajoule (for ease of comparison). The rationale underlying these projections follows.

#### *Price of Natural Gas*

Natural gas prices are currently regulated in Nigeria for the power, industrial, and domestic sectors. In 2010 the price of gas for power production in Nigeria was about US$0.90 per MMBtu, or $4.20 per gigajoules (compared to the Henry Hub price in the United States of about $4.43/MMBtu). These prices, much lower than prices available for export, may be part of the reason for the domestic gas shortages that have bedeviled power production. In 2011, the Ministry of Petroleum Resources (MPR) and the National Electricity Regulatory Commission (NERC) signed a memorandum of understanding on gas pricing. This is reflected by the slight increase in gas prices to $1.00/MMBtu in 2013, a forecast of the Multi-Year Tariff Order (MYTO 2011). The present study assumes that beyond 2013 further deregulation will result in natural gas prices in Nigeria reaching export parity by 2015. Beyond 2015, it assumes that domestic gas prices will be

**Figure 17.3 Levelized Fuel Costs over Plant Lifetimes, 2009**




*Sources:* EIA 2011; MYTO 2011; World Bank 2011.

pegged to the global gas price, as projected by the U.S. Department of Energy's *Annual Energy Outlook* (AEO)(EIA 2011), discounted by 12 percent to account for the advantages of local production. Thus, it projects that gas prices will reach $3.91/MMBtu ($4.50/GJ) by 2015, growing to $6.1/MMBtu ($7.20 per gigajoules) by 2035.

### *Price of Diesel*

The diesel price at the pump in 2009 was about $0.64 per liter (EIA 2011), growing to about $0.77 per litre in 2010 (World Bank 2011b), and was about $1.00 per liter in early 2012. This study assumes that the diesel price is approximately at import parity—that is, the price of diesel on global markets (EIA 2011) increased by 12 percent to reflect transportation back to Nigeria plus importation and distribution costs. However, as production of diesel increases from domestic refineries, the study expects domestic prices to approach *export* parity by 2020, pegging diesel to the global price projected to 2035 by AEO (EIA 2011), discounted by 12 percent to reflect the cost of export. The peak in diesel prices around 2015 and subsequent decline reflect the switch from import to export parity prices for Nigeria.

### *Price of Gasoline*

Historically, FGN has subsidized the price of gasoline in Nigeria, fluctuating around naira 65 per liter ($0.40 per liter) in 2009–11. On January 1, 2012, FGN announced an immediate end to the subsidy. This caused some unrest, and after negotiation the size of the subsidy was approximately halved, leaving the price at about naira 97 per liter or $0.64 per liter, with the prospect of future gradual elimination of the subsidy. The study projects gasoline will reach import parity in 2013 (12 percent above global market prices, as forecast by the AEO). Subsequently, as domestic refinery production grows between 2015 and 2020, it projects long-term gasoline prices, like diesel, will reach export parity by 2020 and thereafter—that is, AEO projections (EIA 2011) discounted by 12 percent, reaching $0.93 per liter ($27 per gigajoule or naira 140 per liter) by 2035. As with diesel prices, the peak in gasoline prices around 2015 and subsequent decline thereafter reflect the switch from import to export parity prices.

### *Price of Coal*

Little coal is currently produced in Nigeria, which limits the basis for estimating current prices. Projections assume that a coal price for electricity generation is $46 per ton (2009$) in 2009 increasing to $50 per ton in 2011, consistent with the coal price assumptions in the MYTO (MYTO 2011). After that, they project growth at 3 percent per year consistent with AEO 2012 coal prices, reaching about $80 per ton by 2028, after which coal prices stay constant.

### *Costs of Solar Power*

The economic viability of a low-carbon plan depends in part on the costs of renewables. From 2008 to 2012, rapid expansion in production capacity for PV modules, especially China's 20-fold increase and the end of the shortage of crystalline silicon has led to recent dramatic price reductions. The price of solar panels fell by a factor of nearly four since 2008, with a factor of almost 2 in 2011 alone (Barbose, Darghouth, and Wiser 2012). The rate of PV installation has increased about 65 percent per year in recent years, with 27.7 gigawatts added in 2011 (EPIA 2012). In 2011, China's Quin-Hai province in installed over 1 gigawatt, with prices reported at 1.15 RMB/kwh kWh (US$0.182). In 2011 India accepted bids to provide 300 megawatts electricity to the grid over 25 years at 8.78 rupees (US$0.177) per kWh. (Trivedi 2011).

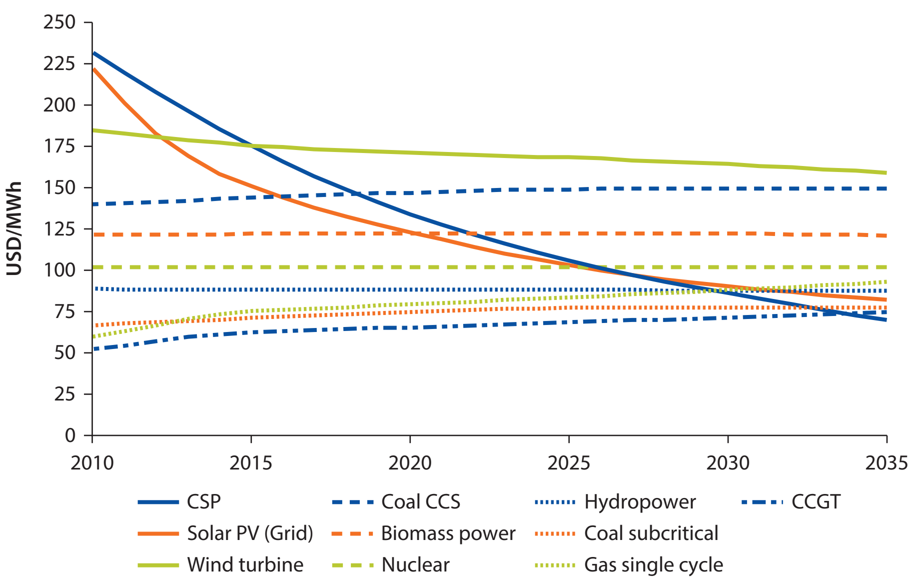
Given the rapid pace of change, current prices are quite variable, and long-term projections are challenging. The IEA *World Energy Outlook 2010* (IEA 2010) projected US$2.20 to $2.40 per watts-peak by 2020, and $1.30 to 1.46 per watts-peak by 2035. In 2011, the IEA projected $2.06 per watts-peak by 2025 and $1.44 per watts-peak by 2035 (IEA 2011). National Renewable Energy Laboratory (NREL) (NREL 2012) recently projected that the United States would not reach DOE's Sunshot target of US$1.00 per watts-peak for a utility-scale system with fixed plates by 2020, but rather US$1.70 per watts-peak. The present study adopts $3.00 per watts-peak for 2012, $1.90 for 2020, and $1.30 for 2035 as mid-values for utility-scale PV. At a 22 percent capacity factor, and 10 percent discount rate, these translate to $0.18 per kilowatt-hour in 2012, $0.12 per kilowatt-hour in 2020, and $0.82 per kilowatt-hour in 2035.

### *Costs of Grid-Connected Technologies*

Figure 17.4 projects the levelized cost of electricity (LCOE) for a wide variety of grid-connected technologies in Nigeria by year of installation to 2035. Those technologies that use fossil fuel are based on the fuel costs presented in figure 17.3. These costs are based on the unit costs, O&M costs, heat rate (efficiency), capacity factor, and other performance characteristics for 2009 listed in appendix table A16.2. The estimates for the fossil-fuel technologies are obtained from the *International Energy Outlook* (EIA 2010) (see appendix P). The costs for biomass power and CSP were taken from the IEA *World Energy Outlook 2010* (IEA 2010d), while those for wind were obtained from IEA *Projected Costs of Generating Electricity 2010* (IEA 2010e), adjusted for transportation charges for Nigeria. The LCOE estimate for CSP assumes a DNI of 2000 kWh/m$^2$/yr, which is typical in the northern part of Nigeria, as described earlier. Projections for PV were described in the last section.

The costs of most of these technologies, especially for solar and wind, assume a reduction in capital cost over time to reflect experience curves, sometimes called "learning by doing." The increase in global capacity of a technology is associated with cost reductions, as a result of both technological improvements and the economies of scale. If cumulative deployment of a technology doubles, the learning rate represents the achieved reduction in costs. It is worth noting that the implied technology growth in learning rates slows as it approaches an upper limit and eventually flattens out as the market for a technology gets saturated. For CSP and wind, projections adopt the learning rates provided by the IEA

**Figure 17.4 LCOE Projections for Grid Supply Technologies**




*Sources:* EIA 2009; IEA 2011.

*Roadmaps*. (IEA 2010a, 2010b, 2010c). The IEA estimates incorporate a 10 percent learning rate for CSP, 17 percent for PV, and 7 percent for wind—that is the decline in cost per doubling of capacity (IEA, 2011). The base year levelized cost reduces over time by applying these learning rates to the nonfuel LCOE component (mostly capital cost), while the levelized fuel costs in future years are driven by the fuel price projections illustrated in figure 17.3. For fossil-fuel technologies, like gas turbines and coal, a modest compound annual growth rate (CAGR) learning rate of 0.05 percent per year is assumed to reflect improvements in technical efficiency over time.

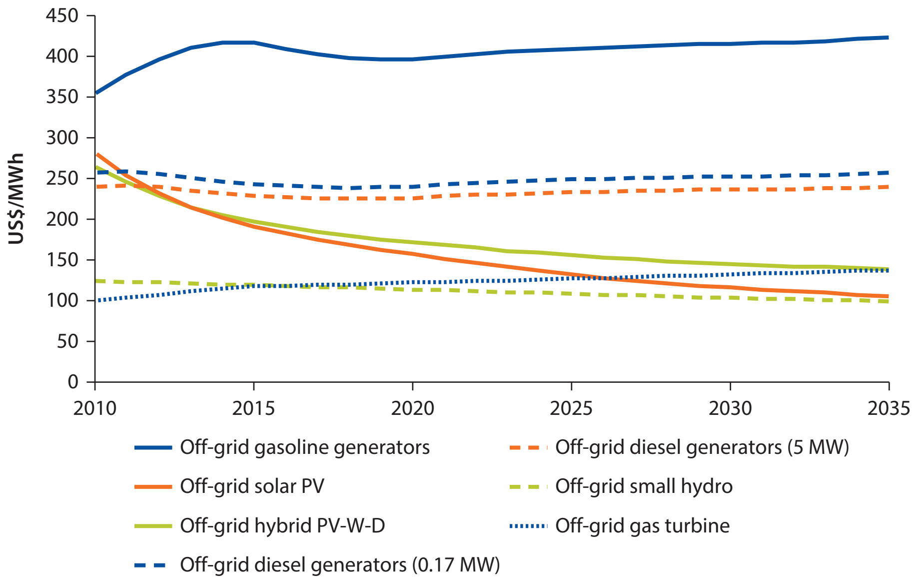
The LCOE for CSP used here, at $134 per megawatt-hour in 2020 and $85 per megawatt-hour in 2030, may be compared with the corresponding values of $70 per megawatt-hour and $63 per megawatt-hour estimated for the Desertec project proposed for Middle East and North Africa, based on a global capacity of 140 gigawatts by 2030 (Desertec 2009).

The early growth in the LCOE for gas turbines (both SCGT and CCGT) is driven by the expected increase in gas prices, reflecting the FGN's policies to allow gas prices to approach global market prices. The economic benefits of more efficient CCGT over SCGT increase over time as gas prices increase. The projected LCOE for CSP and PV, assuming IEA learning rates, suggest that they are likely to become cost-competitive with SCGT before 2030 and with CCGT before 2035. Wind energy does not seem widely competitive in Nigeria based on the limited wind-speed data available, but a more extensive survey of wind speeds may still identify economically viable locations. Neither coal with CCS nor biomass power is likely to be competitive with gas purely on economics, unless the carbon savings can be monetized with clean development or other mechanisms. However, it is important to note that there is great uncertainty about future learning rates for renewables as well as about the possibility of larger increases in global fuel prices than those in EIA's reference scenario.

### *Cost of Off-grid Technologies*

Current costs for diesel and gasoline generators were based on information obtained from vendors in Nigeria. For off-grid technologies, the cost estimates for solar PV were obtained from the IEA *Technology Roadmap for Solar PV* (IEA 2010b), adjusted to reflect the more rapid cost reductions in the last two years, as discussed (see appendix P) For hybrid PV-wind-diesel systems, the HOMER software package was used to analyze the economics of hybrid systems for a small community in Egbeda, Nigeria, as described in appendix O. The analysis accounts for the future decrease in the capital cost of hybrid systems due to learning by taking an average of the CAGR learning rates for PV and wind from IEA, as 4.4 percent per year reduction. For small hydropower (SHP) plants, the study uses the capital cost projections for future years from the World Bank ESMAP report to estimate a 1 percent per year CAGR learning rate (ESMAP 2007). Figure 17.5 compares these projected LCOE estimates for off-grid technologies.

**Figure 17.5 Projected LCOE for Off-Grid Technologies in Nigeria**




*Source:* ESMAP 2007; IEA 2011.

It is noteworthy that off-grid costs of electricity are typically considerably greater than grid generation costs. The costs of diesel generators and, even more, of gasoline generators, reflect the higher cost of these fuels, the low efficiency of the generators, and low utilization factors. Clearly, off-grid gas turbines are much more economical, but unfortunately, natural gas distribution lines are usually not available off-grid. In 2012 PV and hybrid systems were already competitive with diesel and even more for gasoline generators. PV and hybrid systems are close to each other, with a slight advantage to hybrid initially. The advantage of hybrid systems is that they provide power over the entire time without requiring large quantities of battery storage. With the projected learning curves for PV and likely increase in diesel costs, the relative advantage of these renewable sources is likely to improve substantially over the next decade and beyond, subject to the usual caveats about the inevitable uncertainties.

## Analysis for a Low-Carbon Technology Mix

The study team's approach to developing the technology generation mix for the low-carbon scenario reflects four criteria: physical potential for renewable resources, economic competitiveness, geographic balance, and portfolio diversity. The projected effects of instituting this mix are as follows.

### *Resource Potential*

Earlier, the researchers estimated the resource potential in Nigeria for a variety of renewable energy sources. Large-scale hydropower is an appealing renewable energy resource, with an estimated resource potential of about 11.2 gigawatts. While the wind resource has not yet been well characterized, based on available data, a resource of about 19 gigawatts (assuming 1 percent of suitable land area) is estimated. For CSP and solar PV, the resource potential is so large that it is unlikely to be the limiting factor. The availability of capital to develop the resource is more likely to limit development. Biomass has also not been well characterized, but based on existing data, there may be a potential for about 2 gigawatts from combustion of biomass for thermal generation. Other sources, including small hydropower and waste-to-power, could provide attractive moderate-cost, low-emission power locally where resources are available, but their small national resource potential limits their overall contribution to a low-carbon plan.

### *Economic Competitiveness*

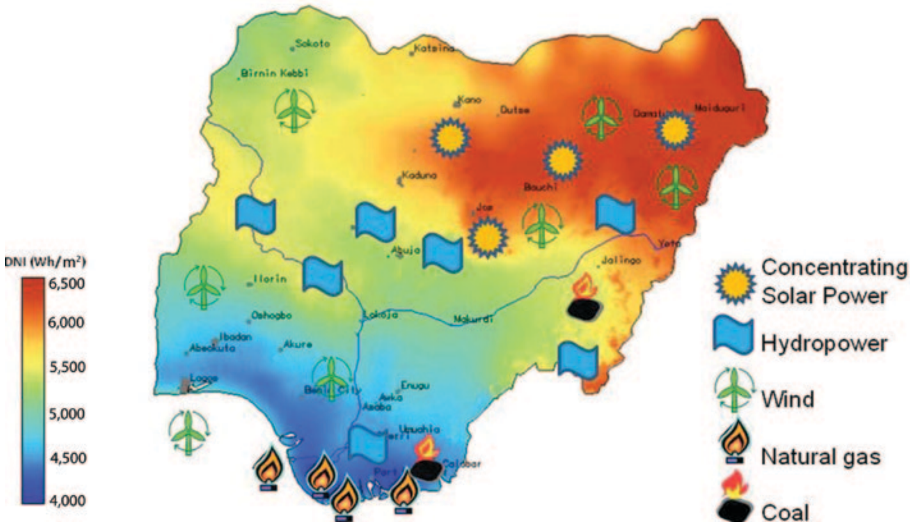
While renewable technologies may be appealing for reducing carbon emissions, given Nigeria's urgent need to rapidly expand availability of power, it is unrealistic to expect rapid adoption of more costly resources when low-cost alternatives, notably natural gas, are easily available. For grid-connected technologies, it appears that CCGT, with its lower carbon intensity, will become less expensive in terms of LCOE than SCGT, as the price of gas rises nearer to international market rates. CSP is projected to be competitive with SCGT in the late 2020s, according to IEA and other studies (IEA 2011), possibly sooner if gas prices continue to increase. Gas turbines can provide power much more economically than diesel or gasoline generators and at lower carbon emissions, where gas is available. However, gas distribution will not reach most areas of demand where the grid is unavailable. Given the high cost of diesel generators in many areas, solar PV, either alone or as hybrid systems, is already competitive, and is projected to become significantly less expensive over the next few years. Accordingly, the study projects a high penetration of PV and PV-hybrid systems for off-grid generation.

### *Geographic Balance*

A key objective is to use domestic resources where possible to provide energy in each region of Nigeria. Nigeria is fortunate to have a variety of energy resources distributed around the country (see map 17.4). No single region has a monopoly on sources of energy. The oil and gas fields are primarily in the South, especially the Niger Delta and offshore. There is coal in the Southeast, in Enugu, Abia State, and other parts of the east, although the amount of coal has yet to be well characterized. There are several opportunities for large-scale hydropower beyond those already developed, mostly on the Niger and its tributaries in a band across central Nigeria from East to West. The *Africa Wind Atlas* indicates that the best wind resources are primarily in the North-East of Nigeria, plus a significant opportunity off the South Western shore. Wind resources require a more careful evaluation.

Maps of the direct solar normal irradiation (DNI) (maps 17.2 and 17.4) indicate large solar resources for CSP in the North and especially North-East areas whose natural energy resources are otherwise limited. Finally, maps of solar

**Map 17.4 Diversification of Energy Sources in Low-Carbon Scenario**




*Source:* PVGIS © European Communities, 2001–2012, HelioClim-1 © MINES ParisTech, Centre Energetique et Procedes, 2001–2008, amended and reproduced by the World Bank study team with permission.
*Note:* Map color represents Direct Normal Irradiation (DNI), a measure of solar intensity relevant to concentrating solar power (CSP). The map provides a stylized illustration of the distribution across Nigeria of sources of energy. Oil and gas are concentrated in the South and offshore; hydropower in central and southern Nigeria; coal deposits in the South and East; direct solar radiance for CSP in the Northeast (orange areas); good photovoltaic (PV) potential is found in most areas; and promising wind sites in the North and offshore.

radiation for tilted flat-plate suggest that, as in most tropical regions, there is a good solar resource for PV over much of the country (map 17.3). This may be used in both pure PV installations and in hybrids with batteries for storage, wind turbines, and diesel generators.

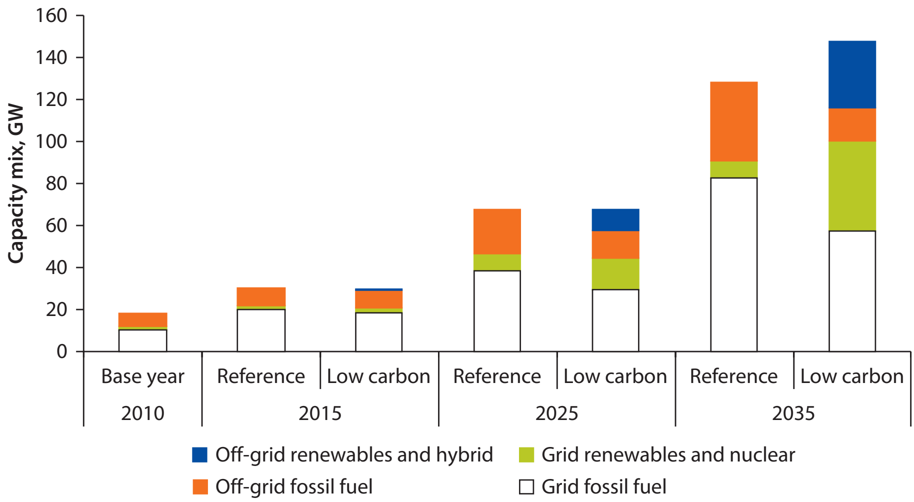
### *Portfolio Diversity*

A portfolio of energy resources should avoid undue domination by any single resource. A diversity of resources minimizes risks from resource availability, climate change, or carbon-related policies that might unexpectedly increase the relative cost or reduce availability of that resource. It is also desirable to keep intermittent renewable resources, pure solar or wind, to less than about 20 percent each of the total supply to avoid capacity problems associated with variability in supply. An efficient grid, coupled with storage—for example, using hydropower dams with large generation capacity, batteries; or diesel with hybrid PVl; heat storage with CSP; or integrated CCGT with CSP—can somewhat relax these limits.

### *Technology Mix Model*

Geographic balance and portfolio diversity have various impacts on the capacity needs and costs of the transmission network. Distributed generation could reduce need for transmission capacity for gas-fired power from South to North.

**Figure 17.6 Generation Capacity Mix in the Reference and Low-Carbon Scenarios**




*Source:* Calculations based on data sources listed in chapter 14 references.
*Note:* Grid fossil fuel includes gas and coal-fired generators. Grid renewables include hydropower, biomass, concentrating and PV solar, and wind turbines. Off-grid fossil fuel includes gasoline, diesel, and gas turbines. Off-grid renewables include small hydropower, PV solar, and hybrid systems.

However, the intermittency of renewables may require expanded transmission capacity to enable hydro and fossil power to compensate when renewables are not available. The model uses an estimated capacity value for each technology, resulting in a higher installed capacity for intermittent renewables than fossil technology to provide the same demand, as illustrated in figure 17.6. A detailed quantitative analysis of these issues requires a spatially disaggregated, power systems engineering model and is beyond the scope of this study.

The low-carbon scenario shown in table 17.5 reflects the four criteria listed above: physical potential, geographical balance, portfolio balance, and economic competitiveness, with the last having the greatest weight. When technologies have similar costs, priority was given to options with lower carbon intensity as reflected in their lower marginal abatement cost (MAC), discussed in the next section.

The technology mix was refined in a series of discussions and workshops with a range of Nigerian stakeholders on the value and availability of energy resources. The selection of the future grid and off-grid mix involved an iterative process of exploration and analysis of plausible low-carbon scenarios along with application of the aforementioned methodological framework to carefully screen them.

Figure 17.6 shows the capacity make-up graphically, comparing the LC scenario with the reference scenario in table 17.5. The following are the key ways that the LC scenario differs from the reference scenario and their rationale:

- The overall demand is reduced by energy efficiency measures, both ongrid and off-grid reducing the total demand and generation needed.

**Table 17.5 Projected New Generation Capacity by Technology for the Low-Carbon Scenario**

| | *Projected capacity in GW* | | | |
|---|---|---|---|---|
| *Low-carbon scenario* | *2010* | *2015* | *2025* | *2035* |
| ***Grid technologies*** | | | | |
| Gas single cycle (SCGT) | 6.5 | 17 | 16 | 15 |
| Gas combined cycle (CCGT) | 1.1 | 2 | 11 | 36 |
| Hydropower | 1.9 | 2 | 8.1 | 11.2 |
| Coal subcritical | 0 | 0 | 0 | 0 |
| Coal supercritical with CCS | 0 | 0 | 2 | 5 |
| Wind turbines | 0 | 0.2 | 3 | 10 |
| Solar concentrating power | 0 | 0.1 | 2 | 10 |
| Solar photovoltaic | 0 | 0.1 | 2 | 10 |
| Biomass | 0 | 0.25 | 1 | 2 |
| Subtotal | 9.5 | 21 | 45 | 100 |
| ***Off-grid technologies*** | | | | |
| Diesel generators | 3 | 4.3 | 7 | 6 |
| Gasoline generators | 1.3 | 2.5 | 3 | 4 |
| Gas turbines | 0 | 1.3 | 3 | 5 |
| Small Hydro | 0 | 0.16 | 1.5 | 3.4 |
| Solar photovoltaics | 0 | 0.21 | 6 | 16 |
| Hybrid PV-Wind-Diesel | 0 | 0.26 | 3 | 11 |
| Subtotal | 4.3 | 9 | 23 | 47 |
| **Total** | **14** | **30** | **67** | **147** |

*Source:* Calculations based on data sources listed in chapter 14 references.

- The total capacity is 30 gigawatts for both scenarios in 2015. By 2025, the capacities are larger but still very close, 68 gigawatts vs. 67 gigawatts, respectively. By 2035, the low-carbon scenario requires significantly more capacity at 147 gigawatts vs. 128 gigawatts for reference scenario, to compensate for the intermittency of wind and solar.

- Much more of the gas turbines are combined cycle (70 percent in 2035), because CCGTs have lower LCOE and emissions. The remaining 30 percent SCGTs are primarily for peaking power, where the lower utilization makes CCGT uneconomic. Ongrid gas generation forms a smaller part of capacity, partly displaced by lower-carbon technologies by 2035.

- Large hydropower is expanded up to its maximum known potential of 11.2 gigawatts.

- In 2015, the scenario adds 100 megawatts of CSP and PV, 200 megawatts wind, and 250 megawatts biomass power as demonstration plants for Nigeria to test out the technology and economics of building, connecting, and operating a significant quantity of renewables. These will also serve to start training a renewables workforce to enable Nigeria to ramp up its renewable capacity more rapidly.

- By 2035, the grid mix increases to 10 gigawatts each of CSP, PV, and wind. For simplicity, CSP and PV are added in equal quantities. At present, the costs of CSP and PV appear similar, although PV has recently moved more rapidly down the cost curve. They could evolve quite differently in the future, in which case it would make sense to increase the share of whichever technology has the lowest cost—after allowing for the higher utilization and dispatchability of CSP, with heat storage, or as a hybrid with gas combined cycle.

- LC scenario adds 2 gigawatts of power from biomass, limited by available potential and possible competition for biofuel production.

- LC scenario retains 5 gigawatts of the 10 gigawatts coal of the reference scenario, but uses supercritical technology with carbon capture and storage (CCS) to minimize emissions, the cost of which remains quite uncertain.

- The 1 gigawatt nuclear power plant in the reference scenario is not included in the low-carbon scenario, in part due to its higher costs.

- For off-grid generation, the low-carbon scenario ramps up diesel generators to 7 gigawatts and gasoline generators to 3 gigawatts to meet increasing demand by 2025, but less rapidly than the reference scenario. Off-grid generators stay at 10 gigawatts through 2035. Some diesel generators may not actually be retired but rather are integrated with PV and/or wind to become part of hybrid systems, in which they provide power when sun or wind is unavailable.

- Some off-grid gas turbines are added, reaching 4 gigawatts by 2025 to meet the off-grid demand. These generate electricity at much lower cost than diesel generators, but are practical only where gas can be made available.

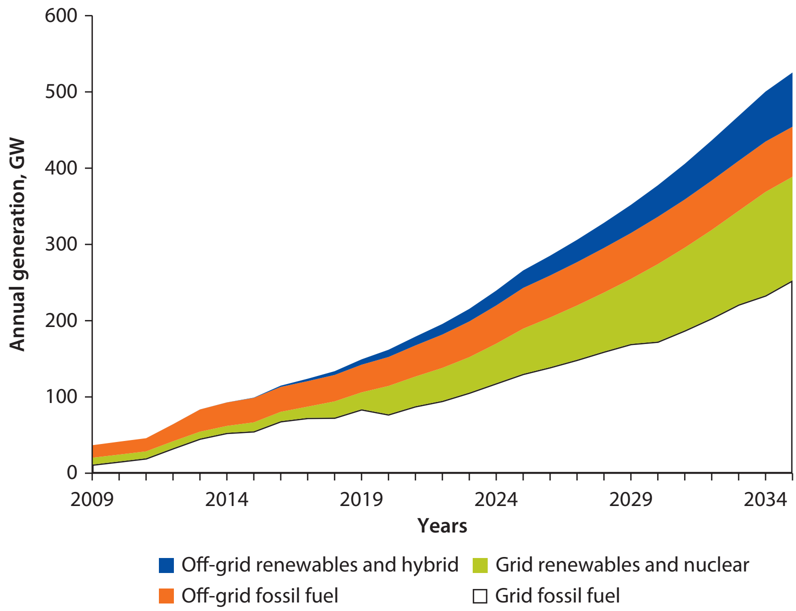
- Some off-grid PV and hybrid systems (50 and 62 megawatts) are added by 2015, mostly for demonstration, evaluation, and training. Significant further capacity is added over the next 20 years resulting in 16 and 11 gigawatts, respectively. These help meet the growing demand for electricity in rural areas not yet reached by the grid. In future years, they will have substantial cost advantages over gasoline and diesel generators. The exact mix of PV, hybrid, and fossil technologies will depend on the future evolution of their costs and the need to balance intermittency for off-grid systems and local micro-grids.

- For off-grid, small hydropower is expanded to its maximum physical potential of 3.6 gigawatts by 2035. It is attractive because of its low cost, low emissions, and dispatchability, making it, where available, a valuable complement to off-grid PV and wind.

### *Energy Generation and Emissions for Low-Carbon Scenario*

Based on the capacity by technology for the two scenarios shown in figure 17.6, the EFFECT model was chosen to estimate energy generation by technology as

**Figure 17.7 Projected Generation (GWh/year) by Technology for Low-Carbon Scenario**




*Source:* Calculations based on data sources listed in chapter 14 references.

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**Box 17.1 Simulating Merit Order Dispatch and Intermittency of Renewables**

The EFFECT model compensates for intermittent availability of renewables, including solar PV, CSP, and wind, using a capacity value to adjust their capacity factors, and increasing the required reserve capacity to meet peak demand. Hybrid off-grid systems include diesel as a backup for PV and wind to maintain high availability. EFFECT simulates merit-order dispatch, using solar and wind whenever available, then hydro, nuclear and coal, having the lowest marginal operating costs, followed by CCGT, with SCGT used as peaking plants.

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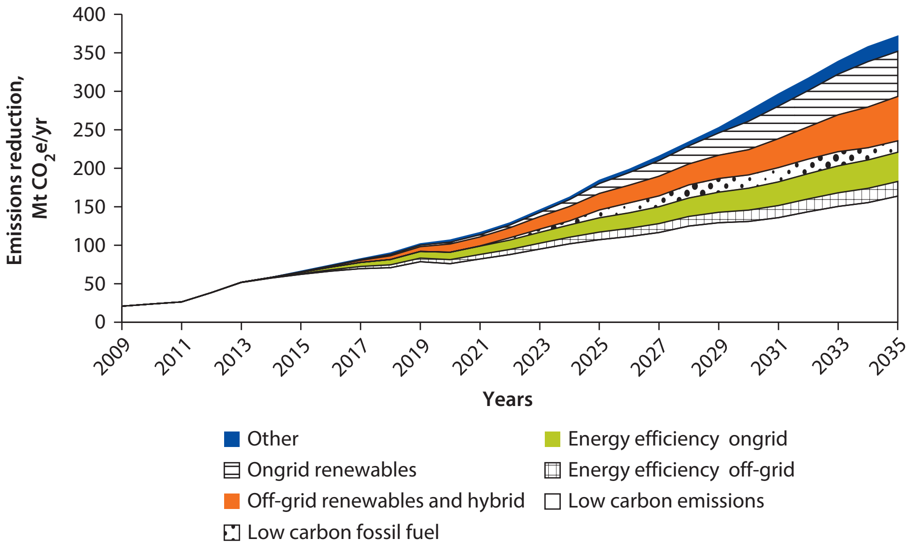
shown in figure 17.7. The percentage of generation in gigawatt hour per year by technology varies from installed capacity in GW due to variations in capacity factors: Renewables and nuclear are dispatched ahead of fossil when available. Combined cycle is dispatched ahead of single cycle gas. Wind and solar have lower-capacity factors since they can only generate power when the wind is blowing or the sun is shining, except for CSP, which has storage to even out daily variations. The calculation assumes that all the electricity produced from wind and solar (without storage) will be used (see box 17.1).

The wedge diagram in figure 17.8 shows the reduction in emissions from the reference scenario (top line reaching 371 Mt $CO_2$e/year by 2035) to low-carbon scenario (reaching 164 Mt $CO_2$e/year by 2035). The rainbow of wedges assigns credit for emissions reduction to classes of low-carbon technologies. Total emissions

**Figure 17.8 Projected Annual Emissions Reductions in Low-Carbon Scenario, with Energy Efficiency**




*Source:* Calculations based on data sources listed in chapter 14 references.
*Note:* Wedges for energy efficiency for grid and off-grid includes lighting and other sources of efficiency. Low-carbon fossil fuel includes gas-combined cycle replacing single-cycle gas turbines and adding carbon capture and storage (CCS) to coal. Off-grid renewables include small hydropower, PV solar, and hybrid systems. Grid renewables include hydropower, biomass, concentrating and PV solar, and wind turbines. Other includes nuclear, biomass power, and transmission and distribution loss reduction.

for the low-carbon scenario through 2035 is 43 percent less than for the reference scenario.

### *Marginal Abatement Cost Analysis*

In the cases where low-carbon technologies cost more than the higher-carbon technologies they replace, the question arises as to how much it is worth paying to reduce carbon emissions and which technologies to select. The marginal abatement cost (MAC) of a technology is the cost per unit reduction in GHG emissions, which may be measured as US dollars per metric ton of carbon-dioxide equivalent saved ($/t$CO_2$e).

Each low-carbon technology is compared to a reference technology that provides the same services, for example, lighting or electricity. For low-carbon grid technologies, the reference technology is SCGT, except for supercritical coal with CCS, which is compared to subcritical coal. Off-grid technologies are compared to diesel generators that they replace. Energy-efficient lighting compares CFLs and other high-efficiency lamps against incandescent bulbs. Table 17.6 lists the various low-carbon technologies, each with its reference technology, mitigation potential (that is, emissions reduction to 2035), and MAC.

The emissions reduction in table 17.6 is the cumulative reduction in GHG emissions due to replacing the reference technology by each low-carbon

**Table 17.6 Mitigation Potential and Marginal Abatement Cost of Low-Carbon Alternatives vs. Reference Technologies**

| *Low-carbon technology* | *Reference technology* | *Emissions reduction (2009–35) Mt $CO_2$* | *MAC 2009 \$/t$CO_2$* |
|---|---|---|---|
| Off-grid hybrid PV-wind-diesel | Off-grid diesel gen | 153 | 31 |
| Off-grid solar PV | Off-grid diesel gen | 196 | –46 |
| Small hydropower | Off-grid diesel gen | 54 | –32 |
| Wind turbines | SCGT | 146 | 41 |
| Concentrating solar thermal power (CSP) | SCGT | 114 | 1 |
| Solar PV (grid) | SCGT | 76 | 7.3 |
| Biomass | SCGT | 78 | 15 |
| Hydropower | SCGT | 481 | –5 |
| Supercritical coal with CCS | Subcritical coal | 20 | 70 |
| CCGT | SCGT | 368 | –14 |
| EE CFL lighting (grid) | Incandescent lighting | 278 | –152 |
| EE CFL lighting (off-grid) | Incandescent lighting | 255 | –355 |

*Source:* MAC costs estimated using cost and performance data discussed in the section, "The Costs of Power Generation by Technology."
*Note:* Present value costs use 10 percent discount rate.

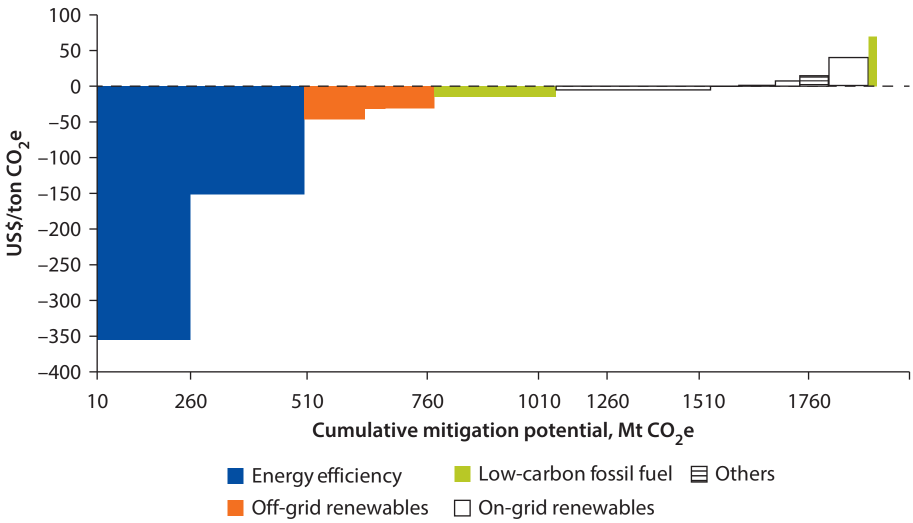
technology that adds generation capacity (or replaces lighting) according to the low-carbon scenario each year through 2035. The cumulative emissions reduction is a measure of the technology's contribution to reducing global damages from climate change, due to the long atmospheric residence time of $CO_2$. The corresponding MAC is the total cost (or, if negative, the savings) calculated as the present value of the capital cost, operations and maintenance costs, and fuel costs relative to the reference scenario, over the life of the longer-life technology. The costs of each technology may change over time, as fuel costs increase and renewables capital cost decreases. The analysis takes the present value over the capital cost of each technology according to the number of units of capacity installed in each year and fuel and O&M costs relative to its reference technology. The present value of costs uses a discount rate of 10 percent per year as the social discount rate for projects in Nigeria, based on feedback from Nigerian stakeholders.

The low-carbon scenario specifies a phased adoption of low-carbon technologies, adding capacity over time. In many cases, costs vary over time, as fossil fuel prices increase and some low-carbon technology capital costs decrease over time due to the learning curve. The MACs in the table use the present value average cost weighted over time according to the projected cost of new capacity added each year of each low-carbon technology compared to the reference technology it replaces.

### *Marginal Abatement Cost Curves*

Figure 17.9 is a MAC curve that plots the numbers from table 17.6 by ordering the low-carbon technologies from left to right by increasing marginal abatement cost.[1] It provides a way to identify which low-carbon technologies are most cost-effective for a given budget. Each technology is shown as a colored rectangle: Its

**Figure 17.9 Marginal Abatement Cost Curve for the Power Sector**




*Source:* Calculations based on data sources listed in chapter 14 references.

width indicates its mitigation potential—that is, cumulative carbon savings for the projected maximum capacity of the technology through 2035. Its height indicates its MAC—that is, the ratio of the net present value (NPV) of relative costs to 2035 of the technology to its mitigation potential. The technologies on the left side have *negative* MACs, indicating that they would actually *reduce* costs as well as emissions.

The first two bars, EE lighting off-grid and EE lighting ongrid, represent energy efficiency programs to substitute efficient lamps, such as compact fluorescent lamps (CFLs) for conventional incandescent bulbs. EE lighting off-grid provides a huge savings of $352/tCO_2e, because it reduces use of diesel generators that are high cost and emissions intensive. EE lighting ongrid also saves funds and emissions.[2] The next three bars, off-grid PV, small hydro (SHP), and off-grid PV/diesel hybrid, also reduce both costs and emissions, since they generate low-carbon power at lower cost than the diesel generators they displace. Gas combined cycle (dark red, 6th bar) is another win-win option, reducing emissions relative to the less efficient SCGTs at a lower cost, saving $14/tCO_2e, especially as fuel price changes over the modeling period. Expanded hydropower has a large potential to reduce emissions at near zero cost (saving $5/tCO_2e).

The remaining grid-connected options in the table each can reduce emissions at a positive cost, from only $1 for CSP up to $70/tCO_2e for coal with CCS. These mitigation costs ($/tCO_2e) account for a changing cost profile over the modeling period and are estimated as the present value average cost weighted over time according to the projected cost of new capacity added. It would be worthwhile if the carbon savings were valued as greater than the MAC, or if

CDM or other financing instruments could be used to obtain payment for the carbon savings to compensate for the extra cost.

The costs of the renewables are projected to fall over time based on experience curves, as shown in figure 17.5, suggesting CSP and PV will become competitive with gas generation between 2030 and 2035. Of course, the future costs of renewable technologies and fossil fuels are quite uncertain and will vary depending on location within Nigeria—for example, with the intensity of sunshine and wind. So, these lines may actually cross much sooner than later.

The MAC curve, like the scenarios on which it is based, is intended to provide insights into plausible futures, but not a prediction. If those options with positive MAC values in figure 17.9 are excluded, the total savings can be estimated as the area of the rectangles under the X-axis—that is, up to expanded hydropower—with a total NPV of $157 billion. Note that the MAC values represent costs over the lifetime of the longest-lived technology, not just through 2035. These numbers ignore the possibility of selling offsets on global carbon markets to support the costs of some low-carbon options.

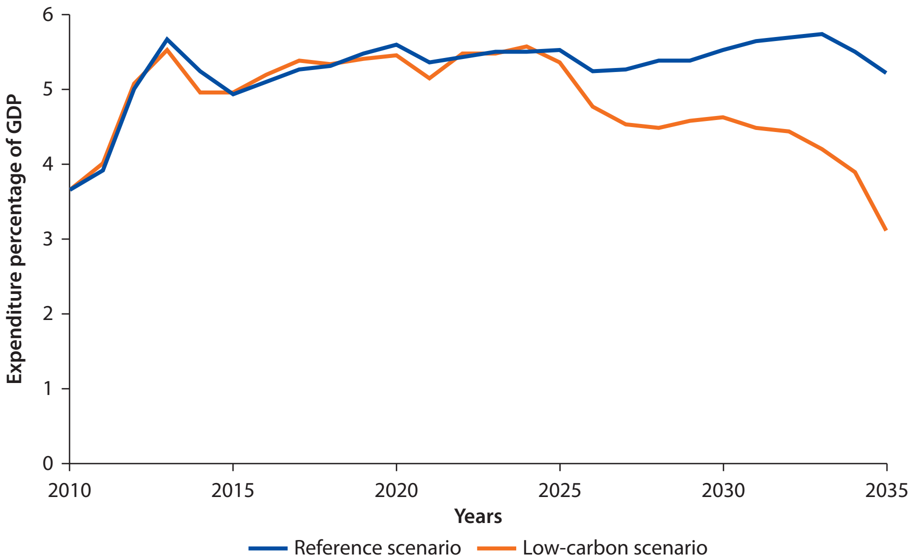
## Comparing Scenarios by Cost of Generation

A key goal in developing the low-carbon scenario was that it should not increase expenditures on electricity. Figure 17.10 shows the total expenditure on generation of electricity over time for these two scenarios as a percentage of GDP. These expenditures include capital costs spent during acquisition and installation, as well as annual O&M and fuel costs. For both scenarios, the total cost increases from about 3.5 percent to 5.5 percent of GDP in 2013, reflecting the expansion and consequent capital expenditures planned in the Roadmap (FGN 2010b). For the reference scenario, expenditures stay between 5 and 6 percent, reflecting a GDP that grows at a similar rate as expenditures on power. The two scenarios remain close until 2025, after which the cost of the low-carbon scenario declines almost to 3 percent in 2035. This reflects savings from energy efficiency programs and from the lower operating costs of renewable power, especially off-grid.

The NPV savings to 2035 of the low-carbon scenario are $12 billion or 7 percent relative to the reference scenario.

Figure 17.11 breaks down the total costs for the two scenarios by capital, O&M, and fuel costs. It reveals that (1) capital costs are significantly larger for the low-carbon scenario, as expected since the renewables have higher capital cost and zero fuel costs, and (2) its higher capital costs are outweighed by its much lower fuel cost after 2025, resulting in significantly lower total costs. Although the annual cost of the low-carbon scenario is almost the same or lower each year in total, the higher capital costs could create financing challenges for particular power generating organizations, whether large-scale grid utilities or small off-grid microgrids if there are constraints on available capital even if they reduce total costs in the long run.

**Figure 17.10 Total Annual Electricity Expenditure[a] for Reference and Low-Carbon Scenarios as Percentage of GDP**

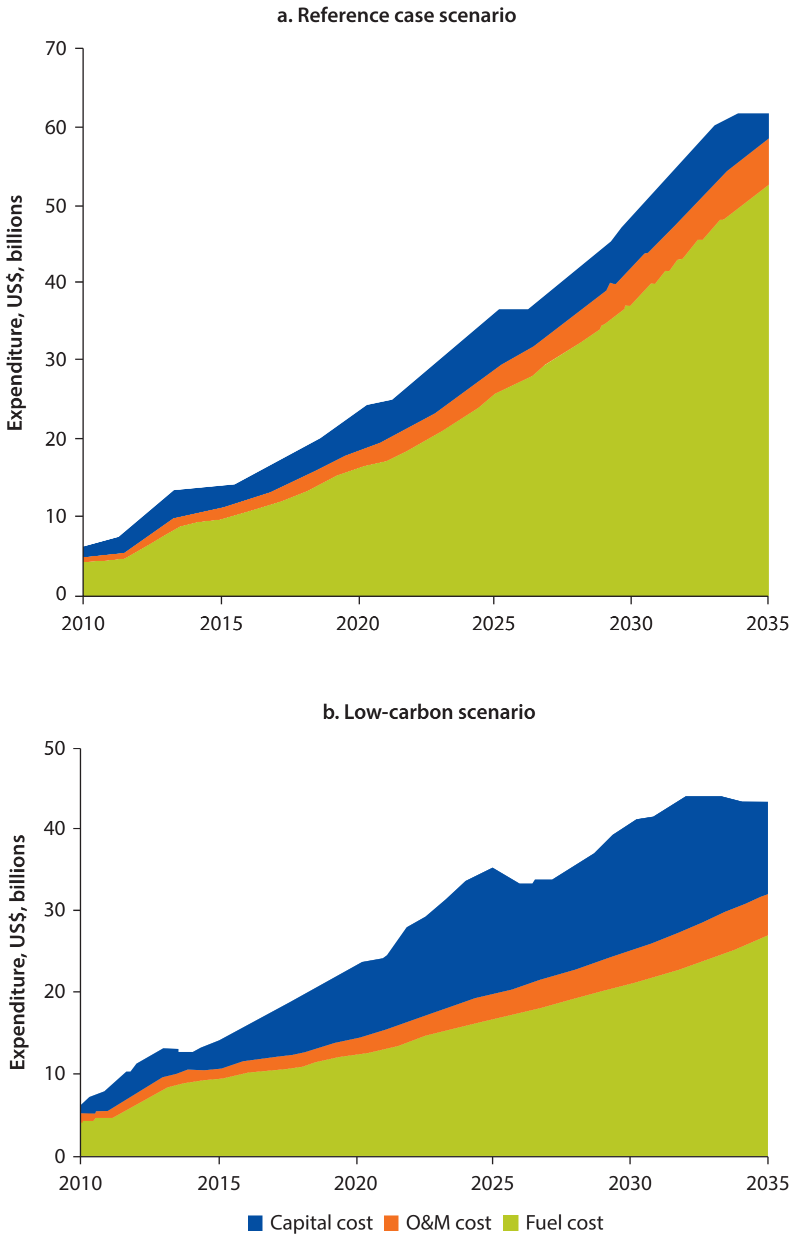



*Source:* Calculations based on data sources listed in chapter 14 references.
a. Total annual expenditure includes capital, operation and maintenance, and fuel costs.

Figure 17.12 compares the cost of generation of the reference and low-carbon scenarios with the business-as-usual (BAU) scenario that generates the same energy per year as the reference scenario using the same-generation mix (including off-grid generation) as today. The reference scenario reduces total generation costs (including capital, O&M, and fuel) by 21 percent from the BAU scenario by 2035—from $84 billion to $62 billion per year. This is partly due to the reduced percentage from 50 percent to 30 percent of off-grid generation with its high proportion of diesel and gasoline generators that are inefficient and expensive to run. Note that the projected economic growth rate of 9 percent per year through 2025 is extremely ambitious, and is unlikely to be compatible with a BAU that assumes off-grid electricity continues at 50 percent of total generation through 2035, given its economic drain from electricity costs. We include these numbers simply as an illustration of the reduction in emissions and costs of the reference scenario compared to a hypothetical BAU scenario.

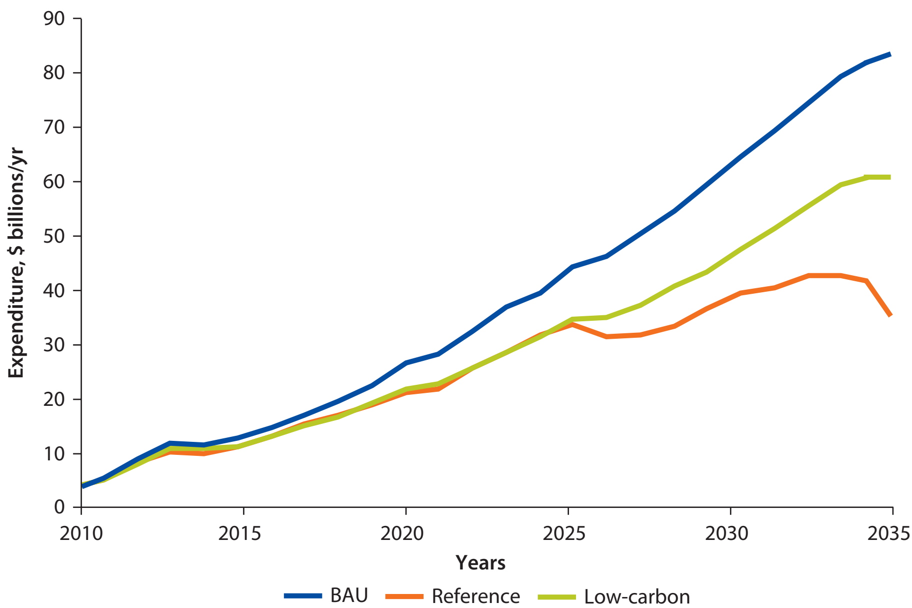
Figure 17.13 shows the cost of generating electricity per kilowatt-hour off-grid and ongrid for reference and low-carbon scenarios, calculated by dividing the total expenditure (capital, O&M, and fuel costs) by electricity consumption. Cost of generation is the largest component of the price of electricity, but it does not include the costs of transmission and distribution, billing, and retailing costs. Off-grid generation costs are roughly twice grid generation costs. Both costs increase in early years, reflecting early increases in fuel costs, especially gas, and the investments in new generation capacity. It is interesting that costs decrease thereafter for grid and off-grid for both scenarios. However, the grid cost for

**Figure 17.11 Breakdown of Total Expenditure into Capital, O&M, and Fuel Costs**



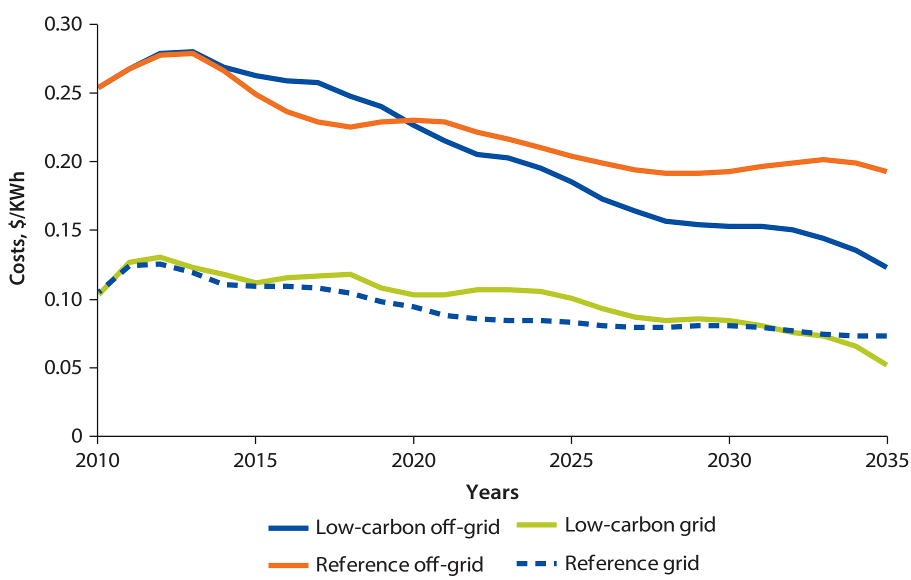

*Source:* Calculations based on data sources listed in chapter 14 references.

**Figure 17.12 Total Expenditure on Generation (capital, O&M, and fuel) for BAU, Reference, and Low-Carbon Scenarios**




*Source:* Calculations based on data sources listed in chapter 14 references.

**Figure 17.13 Cost of Generation Per Kilowatt-Hour, Grid and Off-grid, for Reference and Low-Carbon Scenarios**




*Source:* Calculations based on data sources listed in chapter 14 references.

the low-carbon scenario costs slightly more than the reference scenario until the last three years, but off-grid the low-carbon scenario cost is lower after 2020 and ends up considerably lower—US$0.15 vs. $0.20 per kilowatt-hour, respectively. The recent MYTO (MYTO 2011) calls for electricity prices to fully reflect all costs.

## Notes

1. The total cumulative emissions savings are 1,534 Mt $CO_2$e. This is less than the sum of the savings from table 17.6 to account for subadditive interactions among the low-carbon technologies.
2. The MAC curve does not show "EE other" and "T&D efficiency" options, since there is not sufficient data to estimate the costs of these programs, although they are likely also to have negative costs.

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CHAPTER 18

# Sensitivity to Costs of Fuel and Renewables

Inevitably, the future costs of renewables are uncertain, as are fossil fuel prices. How might these uncertainties affect the adoption of renewables, energy costs, and greenhouse gases (GHG) emissions? This section analyzes a delayed low-carbon scenario (DLC) that might reflect a delay in the times when renewable technologies become competitive with fossil fuels. Its goal is to examine the robustness of the conclusions to the inevitable uncertainties in future costs of fuels and learning rates for cost of renewable technologies.

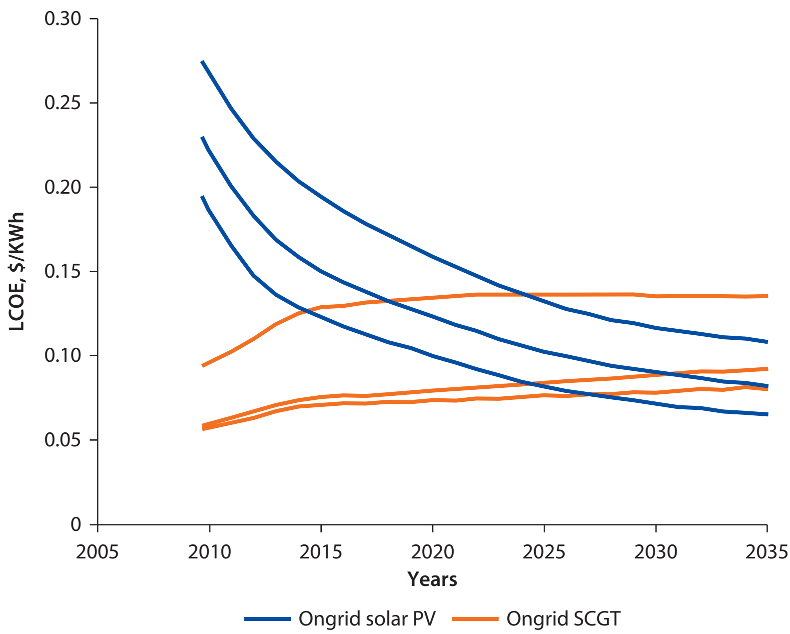
## Uncertainties in Costs of Fuels and Renewables

Figure 18.1 projects the levelized cost of electricity (LCOE) with uncertainty bands (low, mid, and high) for grid solar photovoltaic (PV) and single-cycle gas turbine (SCGT). Figure 18.2 projects LCOE with uncertainty bands for off-grid PV and diesel generators. The mid-costs in each case are the same as shown in figure 17.4.

For SCGT ongrid, the major source of uncertainty is the price of natural gas. The unexpected expansion of production shale gas and hydraulic fracturing has reduced recent gas prices in North America and could reduce global gas prices over time. The low case corresponds to a 1 percent compound annual growth rate (CAGR) around the *Annual Energy Outlook* (AEO) projected price of gas to 2035, to which the Nigerian price tends after 2015, adjusted for export parity. The high natural gas price projection corresponds to projections from the UK Department of Energy and Climate Change (DECC), extrapolated from 2030 to 2035, assuming that they keep constant, as DECC projects them to be from 2022 onwards (DECC 2011). The low and high cases for off-grid diesel generation correspond to the price of diesel in the low and high oil price scenarios of EIA (2011) adjusted for export parity.

For the renewable technologies, PV (grid and off-grid), the high and low bands depict a delay and acceleration respectively in the experience curves (learning rates) so that PV costs reaches the values projected by IEA for 2015, 3 years later or earlier—that is 2012 or 2018—and the values projected for 2020 onward,

**Figure 18.1 Levelized Cost of Energy for On-grid Solar PV and SCGT, Showing Low-, Mid-, and High-Uncertainty Cases**




*Sources:* IEA 2010b; EIA 2011; DECC 2011; this study.
*Note:* Low-, mid-, and high-uncertainty cases are depicted by top, middle, and bottom line for each technology.

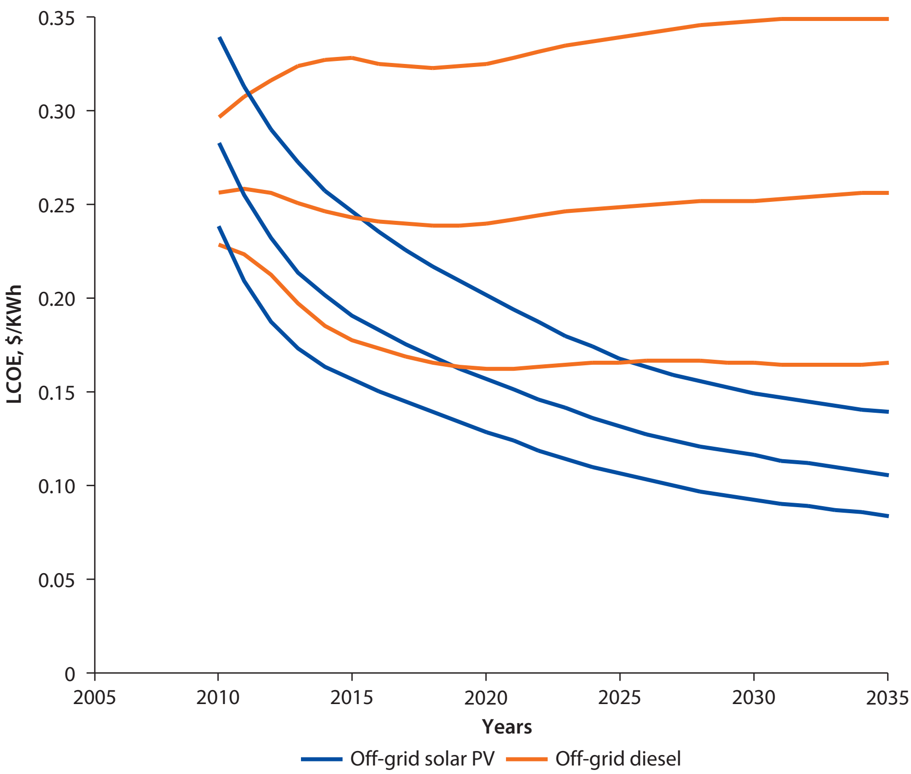
10 years later or 8 years earlier. With the high-cost gas scenario based on DECC projections, PV would become more economical between 2014 and 2024, depending on the choice of PV cost scenario.

With these uncertainty bands, it becomes challenging to project exactly when concentrating solar (thermal) power (CSP) will be cost-competitive with SCGT. The lines could cross at any time from 2020 to 2035 or later. For off-grid, there is in 2012 already a high probability that PV is lower of cost than diesel generation; but, looking at where the low diesel and high PV cost lines cross, there is a small chance that PV will not become cheaper than diesel until 2026. In reality, the actual cost for any technology in Nigeria is not a single value at any time. There is a spread in fuel costs because of variations in transportation costs from the coast to Northern rural areas. PV costs vary by manufacturer and importer as well as with variations in solar intensity from South to North. For these reasons, PV and CSP are likely to be competitive with diesel and gas much earlier in Northern Nigeria than on the South Coast.

## Technology Mix for the Delayed Low-Carbon Scenario

This chapter examines the effect of a ***delayed low-carbon scenario (DLC)***—which combines lower fossil fuel costs and later adoption of renewables due to slower technology learning delaying the time at which renewables become

**Figure 18.2 Levelized Cost of Energy for Off-grid PV and Diesel Generators, Showing Low-, Mid-, and High-Uncertainty Cases**




*Sources:* IEA 2010; AEO 2011; Lumina, 2012.
*Note:* Low-, mid-, and high-uncertainty cases are depicted by top, middle, and bottom line for each technology.

competitive with fossil generation technologies. In this scenario, diesel prices stay low longer and challenge the cost-effectiveness of off-grid PV. This delayed low-carbon scenario provides a sensitivity analysis of the possibility that the cost of fossil fuel, especially natural gas and diesel might be lower—and/or the cost of renewable technologies, especially PV, wind, and CSP might be higher—than the best estimate low-carbon scenario. The purpose of this scenario is to recognize the uncertainties and inform plans by evaluating a range of future possibilities so that Nigeria can avoid major risks and take advantage of opportunities as they arise.

Comparing the delayed low-carbon scenario with the original low-carbon scenario results in the following observations:

- **Off-grid PV and hybrid.** The delayed low-carbon scenario assumes a delay in the start of off-grid PV and hybrid systems deployment by five years, from 2015 to 2020. It assumes that gasoline and diesel generators with some off-grid gas turbine generation will satisfy the demand not met by the delayed renewables.

- **Grid-connected renewables.** The delayed low-carbon scenario retains the demonstration projects of grid-connected PV, CSP, wind, and biomass power of 100, 100, 200, and 250 megawatts, respectively, proposed for 2015, assuming that information about the fuel and renewable costs may not be apparent before they are deployed. However, further deployment of these technologies is delayed by five years relative to the low-carbon scenario. The study adds gas turbine capacity to meet the remaining demand unmet by renewables. Hydropower is assumed to stay the same as in the low-carbon scenario.
- **Same energy efficiency.** The delayed scenario assumes the same energy efficiency measures as the original low-carbon scenario, because they are cost-effective with or without renewables and should be pursued in any case.
- **Same mix in 2035.** The delayed low-carbon scenario catches up with the original low-carbon scenario by 2035, by which time they both have the same technology mix.

Table 18.1 shows the resulting technology mix over time.

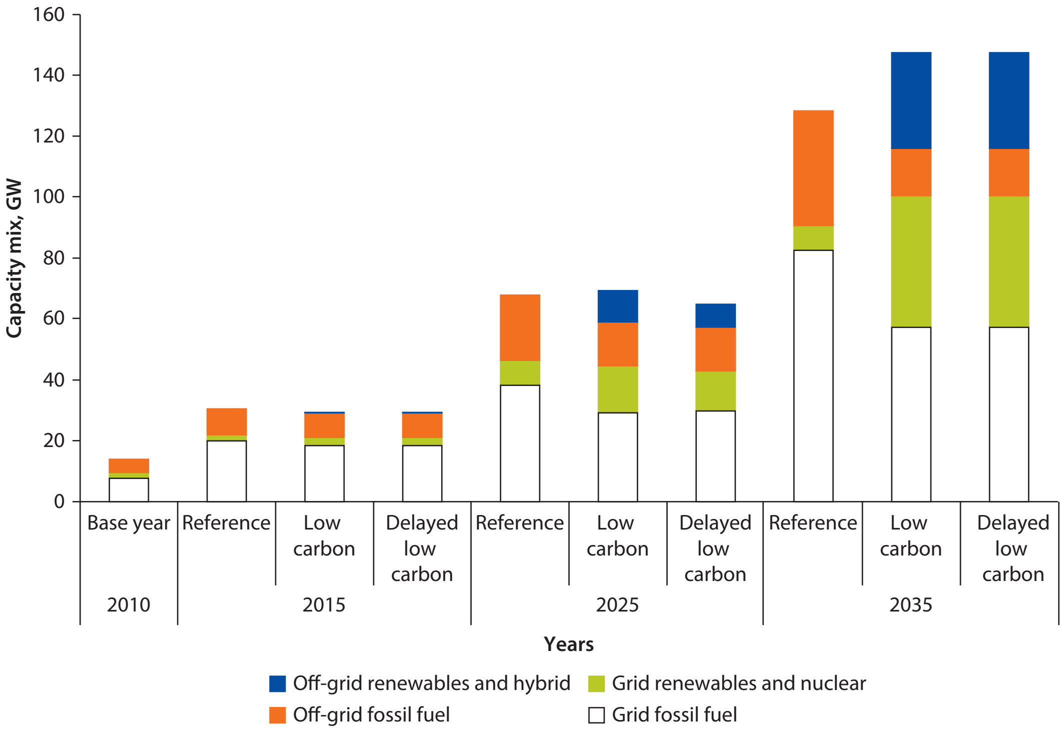
Figure 18.3 compares the technology mix graphically with the reference and original low-carbon scenarios. The delayed low-carbon scenario (DLC) looks similar to the original low-carbon scenario (LC) in 2015. In 2025, it has

**Table 18.1 Technology Mix by Generation Capacity for the Delayed Low-Carbon Scenario**

| | *Projected capacity in GW* | | | |
|---|---|---|---|---|
| *Delayed low-carbon scenario* | *2010* | *2015* | *2025* | *2035* |
| ***Grid technologies*** | | | | |
| Gas single cycle (SCGT) | 6.5 | 17 | 16 | 15 |
| Gas combined cycle (CCGT) | 1.1 | 2 | 12 | 36 |
| Hydropower | 1.9 | 2 | 8.1 | 11.2 |
| Coal subcritical | 0 | 0 | 0 | 0 |
| Coal supercritical with CCS | 0 | 0 | 2 | 5 |
| Wind turbines | 0 | 0.2 | 2 | 10 |
| Solar concentrating power | 0 | 0.1 | 0.5 | 10 |
| Solar photovoltaic | 0 | 0.1 | 0.5 | 10 |
| Biomass | 0 | 0.25 | 1 | 2.0 |
| **Subtotal** | **9.5** | **21** | **43** | **100** |
| ***Off-grid technologies*** | | | | |
| Diesel generators | 3 | 4.3 | 7 | 6 |
| Gasoline generators | 1.3 | 2.5 | 4 | 4 |
| Gas turbines | 0 | 1.3 | 3.6 | 5 |
| Small hydro | 0 | 0.16 | 1.5 | 3.4 |
| Solar PV | 0 | 0.21 | 4 | 16 |
| Hybrid PV-Wind-Diesel | 0 | 0.26 | 2 | 11 |
| **Subtotal** | **4.3** | **9** | **22** | **47** |
| **Total** | **14** | **30** | **65** | **147** |

*Source:* Calculations based on data sources listed in chapter 14 references.

**Figure 18.3 Technology Mix of Installed Capacity for Reference, Low-Carbon, and Delayed Low-Carbon Scenarios**




*Source:* Calculations based on data sources listed in chapter 14 references.
*Note:* Ref = reference; LC = low-carbon; DLC = delayed low-carbon scenarios.

significantly less renewables. By design, it is the same in 2035. Comparing figure 18.3 with the corresponding wedge chart for the (undelayed) LC in figure 17.8, shows them to be similar, with less reduction in emissions between 2015 and 2030 and catching up to the same final emissions reduction by 2035.

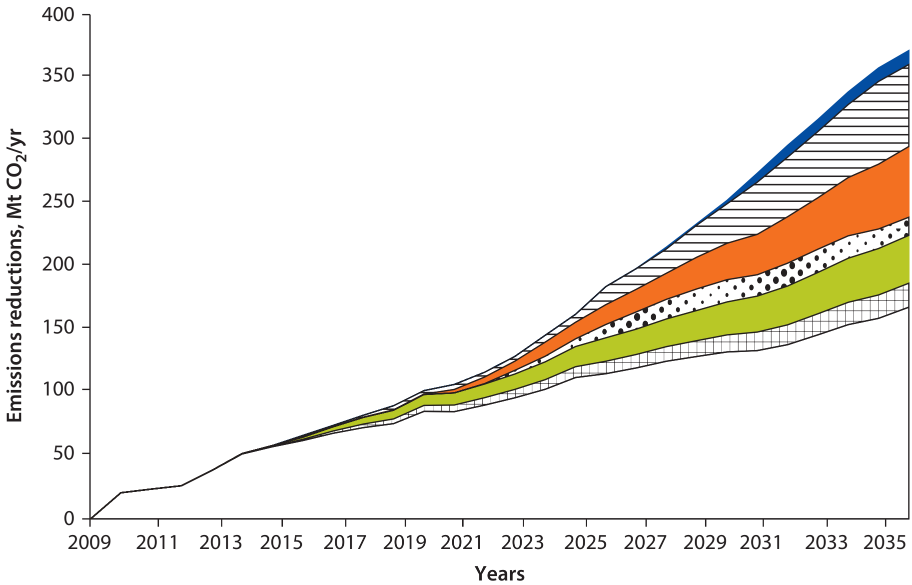
Figure 18.4 shows the emissions reduction wedges for the DLC scenario. It is similar to the wedge chart for the LC scenario, but with a visible delay in adoption of renewables. The reduction in cumulative emissions through 2035 is 40 percent, compared to 43 percent for the LC scenario.

## Marginal Abatement Cost Curves for Delayed Low-Carbon Scenario

The emissions reduction in table 18.2 is the cumulative reduction in GHG emissions resulting from replacing the reference technology by each low-carbon technology adding generation capacity (or lighting efficiency) according to the DLC scenario each year through 2035.

As in the low-carbon scenario, the marginal costs for each technology option are calculated using a present value with a 10 percent social discount rate. The main difference in the DLC scenario is that the total emissions reduction over

**Figure 18.4 Emissions Reduction Wedges by Low-Carbon Option for the Delayed Low-Carbon Scenario, with EE**



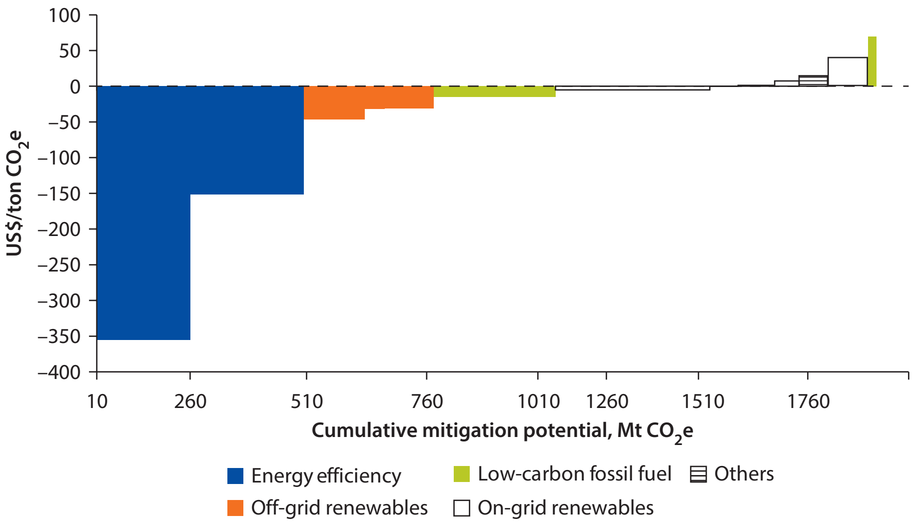

*Source:* Calculations based on data sources listed in chapter 14 references.
*Note:* Wedges for energy efficiency for grid and off-grid includes lighting and other sources of efficiency. Low-carbon fossil fuel includes gas-combined cycle replacing single-cycle gas turbines and adding CCS to coal. Off-grid renewables include small hydropower, PV solar, and hybrid systems. Grid renewables include hydropower, biomass, concentrating and PV solar, and wind turbines. Other includes nuclear, biomass power, and transmission and distribution loss reduction.

**Table 18.2 Mitigation Potential and Marginal Abatement Cost of Delayed Low-Carbon vs. Reference Technologies**

| | | *Emissions reduction (2009–35)* | *MAC* |
|---|---|---|---|
| *Low-carbon technology* | *Reference technology* | *Mt $CO_2$* | *2009 \$/t$CO_2$* |
| Off-grid hybrid PV-wind-diesel | Off-grid diesel gen | 134 | –31 |
| Off-grid solar PV | Off-grid diesel gen | 168 | –46 |
| Small Hydro | Off-grid diesel gen | 54 | –31 |
| Wind | SCGT | 119 | 41 |
| Concentrating solar thermal power (CSP) | SCGT | 101 | 1 |
| Solar PV (grid) | SCGT | 67 | 7.3 |
| Biomass | SCGT | 78 | 15 |
| Hydropower | SCGT | 481 | –5 |
| Supercritical coal with CCS | Subcritical coal | 21 | 70 |
| CCGT | SCGT | 381 | –144 |
| Energy-efficient CFL lighting (Grid) | Incandescent lighting | 278 | –151 |
| Energy-efficient CFL lighting (Off-grid) | Incandescent lighting | 255 | –355 |

*Source:* MAC costs estimated using cost and performance data discussed in the section, "The Costs of Power Generation by Technology."
*Note:* Present value costs use 10 percent discount rate.

**Figure 18.5 Marginal Abatement Cost Curve for the Power Sector**




*Source:* Calculations based on data sources listed in chapter 14 references.

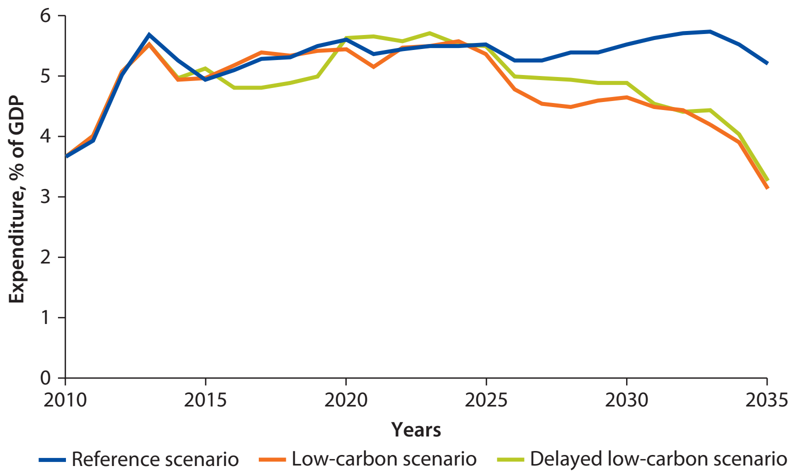
the modeling horizon for the renewable energy technologies—including off-grid solar PV, hybrid systems, CSP, ongrid solar PV and wind—are notably lower and account for a difference of 112 Mt $CO_2e$ relative to the low-carbon scenario in total. The corresponding MAC curve for this scenario is shown in figure 18.5.

## Comparing Costs for the Three Scenarios

Earlier, this chapter discussed low and high projections of costs for fossil fuels and renewable technologies. The delayed low-carbon (DLC) scenario is designed to adapt to low fuel costs and slower learning curves for renewables, leading to a delay in the time at which renewables become economically competitive. Figure 18.6 compares the projected total expenditure by year (including capital, operating, and fuel costs) for each of the three scenarios as a percentage of GDP, assuming the original (mid level) cost scenario.

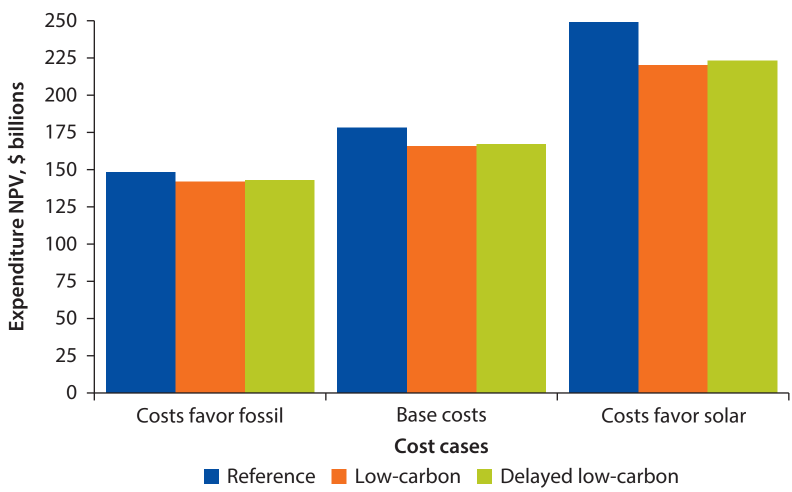
The three scenarios are almost identical through 2015. In 2016/17, the low-carbon scenario costs slightly more than the reference scenario due to initial spending on more capital-intensive low-carbon technologies. The DLC scenario costs significantly less as a result of early savings from energy efficiency and delayed investment in low-carbon technologies; it has a peak around 2020 with a delayed investment in low-carbon technologies. In later years, both low-carbon scenarios reap the rewards of lower cost renewables compared to the reference scenario, but with a greater advantage for the nondelayed low-carbon scenario. The original and DLC scenarios both end up by 2035 with annual costs substantially lower than the reference scenario, at 40 percent and 38 percent, respectively.

**Figure 18.6 Electricity Generation Total Cost as % of GDP for the Three Scenarios**




*Source:* Calculations based on data sources listed in chapter 14 references.
*Note:* Total annual expenditure includes capital, operation and maintenance, and fuel costs.

**Figure 18.7 NPV of Total Expenditures to 2035 for Three Scenarios Against Three Cost Cases**




*Source:* Calculations based on data sources listed in chapter 14 references.

### *The Effects of Uncertainty on Future Costs of Fuel and Technology*

How are the costs of the three scenarios affected by uncertainty about future fuel and technology costs? Figure 18.7 compares these three scenarios according to their NPV cost to 2035 (at 10 percent per year discount rate) against the three (low, mid, and high) cost scenarios for solar PV and fossil (gas or diesel) costs shown for grid-power in figure 18.1 and off-grid in figure 18.2. These cost cases represent two extreme combinations of assumptions:

- **"Costs favor fossil"** means both low fuel cost and high renewables cost (with delayed learning).
- Conversely, **"Costs favor solar"** means both high fuel cost and low renewables costs (with accelerated learning).

All three scenarios have higher NPV cost for the "costs favor solar" cost case, because the higher cost of fuel outweighs the lower cost of renewables, even for the low-carbon scenarios. In all three cases, the reference scenario has the highest cost, although when "costs favor fossil," the NPV cost of the three scenarios are almost the same. The cost reduction from reference to low-carbon scenario is largest in the case of "costs favor solar," as expected. The two low-carbon scenarios are close in all three cases, with the original scenario having marginally lower cost than the delayed low-carbon scenario. It is interesting that the low-carbon scenarios cost less even when "costs favor fossil."

### *Comparing Delayed Low-Carbon with the Other Scenarios*

Table 18.3 summarizes key indicators for comparing the reference, low-carbon, and delayed low-carbon scenarios. The delayed low-carbon scenario provides a sensitivity analysis to explore the possibility that fuel costs remain low and the cost of renewables do not come down as quickly. It modifies the original low-carbon scenario by delaying the adoption of renewables by five years to reflect the later dates on which they reach parity with their fossil alternatives. The delayed and original low-carbon scenario end up with identical technology mixes in 2035.

The first row of the table shows cumulative emissions from 2010 to 2035. The original and delayed low-carbon scenarios have fairly similar total emissions, both significantly reduced from the reference scenario. The second row quantifies the

**Table 18.3 Scenario Comparions by Cumulative Emissions, Diversity of Resource Portfolio, and NPV of Capital, O&M, and Fuel Costs to 2035**

| | | *Scenarios* | | |
|---|---|---|---|---|
| *Comparison factors* | | *Reference* | *Low-carbon* | *Delayed low-carbon* |
| Cumulative emissions | Mt CO2e | 4,335 | 2,475 | 2,587 |
| Diversity of energy source | Complement Gini indexa | 18% | 34% | 34% |
| ***NPV of generation costs*** | | | | |
| Capital | US$ billions | 35 | 56 | 54 |
| O&M | US$ billions | 17 | 15 | 15 |
| Fuel | US$ billions | 127 | 94 | 98 |
| **Total** | **US$ billions** | **178** | **166** | **167** |

*Source:* Calculations based on data sources listed in chapter 14 references.
a. The Gini index is often used to measure income inequality. The complement of the Gini index may also be used as a measure of the diversity of a portfolio of generation technologies. A perfectly diverse portfolio with equal generation from each technology would have a complement Gini index of 100 percent. A totally concentrated portfolio with all generation from a single technology would have an index of 0 percent.

degree of concentration of the portfolio of technologies using the Gini index on the distribution of generation over technologies in the horizon year. The two low-carbon scenarios have identical portfolios at the end, thus the same Gini index, 14 percent less than the reference scenario, indicating a greater diversity of sources. The remaining rows show the NPV of generation costs (at 10 percent discount) broken out into capital, O&M, and fuel costs. As seen before, the low-carbon scenario has lower overall cost, but a higher capital cost—$56 billion vs. $35 billion for the reference scenario.

In conclusion, there are only modest differences between the original and delayed low-carbon scenarios in terms of total cost for any of these three cost cases. Of course, Nigeria does not need to select a single scenario as an unalterable plan: Recognizing the current uncertainty about the future practicality and costs of each technology, Nigeria can and should choose the technology mix for new capacity year by year (subject to build time), taking into account the actual costs of fuel and technologies available at that time. If there is a delay in the anticipated cost reductions for renewables, it makes economic sense to add a larger proportion of fossil generation. Or, if renewables become cheaper sooner than expected, it makes sense to adopt them more aggressively as soon as that becomes clear.

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CHAPTER 19

# Developing an Integrated Low-Carbon Plan for Nigeria's Power Sector

Nigeria has the opportunity to forge a new path in the way it produces and uses energy that could make the nation a leader in Africa. As well as being the most populous country in Africa, it is blessed with a wide variety of indigenous sources of energy—oil, gas, coal, hydro, wind, solar, and biomass—distributed around the country and offshore. Admittedly, the current state of Nigeria's electric power sector is challenging. But Federal Government of Nigeria (FGN) has already put in place the *Roadmap for Power Sector Reform* (FGN 2010) to rectify this situation by rapidly expanding the grid and generation capacity by a factor of 6 by 2020. President Goodluck Jonathan's administration is strongly committed to executing on that plan.

The reference and low-carbon scenarios developed in the study project *possible* futures for Nigeria's energy sector through 2035. These scenarios are neither intended as predictions of what *will* happen nor prescriptions of what *should* happen. The development of detailed plans for such strategy is beyond the scope of the present study. However, these scenarios do provide useful insights into constraints and opportunities that could provide the basis for such a strategy.

This chapter identifies key challenges that face development of a low-carbon plan for Nigeria as well as the opportunities such a plan offers. It then outlines five essential principles as the foundation of the plan. The remaining sections present a set of recommendations for elements of a comprehensive plan based on these foundations for the near and medium term.

## Challenges and Opportunities for Low-Carbon Development

Nigeria faces a number of serious challenges in developing and executing a low-carbon plan, but it can also realize a number of corresponding opportunities.

### *Data Limitations and Uncertainties*

Low-carbon planning must contend with limitations on data and uncertainties about the future, such as GDP growth rates and the consequent growth in demand for electricity. Although information is available on Nigeria's existing and planned grid-connected supply, there is little data on current off-grid generation. There is also little data on consumption patterns, such as the percentage used for lighting, and other applications on and off-grid, needed to estimate the potential and costs of energy efficiency programs. The study bases projections of fossil fuel prices and the costs of renewable energy technologies on the most credible international sources, including U.S. Department of Energy and the International Energy Agency.

However, there are inevitable uncertainties in these projections, with large volatilities in fuel prices and learning curves for renewables that may be much shallower or steeper than expected. While there is evidence that photovoltaic (PV) and hybrid systems are already competitive with off-grid gasoline and diesel generators in many situations, it is hard to estimate when grid-connected renewables will become competitive with gas turbines. Accordingly, the study projects that significant capacity for grid-connected renewables will not be added until the mid-2020s and later, with more modest additions in the medium term proposed as a catalyst for low-carbon development in Nigeria. It makes sense to develop specific long-range scenarios for planning purposes to identify plausible possibilities, while bearing in mind that plans will and should be modified dynamically as new information and experience of actual costs become available.

### *The Challenges of Rapid Growth and Technology Change*

Certainly, an adequate power supply is essential to support Nigeria's planned growth in gross domestic product (GDP). The planned expansion of Nigeria's power supply as specified in the *Roadmap* (2010) is ambitious by any standard. The study team estimates that investments in new generation capacity, plus O&M and fuel costs, for the reference scenario may require 16 percent of a rapidly growing GDP in the near term (see figure 17.10). While a low-carbon path could somewhat moderate the total costs in the longer run, especially for off-grid supply, the planned rate of growth remains challenging. The rapid adoption of relatively new technologies will require consumer acceptance, training of a new workforce, and the rapid development of new markets businesses to finance, deliver, install, operate, and maintain these technologies. The rate of change would be difficult for any society, not least for Nigeria, which is already coping with a variety of economic, cultural, and institutional challenges.

However, this situation also presents a "leapfrogging" opportunity that countries only get when growing fast: employment opportunities such as clean-technology jobs as well as greater business opportunities for private enterprises. As an example, it is well recognized that private enterprises made a tremendous contribution to China's rapid transition into a market economy. In terms of rapid technology adoption, China's massive scale-up of manufacturing especially for

PV and wind continue to bring about a rapid downward trend in technology costs, which bodes well for other developing countries like Nigeria that are looking to adopt these technologies in the immediate future. Thus, it is clear that while rapid growth and technology change pose numerous challenges, they also provide tremendous opportunities and quick-wins for Nigeria.

### *Institutional and Policy Barriers to Low-Carbon Adoption*

The deployment of low-carbon options in the Nigerian power sector faces institutional and policy-related barriers. While a number of agencies and institutions are involved in low-carbon development at different levels in Nigeria, there is a lack of interagency coordination. The result is a weak institutional framework and problems with the implementation of policies and projects. Another institutional need is for a stronger national system of innovation at the federal level to promote research and development, knowledge transfer, and capacity building through collaboration with international agencies and organizations, equipment manufacturers, and the development of public-private partnerships.

Lack of a strong institutional framework to support low-carbon development is likely to hinder private-sector investment in the renewable energy sector. For example, the *Roadmap* indicates that large-scale private sector investments in the upstream and downstream sectors of the electricity industry are unlikely without proportionate investments and reforms in the midstream sector, which requires that management of the Transmission Company of Nigeria (TCN) be contracted out to a private company (FGN 2010).

As for government, the absence of a well-defined and properly enforced policy environment is a critical barrier to low-carbon development in Nigeria. Lack of political will and a constantly changing political environment could limit the growth of low-carbon technologies. Without carefully structured policies, such as feed-in-tariffs, challenges will continue in setting emissions reduction targets or federal efficiency standards for appliances and buildings, and incentivizing low-carbon technology investment. However, there is also a unique opportunity to create a robust institutional framework and clear and consistent policy signals to spur low-carbon development.

### *Financial Barriers and Energy Microcredit*

Low-carbon technologies often have higher up-front capital costs and are sometimes perceived as having high risks from an investment perspective, even when their long-run costs are lower than those of fossil-fueled energy. This poses arguably one of the toughest obstacles to development. The current financial climate in Nigeria makes access to long-term investment challenging, as most lending institutions favor a short-term lending policy (Eleri, Ugwu, and Onuvae 2011).

Since off-grid generation holds great promise for low-carbon development in Nigeria, it becomes all the more important to address the current paucity in "leapfrog funds" to promote community-based low-carbon projects in rural areas. The provision of such funds could help turn these barriers into unique opportunities for rural development including the creation of microgrids run by small power companies or local cooperatives with the economies of scale and access to finance not directly available to individual consumers.

Another related financial barrier for developing countries, including Nigeria, is financing for the private sector. Current end-user tariffs as specified within the Multi-Year Tariff Order (MYTO) are too low to attract private investment from independent power producers (IPPs). Thus, the Nigeria Electricity Regulatory Commission (NERC) has undertaken a major review of the current tariff regime. IPPs will also require that distribution companies and other counterparties are creditworthy when entering into power purchase agreements (PPA), a process which currently takes up to four years in Nigeria. This poses a challenge to accelerate private sector investment. However, according to the *Roadmap*, the FGN is looking into provisions for FGN credit enhancement that could speed up this process and enable greater private sector investment.

### *Carbon Market Challenges and Opportunities*

On the upside, finance for some low-carbon options may be available from global carbon markets. Though the future of the Kyoto Protocol itself remains unresolved, emission trading and the project-based mechanisms under the Kyoto Protocol will continue to be available to Appendix I Parties as a means to meet their quantified emission limitation and reduction objectives (World Bank 2011). As developing countries build low-carbon strategies, their Nationally Appropriate Mitigation Actions (NAMAs) (UNFCCC 2011) could also expand carbon markets in developing countries post-2012. The future supply of carbon credits will depend on (1) the approach to compliance by countries with emission limits, for example, KP Appendix 1 Parties; (2) the clarity of national allocation plans in these countries; (3) uncertainties about post-2012 negotiations; (4) future carbon prices; and (5) the economic health of countries expected to buy carbon offsets (Dayo 2009; Dayo and Gilau 2009). Well-prepared countries like China, India, and Brazil have benefitted from CDM (Clean Development Mechanism) projects in recent years. It is an opportune moment for Nigeria to position itself to benefit from the carbon market post-2012.

Nigeria has a huge potential to participate in the future of the carbon market. The recent World Bank study (de Gouvello, Dayo, and Thioye 2008) on low-carbon potential in Sub Saharan Africa (SSA) identified over 750 CDM opportunities for Nigeria. It concluded that if they were all implemented, Nigeria could reduce over 100 million $tCO_2e$ of GHG emissions annually. The clean technology investment potentials identified in this study, particularly wind and solar, could substantially increase the carbon market benefits for Nigeria. Investments in clean energy are the best way to increase Nigeria's participation in the CDM process and hence the global carbon market. Success will require a detailed evaluation of scope and coverage plus strategies to overcome the barriers that have limited Nigeria's participation in the recent past (Dayo 2009; Dayo and Gilau 2009).

## Foundations for a Low-Carbon Plan

The study analysis suggests that the development of a low-carbon plan should be based on five foundations:

1. Immediately expand power supply.
2. Ensure that economics drives development.
3. Design a diverse, geographically balanced portfolio.
4. Integrate off-grid power.
5. Ensure flexibility in planning

### *Immediate Need to Expand the Power Supply*

The immediate and urgent priority for Nigeria must be to expand the capacity of the national grid to supply power. The current inadequacy of the grid to meet demand and its unreliability are a major obstacle to economic growth. The Government's *Roadmap for Power Sector Reform* provides a clear plan for expanding grid and generation capacity and the natural gas to supply that capacity, along with extensive institutional reform, including deregulation of prices and privatization, to make that practical. Near-term plans appropriately focus on the critical need to meet current demands for more reliable power. A longer-term energy plan aimed at lowering GHG emissions must take these existing priorities and plans as their starting point.

### *Economics Drives Development*

It would be unreasonable to expect a developing economy like Nigeria to limit its GHG emissions if it would slow its economic growth. Any low-carbon plans should support Nigeria's plans for providing a power supply adequate to support its ambitious growth targets. Fortunately, several low-carbon options that can actually accelerate the availability of power are feasible for Nigeria. Most immediately, improving energy efficiency, such as use of compact fluorescent lamps (CFLs), and adopting efficiency standards for air-conditioning and other electrical appliances could bring the benefits of electricity to a wider population faster and at lower cost than adding generation capacity without such efficiency measures. For many rural off-grid applications, such as water pumping, irrigation, and lighting, solar PV is already more economic than conventional gasoline- and diesel-fueled generators. Over time, as the cost of renewables continues to come down the learning curve, other off-grid applications and then ongrid capacity will become economically competitive.

### *Design a Diverse Portfolio with Geographic Balance*

Nigeria is fortunate to have a diversity of energy resources around the country (see map 17.4): Oil and gas in the South and East, including offshore; hydropower in several areas, including the Southeast and Central regions along the Niger river; coal deposits in the Southeast and Eastern areas; biomass and biofuel potential, especially in areas of higher rainfall in the South and central regions; good solar PV potential in most areas; levels of direct normal solar irradiance adequate for concentrating solar power in the Northeast (orange areas in the figure). Wind potential has yet to be well characterized, but there are promising areas in the North and East, and offshore in the Southeast.

A diverse portfolio that includes multiple sources of energy provides flexibility and robustness in the face of uncertainty about resource size and costs. The intermittency of solar and wind power can be balanced by dispatchable gas and hydropower. Geographically distributed sources of power, integrated by an adequate grid, can ensure that the benefits of the power system are shared by all regions of the country.

### *Integrate Off-grid Power*

Due to the limitations of the grid, Nigerians generate an estimated 50 percent of their electricity off-grid, mostly from diesel and gasoline generators. This situation offers an opportunity for Nigeria to leapfrog traditional development pathways based entirely on grid-connected fossil generation. It would incorporate distributed generation, microgrids, and renewable energy, which are increasingly seen as the future of electrical power systems in the industrialized world. This offers a "leapfrog" strategy for power, comparable to the way telecommunications in Nigeria, as in other emerging economies, have directly adopted wireless telephony, leapfrogging the landline telephone technology with its expensive and inflexible infrastructure.

### *Flexibility Provides Robustness in the Face of Uncertainty*

Planning must take place in the face of large uncertainties: What will be the future global prices for oil and gas? How rapidly will the costs of renewable technologies be reduced? How soon will the global community adopt effective carbon policies? Any plan should aim to be robust—it should perform well no matter how these uncertainties turn out. It makes little sense to commit to rigid long-term plans for the mix of generation capacity, given that we are not sure how the relative economics will evolve. However, it makes great sense to make plans that are informed by future possibilities, including the low-carbon plan presented here, so that Nigeria can avoid major risks and take advantage of opportunities as they arise. For example, Nigeria could develop local expertise and experience with renewable technologies through training and demonstration projects to be prepared for expanding installation of renewables rapidly as soon as they reach technical and economic viability. The national grid can be designed so that it can convey power from possible future renewable energy generation sites to load centers, including from hydropower sites that can provide energy storage and low-cost power dispatch to compensate for intermittent wind or solar generation. Such strategies create flexibility to exploit new opportunities with relatively modest initial investment.

## Recommendations for a Low-Carbon Plan for Nigeria

The set of recommendations for a low-carbon plan for Nigeria that evolved from the study analysis are summarized in table 19.1. *Near-term* means a priority by 2015; *mid-term* means a priority by 2020. The immediate priority must be to expand generation and grid capacity in accordance with the *Roadmap* as the first foundation for the low-carbon plan described in the previous chapters. An adequate electricity supply is essential to support economic growth. It will itself start to reduce carbon emissions by replacing some off-grid diesel generation with cleaner gas turbines. Thus it provides an essential foundation for a low-carbon plan. Details of each recommendation then follow.

**Table 19.1 Recommendations for Near- and Mid-Term Low-Carbon Planning**

| | *Near–term recommendations: 2012–15* | *Mid-term recommendations: 2015–20* |
|---|---|---|
| Energy data | • Survey off-grid energy use and generation<br>• Survey power consumption<br>• Measure wind resources<br>• Online sharing of energy data | |
| Energy efficiency | • Promote efficient lighting (CFLs)<br>• Develop appliance efficiency standards<br>• Deploy smart meters<br>• Promote energy literacy and education programs<br>• Create efficiency incentives | |
| Grid-connected power | • Deploy barge-mounted gas turbines<br>• Incentivize CCGT conversion and building by amending tariffs (MYTO)<br>• Conduct feasibility studies for 100 MW demonstration projects (PV, CSP, and wind) | • Expand hydropower<br>• Expand combined-cycle gas generation<br>• Build 100-MW demonstration projects for grid-connected PV, CSP, and wind |
| Off-grid power | • Promote solar PV for water pumping, irrigation, and lighting<br>• Promote natural gas where available to replace diesel | • Promote solar PV and hybrid for off-grid and microgrid power<br>• Develop small hydropower plants |
| Integrated planning process | • Develop a comprehensive, spatially disaggregated, engineering systems analysis of generation, for grid and off-grid technologies as a basis for long-range planning<br>• Consider siting of renewables when expanding power grid | • Integrate planning for gas and CSP<br>• Encourage integration of distributed generation into the grid |
| Policies | • Let prices of fossil fuels revert to global market prices and let electricity tariffs reflect full costs (already happening)<br>• Adopt policy framework for off-grid renewables, with net-zero, feed-in tariffs, light-touch regulation, and other incentives<br>• Develop human resources for low-carbon technology and businesses<br>• Build demonstration and training projects<br>• Develop financing mechanisms | |

*Source:* Calculations based on data sources listed in chapter 14 references.

### Improve Energy Data

To develop a low-carbon plan that reflects actual conditions in Nigeria, rather than estimates adapted from other countries, critical gaps in available data must be filled, particularly in the following areas.

#### *Survey Off-grid Generation*

While it is clear that a large fraction of the power in Nigeria is currently generated off-grid, there is little reliable data on the quantity, sizes, efficiency, and utilization rates for captive generators of various types, fueled by petrol, diesel, and natural gas. A survey could better estimate the contributions by each off-grid category, including (1) backup for the grid, full-time captive generation with (2) large generators and (3) small generators, and (4) generation in rural areas with no grid access. A well-designed survey should examine captive generation by residential, commercial, industrial, and institutional consumers in urban and rural areas around the country. The results would provide a solid basis to plan and evaluate programs to improve design of grid expansion to improve accessibility of power, and coordinate planning for off- and ongrid generation, including future distributed generation as a complement to grid power.

#### *Survey Power Consumption*

Data are also limited on the relative power consumption for lighting, appliances, cooling, and other applications. ECN in partnership with United Nations Development Programme–Global Environment Facility (UNDP-GEF) has initiated studies to inventory the quantity, type, and energy rating of incandescent lamps, refrigeration, air-conditioning, and other appliances (UNDP 2011). The survey includes a sample of 300 residential and 50 public buildings. The goal is to determine the market and energy-saving potential for CFLs and other improvements in energy efficiency. These studies are part of a four-year project to promote energy efficiency in the residential and public sectors. It would be valuable to combine this survey of ongrid consumption with a survey of off-grid and rural generation and consumption to understand how usage patterns vary with source of generation.

#### *Measure Wind Resources*

Solar potentials can be estimated remotely from satellite observations, but terrestrial measurements are needed for reliable estimates of wind potential. As yet, data are limited on the potential for wind power in Nigeria, with measurements at only 10 sites (FMST 2005). The African Wind Atlas (ADB 2004) estimates for Nigeria are based on simulations rather than direct measurements. Since wind power goes up as the cube of wind speed, economic viability is highly sensitive to average wind speeds, which can vary substantially from one site to another within the same region (Vaughan 2011). A high-resolution wind atlas of Nigeria, including offshore areas, is urgently needed to obtain an accurate picture of wind potential and to identify the most suitable sites.

### *Empower Sharing of Energy Data*

Finding existing data and projections relating to energy in Nigeria is often challenging. Many organizations are involved in collecting data, conducting studies, and developing plans related to the Nigerian energy sector, including government ministries, commissions, and other parastatals; companies, consultants, and nongovernmental organizations (NGOs); as well as international organizations, such as International Energy Agency (IEA), United Nations Development Programme (UNDP), and the World Bank. A unified online resource in which these organizations could find and share data, projections, and reports for the Nigerian energy sector could greatly facilitate and coordinate this work.

The Energy Commission of Nigeria (ECN) has made a start at this and is the natural organization to perform this task: One of its mandates is to gather, analyze, and disseminate information relating to energy and to develop a National Energy Databank. To this end, there is a demonstrated need to achieve a continuing stream of data for measurement, reporting, and verification purposes and to provide an accurate and up-to-date foundation for policy planning.

### *Energy Efficiency*

Improvements in energy efficiency are the lowest-cost options for reducing carbon emissions, since they pay for themselves in reduced energy costs, often in only months. Given the severely constrained grid in Nigeria, improving energy efficiency can improve reliability and enable limited power to provide the benefits of electricity to more consumers, while saving funds, especially off-grid. Energy efficiency programs are a valuable complement to the expansion of generation capacity and should be a first priority for a low-carbon development plan. Key elements are as follows:

- **Promote compact fluorescent lights** (CFLs) with a national program and consider phasing out sales of incandescent lamps.
- **Accelerate consumer metering programs:** Improved metering, including wireless smart meters, strengthens incentives for efficient usage of electricity as well as enhancing collection of payments from consumers.
- **Develop efficiency standards** for common appliances, including refrigerators, air-conditioners, and so on, with phase-out of sales of old appliances. In Nigeria's case, since most appliances are imported, a Top Runner Program, like Japan's, would also make sense where the most efficient model on the market is used to set future efficiency standards.
- **Develop energy literacy and education programs** for schools, communities, and religious organizations on the value of using efficient appliances for the consumer and the community.
- **Create incentives** for utility companies and electricity retailers to promote energy efficiency to their customers instead of maximizing power usage.

### *Grid-Connected Power*

The immediate focus for grid-connected capacity is to refurbish existing gas turbines and hydropower generators, and to build new ones. Following are additional elements to be considered in the intermediate term as part of an integrated low-carbon plan.

#### *Consider Barge-mounted Gas Turbines*

Many areas with high population and electricity demand, such as Lagos and parts of the Niger Delta, are in coastal areas near natural gas pipelines, which may be supplied by barge-mounted single-cycle gas turbines (SCGTs). Their immediate advantage over building land-based generators is that they are relatively inexpensive and can be purchased or leased, shipped, and moved into place, and put online much more rapidly. Their longer-term advantage is that they may be moved or sold when better options become available—for example, combined-cycle gas turbines (CCGTs) or renewables. In this way, they enable energy planners to retain the flexibility to adapt to future opportunities with low up-front cost.

#### *Expand Hydropower*

Large-scale hydropower is generally competitive with fossil generation where rivers and topography offer the potential—and it has near-zero-carbon emissions. Some existing hydropower facilities are not generating at full capacity due to poor maintenance; other facilities could be expanded. Generation capacity can be sized to be greater than that required for average river flow so that power can be dispatched to meet peaks in demand. Rapid dispatchability will be even more valuable in the future as a complement to intermittent solar and wind energy. While hydropower projects promise low-carbon electricity, it is essential to consider the social and environmental impacts of large dams, especially putting in place appropriate measures to prepare for population displacement and resettlement.

#### *Expand Combined-cycle Gas Generation*

While CCGTs have higher capital costs than SCGTs, their greater efficiency reduces their fuel costs resulting in lower levelized cost of electricity (LCOE), as well as lower-carbon emissions. Over time, it may make sense to shift to a higher proportion of CCGTs when adding new gas capacity or conversion of existing SCGT. Some existing SCGT plants may be retained to provide peaking power where their lower capital costs reduces their cost at lower utilization factors.

#### *Develop 100-MW Demonstration Projects for Grid-connected PV, CSP, and Wind*

It is likely that wind, PV, and CSP will reach grid parity in Nigeria during the next decade in the most suitable regions. To prepare for that time and to provide a realistic test of the technology and economics, Nigeria should conduct detailed feasibility studies in the next 18–24 months for large-scale grid-connected demonstration projects of about 100 megawatts each for PV, CSP, and wind so that they are ready for construction. Building these projects between 2015 and 2020 would enable Nigerian planners, developers, engineers, installers, and operators to develop expertise with the technologies and position the country to build additional capacity as soon as that they become economically competitive. These projects will also provide greater clarity about when that time arrives. Financing for these demonstration projects might be obtained from CDM or other international funding mechanisms. Such an initiative would lay the foundation for expanding the grid to allow future connection of clean energy generation around the country.

### *Developing a Smart Grid for Nigeria*

In developing countries like Nigeria where power grids have not been fully built, smart-grid technology presents a unique leapfrog opportunity to grow the power sector. The idea is to skip outdated traditional systems and start with smarter, IT-based technology. Smart wireless meters offer more reliable accounting, can be integrated with efficient mobile-phone-based payment schemes, and can discourage power theft, a problem for Nigeria. Smart-grid technologies would also be helpful in managing intermittency from large amounts of solar and wind energy, and in integrating distributed and off-grid generation (Tongia 2009). While smart grids need additional investments, the expected growth in energy needs for Nigeria and the corresponding growth of power consumers are likely to help with return on investment.

### *Off-grid Power*

Today less than 50 percent of Nigerians have access to the power grid. An estimated 50 percent of energy is generated off-grid, mostly by diesel-fueled captive generators. While expanding grid capacity, reliability, and coverage are key priorities, off-grid generation will continue to play a large role as an enabler of economic growth where grid power is insufficient or unavailable. The reference scenario projects that the fraction of electricity generated off-grid will fall to about 30 percent by 2035, but this still implies that the absolute amount of off-grid electricity will grow substantially, by a factor of 3.6 by 2025, due to the huge increase in total generation.

Historically, widespread use of off-grid power has been viewed as a sign of backwardness. But, in recent years, electricity planners in advanced economies are increasingly seeing advantages in off-grid and distributed generation as a valuable complement to the grid. Distributed generation can reduce the need for expensive and inefficient transmission lines. It can improve reliability and security of power supply. Microgrids, using distributed photovoltaics and hybrid generation, present a leapfrog technology by which emerging economies may jump directly to a more advanced technology, bypassing historical paths to industrialization—as they have already done in telecommunications, where mobile phones have leapfrogged conventional landlines. Telephone access in Nigeria increased over 100-fold in 10 years, from 867,000 lines (fixed and mobile) in 2001 to 94 million in 2011, reaching 58 percent of the population (NCC 2011).

Power systems are inherently more challenging to install than mobile telephone systems. But, arguably, rapid roll-out would be easier for off-grid PV and hybrid systems. They can be purchased and installed more easily than grid-connected systems, which depend on a complex chain of national-scale infrastructure including gas pipelines, large gas turbines, and generators, high-voltage transmission grid and transformers, and distribution lines, along with the large and cumbersome organizations necessary to support them. If enabling factors are carefully designed to draw private sector investment to off-grid renewable options, this could potentially free up investment potential for longer-term options like smart grid extensions.

Photovoltaics and hybrid systems are already economically competitive for many off-grid applications. Diesel generators produce electricity at levelized costs between $0.24 and $0.27 per kilowatt-hour, including capital cost and fuel—which is about the same range currently as off-grid PVs and hybrid PV-wind-diesel systems, in the range of $0.25 per kilowatt-hour and $0.27 per kilowatt-hour, respectively. (Gasoline generators are considerably more expensive at about $0.40 per kilowatt-hour or higher.) As the costs of renewables continue down the learning curve, and fossil-fuel prices in Nigeria revert to global market prices ("export parity"), the economic advantages of renewables are likely to become greater over time.

There are several areas in which FGN could encourage independent power producers (IPPs) to expand low-carbon off-grid generation and microgrids as a complement to grid power. This distributed generation can bring the benefits of electricity to rural areas without having to wait until the grid reaches them, which may be a long time. The possibilities are as follows.

#### *Use Natural Gas Where Available to Replace Diesel*

In those areas where natural gas distribution pipelines are available, such as off-grid generation in urban areas, gas turbines are clearly preferable to diesel generators for reasons of both cost and carbon emissions. Small gas-powered turbines up to about 5 megawatts can generate power at about half the cost of off-grid diesel generators, and at 54 percent of the GHG emissions. Even as natural gas prices increase toward export parity, overall generation costs will still favor gas over diesel.

#### *Use Solar PV for Water Pumping and Irrigation*

Initial deployments in Nigeria have confirmed the advantage of PV over diesel generators for pumping water, for domestic use and irrigation (SELF 2008). These applications are "low-hanging fruit" for photovoltaics, providing substantial economic benefits to agriculture, while reducing vulnerability to changes in rainfall patterns. Unlike other applications, there is no need for batteries or back-up power for such applications, since water is easy to store and intermittency is not a problem. Typically, small PV installations need less care and maintenance than diesel generators—and, of course, no need for expensive fuel.

### *Use Solar PV with Batteries and Hybrid PV-Wind-Diesel*

For many other off-grid applications, residential and commercial, PV and hybrid power generation are already competitive with small gasoline and diesel generators based on levelized cost. The cost advantages of PV with batteries, versus hybrids with diesel generators and/or wind, vary by location depending on solar and wind resources. However, PV module and hybrid system costs are declining rapidly and so their advantages over pure fossil sources will increase over time.

### *Develop Small Hydropower Plants*

Small hydropower (micro- or pico-hydro) facilities can provide low-cost and low-carbon power in those places where the resources are available. Dispatchable hydro is a valuable complement to intermittent solar and wind. A more extensive survey of resources would assist in identifying the most promising opportunities.

## An Integrated Planning Process

As Nigeria expands its power system according to the *Roadmap*, it will become increasingly important to develop a longer-range plan to integrate low-carbon options as part of a balanced portfolio of energy sources, ongrid and off-grid. An integrated plan can provide the robustness and flexibility to take advantage of low-carbon technologies as and when they become economically practical. Factors to consider in developing such a plan include the following.

### *Comprehensive Electricity Systems Analysis and Planning*

A comprehensive, spatially disaggregated engineering systems analysis of generation plants, load centers, and transmission networks is needed to developed detailed longer-range plans, both for reference and low-carbon options. It should include off-grid demand and generation to enable study of tradeoffs between expanding the reach of the grid and expanding off-grid generation. Such an analysis will require much more comprehensive data than is currently available and was beyond the scope of this study.

### *Consider Siting of Renewables When Sesigning the Grid*

Nigeria is planning an ambitious expansion of the capacity and coverage of the power grid. When selecting sites for generation and corridors for new and expanded transmission lines, it will be useful to consider not only existing and near-term additions to gas and hydro capacity but also the future transmission needs for potential low-carbon capacity, especially new hydro, solar, and wind. For example, lines from South to North should be able to transmit gas-generated power from southern areas and hydro from central areas, but also potential future CSP generation from the North to the South. The comprehensive systems model can assist in evaluating power load and supply balances, especially with intermittent renewables and geographically distributed supply. Even if the future rate of adding renewable capacity is uncertain, developing the grid with those possibilities in mind retains the option for easy integration of renewables as soon as they become economically viable.

#### *Integrate Planning for Gas and CSP*

Even if Nigeria opts to build significant capacity of wind, PV, and CSP, gas will remain a key element of the energy mix. In particular, hybrid CSP and CCGT provide an attractive combination, with gas using the same CCGT turbines as a back-up when the sun isn't shining. For example, Turkey has recently approved the Dervish integrated solar combined-cycle (ISCC) plant which combines 50 MW CSP with 570 MW gas turbine to come on line in 2016. When gas pipelines reach the Northern areas, selection of new sites for gas generation plants might consider locations with high solar intensity and sufficient land area to enable adding CSP as that technology becomes economic.

#### *Encourage Integration of Distributed Generation into the Grid*

As the national grid expands, it can take advantage of existing microgrids and distributed generation to expand more rapidly at lower cost to the grid. To enable this expansion, the national grid and its independent power producer (IPP) suppliers should treat off-grid and microgrid generation IPPs as partners, not competitors. FGN can encourage this with policies such as net-metering and feed-in tariffs and accessible standards for technical system integration.

### *Policies and Facilitation*

Even as low-carbon technologies become economically competitive in Nigeria, there may remain institutional, regulatory, and financial obstacles to reaping their full benefits. FGN has an important role to play in creating institutions, policies, and programs to remove these obstacles. Designing these is a central part of developing a successful low-carbon plan. Key elements of such a plan follow.

#### *Let Domestic Prices of Fossil Fuels Gradually Revert to Global Market Prices*

Diesel is already unregulated. Regulated and subsidized low prices for natural gas and gasoline have distorted markets, unfairly disadvantaged alternative sources of energy, and, in the case of gas, have led to severe shortages available for domestic power. FGN has already taken action to reverse these trends. In 2010 FGN established policies to let gas prices increase from a floor of \$0.40/MMBtu for power usage, up to \$1.00/MMBtu in 2013, although this is still significantly below export parity, which may be in the region of \$3.00/MMBtu. Gasoline has been subsidized by FGN, resulting in a drain of 1.2 trillion naira (US\$7.4 billion) per year from the national budget, with most refined petroleum imported due to the poor state of Nigerian refineries. On January 1, 2012, FGN removed the subsidy on gasoline, resulting in prices more than doubling, and causing considerable labor unrest, and with a current resolution that has cut subsidies by more than half. In the long run, it appears

FGN is committed to allow fuel prices to reach global prices, consistent with the suggested development plan.

#### *Let Tariffs Fully Reflect Electricity Costs*

In 2002, electricity tariffs in Nigeria were among the lowest in the world, at $0.043 per kilowatt-hour, a significant cause of the underinvestment in maintenance and new capacity. In 2009, the Multi-Year Tariff Order (MYTO 2009) established the principle of cost recovery for each link in the supply chain—fuel, electricity generation, transmission, distribution, and retail—so that prices will fully reflect costs by 2013. Adequate prices are essential to the successful privatization of each segment of the industry. Full market prices for grid electricity are also essential if economics are to drive adoption of energy efficiency, renewable energy, and other low-carbon technologies. Additionally, full market prices for grid electricity are still much cheaper than for off-grid generation.

#### *Promote CCGT over SCGT*

Incentivize investment in combined-cycle gas turbines (CCGT), including conversion of existing single-cycle gas turbines (SCGT) and building new plants, by adjustment of tariffs and tax or duty exemptions—for example, amendment of the new tariffs (MYTO). CCGTs are lower in both levelized generation cost and emissions than SCGTs.

#### *Develop a Policy Framework to Promote Off-grid Renewables*

Carefully designed policies and incentives could play a key role in encouraging adoption of cost-effective low-carbon technologies. The NERC's recently announced feed-in tariffs (FITs) are a good starting point. Other elements of a policy framework might include tax and duty exemptions for renewable equipment and light-touch regulation for renewable facilities under 10 MW. A recent review of FITs, renewable portfolio standards (RPS), and Renewable Energy Certificates (RECs) in developing countries finds that policies have had mixed success (World Bank 2011a). FITs have proved effective in stimulating renewable energy, for example in India and Turkey, but are not always economically efficient. The study recommends tailoring policies carefully to the local situation, considering their interactions, adopting policies in sequence, and refining them over time in the light of experience. In tailoring policies for Nigeria, it will be valuable to review of what has and has not worked elsewhere and why.

#### *Develop Human Resources*

Successful development and execution of a low-carbon plan will require a growing corps of Nigerian scientists, engineers, policy analysts, and technicians with expertise in key technologies. Steps to build this corps might include establishing and expanding degree courses and R&D centers at key Nigerian universities, attracting overseas Nigerians with relevant expertise, creating regional technical training centers, and expanding a curriculum on energy and environment for secondary schools.

### *Build Demonstration and Training Projects*

The number of small-scale pilot and demonstration projects using PV is growing in Nigeria, but PV and hybrid systems are still much less familiar than are gasoline and diesel generators. Further deployments are essential for practical training of technicians and operators, and for developing the markets. As renewables become more competitive economically, especially for off-grid applications, there is a growing business opportunity for new or existing firms and co-operatives to develop, install, and manage renewable off-grid generation. Programs to accelerate adoption and its associated economic benefits could include studies to identify the most promising sites and technologies, additional demonstration projects, promoting training organizations, and developing financing mechanisms to encourage growth of these businesses. Once the business opportunities have been convincingly demonstrated and there are enough experienced people, FGN should be able to step back from direct support and the private sector can take over, as, for example, it has already done for mobile telephones.

### *Develop Innovative Financing Schemes*

Although some off-grid applications of renewables may already be competitive with diesel generators in terms of LCOE at a 10 percent discount rate, and grid-connected renewables may become competitive over the next decade in selected applications, the initial capital costs of renewables are still significantly larger than gas and diesel-fueled generators. Businesses and, even more, residential consumers of electricity are unable or unwilling to make such large up-front investments. There is a commercial opportunity for banks and larger businesses that can borrow at lower interest rates to provide financing to consumers for off-grid renewable generation. This also creates a business opportunity to create microgrids run by small power companies or local cooperatives with the economies of scale and access to finance not directly available to individual consumers. Possible financing mechanisms can include the following:

- **Low-interest loans** for large and small low-carbon projects. As an example, the Nigerian Bank of Industry (BoI) has recently partnered with UNDP to provide finance to micro, small, and medium enterprises (MSMEs) to support energy projects. According to Evelyn Oputu, Managing Director of BoI, "Women are the main beneficiaries of the BoI loan on MSMEs because women constitute more of MSMEs in Nigeria" (Business Day Online 2011).
- Clean Development Mechanism (CDM) offsets and other sources of international financing for low-carbon projects
- Leapfrog funds from global mitigation finance channeled through international donors poised to play a catalytic role in helping Nigeria realize its full low-carbon development potential (Eleri, Ugwu, and Onuvae 2011)
- Emerging mobile phone-based payment systems can support microfinance and payments for small off-grid systems, such as solar lighting. The Central Bank of Nigeria (CBN) has started a cashless project that is planned to reach

20 million Nigerians over the next three years. As a related example, Eight19, a solar light company based in UK, is distributing solar lights in Africa for a modest (about $10) initial payment, plus small periodic payments mediated by mobile text messages enabling purchase of systems at a lower periodic cost than kerosene for a lantern (Eight19.com).

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# GDP Growth and Load Duration Curves

**Table G.1 GDP Compound Annual Growth Rate Assumptions by Scenario**
*Percent*

| *Scenarios* | *2010* | *2015* | *2020* | *2025* | *2030* | *2035* |
|---|---|---|---|---|---|---|
| Vision 2020 (modified) | 8.2 | 13 | 13 | 7 | 7 | 7 |
| High growth | 8.2 | 9 | 9 | 9 | 6 | 6 |
| Medium growth | 8.2 | 6 | 6 | 6 | 6 | 6 |

*Source:* FGN 2010.

**Table G.2 Load Duration Curve Areas for International Comparison**

| *Country* | *Year* | *GDP per capita, PPP (constant 2005 US$)* | *LDC area (%)* |
|---|---|---|---|
| India | 2005 | 2,222 | 79.2 |
| Thailand | 2002 | 6,063 | 73.2 |
| Malaysia | 2005 | 11,678 | |
| Peninsular | | | 75.5 |
| Sabah | | | 68.8 |
| Sarawak | | | 72.8 |

*Source:* World Bank 2008.

**Table G.3 Load Curves Estimating Percent of Peak Power Demand by 5% Time Ranges**

| | *2009–10* | | *2011–15* | | *2016–20* | | *2021–35* | |
|---|---|---|---|---|---|---|---|---|
| *Time (%)* | *Power* | *Area (load factor)* | *Power* | *Area (load factor)* | *Power* | *Area (load factor)* | *Power* | *Area (load factor)* |
| 0 | 100 | | 100 | | 100 | | 100 | |
| 5 | 86 | 4.7 | 95 | 5 | 98 | 5 | 97 | 5 |
| 10 | 76 | 4.1 | 90 | 5 | 96 | 5 | 94 | 5 |
| 15 | 66 | 3.6 | 85 | 4 | 94 | 5 | 91 | 5 |
| 20 | 56 | 3.1 | 80 | 4 | 92 | 5 | 88 | 5 |
| 25 | 48 | 2.6 | 75 | 4 | 90 | 5 | 85 | 4 |
| 30 | 42 | 2.3 | 70 | 4 | 88 | 5 | 82 | 4 |
| 35 | 36 | 2.0 | 65 | 3 | 86 | 4 | 79 | 4 |
| 40 | 35 | 1.8 | 60 | 3 | 84 | 4 | 78 | 4 |

*table continues next page*

**Table G.3 Load Curves Estimating Percent of Peak Power Demand by 5% Time Ranges** (*continued*)

| | *2009–10* | | *2011–15* | | *2016–20* | | *2021–35* | |
|---|---|---|---|---|---|---|---|---|
| *Time (%)* | *Power* | *Area (load factor)* | *Power* | *Area (load factor)* | *Power* | *Area (load factor)* | *Power* | *Area (load factor)* |
| 45 | 34 | 1.7 | 53 | 3 | 80 | 4 | 76 | 4 |
| 50 | 33 | 1.7 | 51 | 3 | 73 | 4 | 75 | 4 |
| 55 | 24 | 1.4 | 46 | 2 | 70 | 4 | 73 | 4 |
| 60 | 16 | 1.0 | 41 | 2 | 67 | 3 | 71 | 4 |
| 65 | 14 | 0.8 | 35 | 2 | 64 | 3 | 69 | 4 |
| 70 | 12 | 0.7 | 33 | 2 | 61 | 3 | 67 | 3 |
| 75 | 10 | 0.6 | 30 | 2 | 58 | 3 | 65 | 3 |
| 80 | 8 | 0.5 | 25 | 1 | 55 | 3 | 63 | 3 |
| 85 | 6 | 0.4 | 20 | 1 | 52 | 3 | 61 | 3 |
| 90 | 5 | 0.3 | 15 | 1 | 49 | 3 | 59 | 3 |
| 95 | 4 | 0.2 | 10 | 1 | 46 | 2 | 57 | 3 |
| 100 | 3 | 0.2 | 8 | 1 | 43 | 2 | 55 | 3 |
| Average | | 64.5 | | 65 | | 74 | | 75 |

*Sources:* Numbers for 2009–10 provided by PHCN, 2010; projections for subsequent years are based on stakeholder discussions and international comparisons in table G.4.

**Table G.4 Load Duration Curve Areas for International Comparison**

| *Country* | *Year* | *GDP per capita, PPP (constant 2005 US$)* | *LDC area (%)* |
|---|---|---|---|
| India | 2005 | 2,222 | 79.2 |
| Thailand | 2002 | 6,063 | 73.2 |
| Malaysia | 2005 | 11,678 | |
| Peninsular | | | 75.5 |
| Sabah | | | 68.8 |
| Sarawak | | | 72.8 |

*Source:* World Bank 2008.

APPENDIX H

# Off-grid Generation

Where electricity is available, it is generated by power plants connected to the national grid and a host of off-grid, onsite, and mini-grid generators. The estimate of electricity usage by the categories described in table 16.1 in the base year 2009 is presented in table H.1.

Using the segmentation of the power sector described in chapter 16 (section on "Electricity demand for grid and off-grid") the total available power generation capacity in 2009 was 4,300 megawatts, and the estimate of electricity generated in that year was 32,720 gigawatt hours. Of this, 3,640 megawatts was available from the National Grid with a total generation of about 16,360 gigawatt hours, with the rest contributed by several categories of off-grid generation.

Category B off-grid generators greater than 1 megawatt must be registered, and so the Ministry of Power has records of the capacity. Capacity and utilization for Category C is estimated to be about the same.

Utilizing data available from the Industrial Survey implemented by the Manufacturing Association of Nigeria in 2009 (ICA Database), it was estimated that the Nigerian grid was available in that year for about an average of about 6,060 hours. The grid supplied electricity to consumers during these hours, while

**Table H.1 Estimate of Electricity Usage by Supply Categories in Nigeria, 2009**

| *Category* | *Generator size* | *Available capacity (MW)* | *Load factor* | *Estimated energy (GWh)* | *Principal type of generation* |
|---|---|---|---|---|---|
| Grid generation | | 3,640 | 6,060 hrs out of 8,760 hrs at 64% | 16,360 | Gas and hydro |
| Off-grid A: Generators for grid backup | All | 1,712 | 2,700 hrs out of 8,760 hrs at 40% | 4,000 | Diesel and natural gas |
| Off-grid B: Generators used full-time where grid is available | > 1 MW | 1,370 | 50% | 6,000 | Diesel and natural gas |
| | < 1 MW | 571 | 50% | 2,500 | Diesel and petrol |
| Off-grid D: Generation with no grid access | All | 881 | 50% | 3,860 | Diesel and petrol |
| Total | | 4,300 | | 32,720 | |

*Source:* Information from Power Holding Company of Nigeria (PHCN) for grid generation and Federal Ministry of Power for the off-grid categories.

off-grid facilities at the sites of consumers who are connected to the grid were assumed to supply electricity to the consumers for the 2,700 hours in that year when the grid was not available. Table H.1 was constructed with data obtained from Power Holding Company of Nigeria (PHCN) and the Federal Ministry of Power.

APPENDIX I

# Grid Power Supplies

Grid-connected power generators in Nigeria include facilities owned by the public utility PHCN and a few, but growing number of, independent power producers (IPPs). If Nigeria is to develop economically, access to electricity must be increased. Vision 2020 projects increasing the percentage of Nigerians with access to grid electricity from 40 percent in 2010 to at least 50 percent in 2020, with further gradual increases thereafter. The fact that grid electricity is unlikely to meet the demand will continue to result in supply shortages. Table I.1 presents a reference scenario energy balance for the evolution of grid power supplies during the period 2010–35.

**Table I.1 Reference Scenario Energy Balance for Grid Power Supplies in Nigeria**

| *Years* | *Demanded grid supply GWh* | *Total spinning reserve %* | *Supplied demand GWh* | *Supplied demand (deficit with –) GWh* | *Required capacity MW* | *Available installed capacity MW* | *Additional capacity required MW* |
|---|---|---|---|---|---|---|---|
| 2010 | 24,528 | 0 | 21,743 | –2784 | 4,338 | 3,846 | 174 |
| 2015 | 76,382 | 0 | 71,165 | –5,217 | 13,511 | 12,588 | 2,626 |
| 2020 | 116,612 | 0 | 123,609 | –5,227 | 19,139 | 17,246 | 1892 |
| 2025 | 216,569 | 6 | 229,564 | 12,995 | 38,630 | 32,580 | 6,059 |
| 2030 | 310,456 | 6 | 329,084 | 18,628 | 55,377 | 51,058 | 4,319 |
| 2035 | 437,309 | 6 | 463,548 | 26,239 | 78,004 | 73,574 | 4430 |

*Source:* Calculations based on data sources listed in chapter 14 references.

APPENDIX J

# Existing and Planned Generating Capacities

Table J.1 summarizes installed generating plants in Nigeria connected to the grid through 2009. For each plant, it shows the year of commissioning, nameplate capacity, totaling 9,480 megawatts, and available capacity, totaling 4,164 megawatts. Table J.2 summarizes planned plants under construction or already financially committed in 2010, scheduled for commissioning by 2022. These projects have a planned available capacity totaling 8,571 megawatts. They are mostly gas-fired, with 5,506 megawatts of CCGT, 2,286 megawatts of CCGT, and 778 megawatts of hydro. They include the FGN plants commonly referred to as the National Integrated Power Projects (NIPPs), located close to gas-producing areas of the Niger Delta.

**Table J.1 Nameplate and Available Capacity for Existing Grid-Connected Plants**

| *Name* | *Technology* | *Nameplate capacity (MW)* | *Available capacity (MW)* | *Year commissioned* |
|---|---|---|---|---|
| Kainji | Hydro | 760 | 445 | 1968 |
| Jebba | Hydro | 570 | 358 | 1984 |
| Shiroro | Hydro | 900 | 305 | 1990 |
| Egbin | SCGT | 1,320 | 481 | 1985 |
| AES | SCGT | 300 | 236 | 2001–02 |
| Sapele | SCGT | 720 | 199 | 1978 |
| Sapele | SCGT | 300 | 199 | 1981 |
| Okpai | CCGT | 450 | 446 | 2005 |
| Afam (1-V) | SCGT | 996 | 64 | 1965–76, 2001 |
| Afam VI | CCGT | 650 | 323 | 2008 |
| Delta | SCGT | 950 | 255 | 1966–90 |
| Geregu | SCGT | 444 | 200 | 2007 |
| Omoku | SCGT | 150 | 96 | 2006 |
| Omotosho | SCGT | 336 | 298 | 2007 |
| Olorunsogo | SCGT | 336 | 255 | 2007 |

*table continues next page*

**Table J.1 Nameplate and Available Capacity for Existing Grid-Connected Plants** (*continued*)

| *Name* | *Technology* | *Nameplate capacity (MW)* | *Available capacity (MW)* | *Year commissioned* |
|---|---|---|---|---|
| Ibom Power | SCGT | 188 | 3 | 2009 |
| Ajaokuta | SCGT | 110 | — | 2005 |
| Totals | Hydro | 2,230 | 1,080 | |
| | SCGT | 6,150 | 2,286 | |
| | CCGT | 1,100 | 769 | |
| | Total | 9,480 | 4,164 | |

*Source:* Federal Ministry of Power.
*Note:* SCGT = single-cycle gas turbine; CCGT = combined-cycle gas turbine; — = not available.

**Table J.2 Planned Capacity Additions with Scheduled Commissioning Dates to 2022**

| *Name* | *Technology* | *Nameplate capacity (MW)* | *Available capacity (MW)* | *Year commissioned* |
|---|---|---|---|---|
| Ihovbor | SCGT | 450 | 365 | 2011 |
| Alaoji | SCGT | 1,074 | 778 | 2010 |
| Olorunsogo NIPP | SCGT | 750 | 607 | 2010 |
| Sapele NIPP | CCGT | 450 | 365 | 2010 |
| Gbarain | SCGT | 225 | 207 | 2011 |
| Calabar | SCGT | 561 | 456 | 2011 |
| Egbema | SCGT | 338 | 274 | 2011 |
| Omoku | SCGT | 250 | 182 | 2011 |
| Geregu | CCGT | 434 | 352 | 2014 |
| Omotosho | SCGT | 500 | 365 | 2012 |
| Mambilla | Hydro | 2,600 | 1,674 | 2018 |
| Zungeru | Hydro | 500 | 322 | 2022 |
| Guarara | Hydro | 300 | 193 | 2022 |
| Kaduna dual-fired | SCGT | 260 | 209 | 2015 |
| Delta (PHCN rehab GT04) | SCGT | 20 | 16 | 2011 |
| Shiroro (PHCN rehab 411G2) | Hydro | 150 | 97 | 2011 |
| Afam (PHCN rehab GT17, GT18, GT19) | SCGT | 265 | 215 | 2011 |
| Afam (PHCN rehab GT20) | SCGT | 138 | 138 | 2013 |
| Omotosho (PHCN rehab GT6, GT7) | CCGT | 76 | 62 | 2013 |
| Olorunsogo (PHCN rehab GT3, GT5, GT8) | SCGT | 90 | 73 | 2012 |
| Eket (Mobil JV) | SCGT | 500 | 405 | 2012 |
| Obite (Total/Elf) | SCGT | 450 | 365 | 2013 |
| Ijede (Chevron) | SCGT | 250 | 203 | 2013 |
| Ijede 2 (Chevron) | SCGT | 800 | 648 | 2013 |
| Totals | Hydro | 3,550 | 2,286 | |
| | SCGT | 6,921 | 5,506 | |
| | CCGT | 960 | 778 | |
| | Total | 11,431 | 8,571 | |

*Source:* FMP (2010); based on feedback from Presidential Task Force on Power (PTFP).
*Note:* SCGT = single-cycle gas turbine; CCGT = combined-cycle gas turbine.

APPENDIX K

# Concentrating Solar Power Potential

Table K.1 shows the numbers underlying the estimate of the physical potential resource for concentrating solar power (CSP). The second column gives the land area of each of the 14 states in the Northern half of Nigeria. The third column estimates the percent area above a threshold of 4.1 kWh/m$^2$/day DNI suitable for CSP (see also map 17.2).

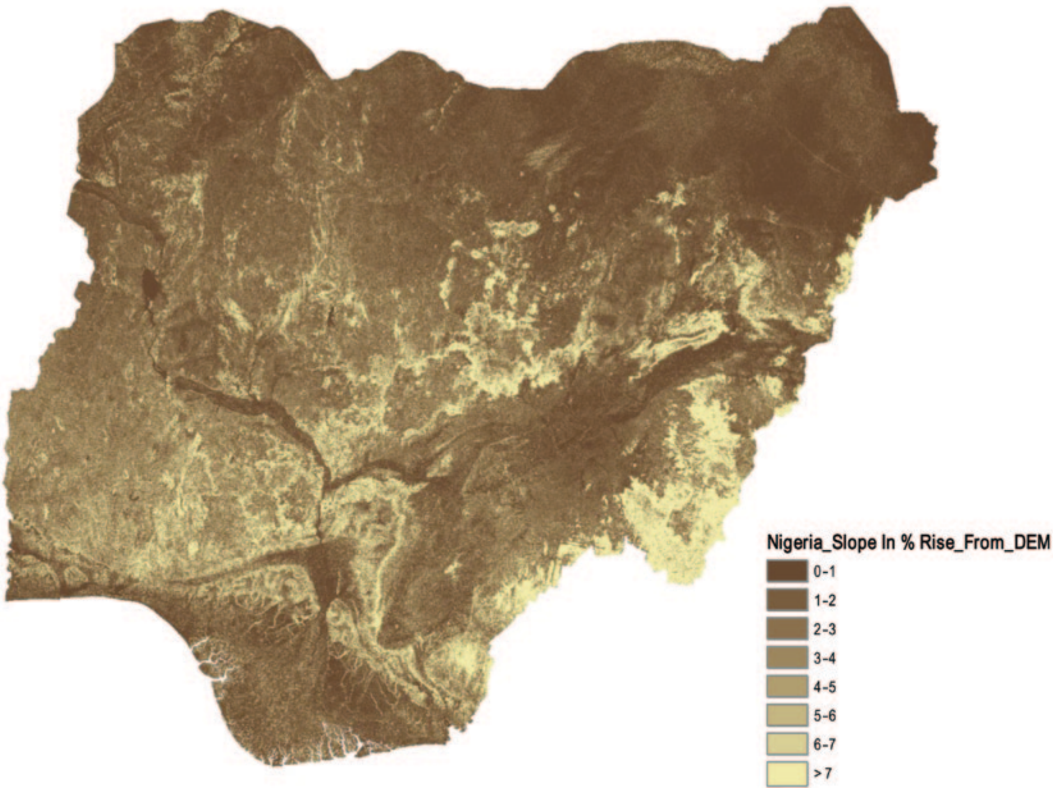
It is easier to build CSP on flat land with a slope less than about three degrees (NREL 2011). For South Africa, Fluri (2009) assumed a suitable slope with gradient below 7 percent for slopes facing southeast to southwest and below 2 percent for other orientations. Map K.1 shows land slope in Nigeria

**Table K.1 Theoretical CSP Potential of Nigeria in TWh/y**

| *Northern states of Nigeria* | *Area km$^2$* | *Percent area DNI > 4.1* | *Percent area slope < 3°* | *2% of eligible area (km$^2$)* | *Potential capacity (GW)* | *Potential generation (TWh/year)* |
|---|---|---|---|---|---|---|
| Adamawa | 37,957 | 50 | 50 | 189.79 | 9 | 25 |
| Bauchi | 48,197 | 100 | 30 | 289.18 | 14 | 38 |
| Borno | 72,767 | 100 | 90 | 1,309.81 | 65 | 172 |
| Gombe | 17,428 | 95 | 80 | 264.91 | 13 | 35 |
| Jigawa | 23,415 | 60 | 80 | 224.78 | 11 | 30 |
| Kaduna | 44,217 | 50 | 50 | 221.09 | 11 | 29 |
| Kano | 20,389 | 100 | 80 | 326.22 | 16 | 43 |
| Katsina | 23,822 | 90 | 80 | 343.04 | 17 | 45 |
| Kebbi | 36,320 | 60 | 80 | 348.67 | 17 | 46 |
| Niger | 72,065 | 50 | 70 | 504.46 | 25 | 66 |
| Plateau | 26,539 | 80 | 80 | 339.70 | 17 | 45 |
| Sokoto | 32,146 | 50 | 70 | 225.02 | 11 | 30 |
| Yobe | 44,880 | 80 | 90 | 646.27 | 32 | 85 |
| Zamfara | 33,667 | 100 | 70 | 471.34 | 24 | 62 |
| Total | 533,809 | 75 | 71 | 5,704 | 285 | 750 |

*Source:* Calculations based on data sources listed in chapter 14 references.

**Map K.1 Nigeria Land Slope Derived from a Digital Elevation Model**




*Source:* SRTM 90-m Digital Elevation Model (DEM).

from the Shuttle Radar Topography Mission (SRTM) 90 meters Digital Elevation Model (DEM). Column four of table K.1 shows the estimated percentage of area with slope under 3 percent for each state. Columns five and six show the resource potential capacity in gigawatt and generation in terawatt hour per year for each state, assuming 2 percent of the eligible land area was used, 50 MW/km$^2$ capacity density for CSP (NREL 2008), and a 30 percent capacity factor.

**APPENDIX L**

# Small Hydropower (SHP) Potential

Small hydropower (SHP) by common definition are hydropower plants below 10 megawatts capacity. They usually serve a local community or industrial plant. The Federal Ministry of Power and Steel of Nigeria further classifies SHP as: small hydro from 2 to 10 megawatts, micro-hydro from 101 kilowatts to 2 megawatts, and pico-hydro under 100 kilowatts (UNIDO 2011).

The National Agency for Science and Engineering Infrastructure (NASEI), responsible for developing capacity in the manufacturing of SHP equipment, estimated that the total SHP Potential in Nigeria could reach 3.5 gigawatts. This is about 31 percent of the country's total hydropower potential estimated at 11.2 gigawatts. To date about 31 megawatts of SHP is installed (see table L.1); the current potential catchment areas for SHP are shown in table L.1.

As of 2013, there are about 0.18 megawatt SHP sites waiting to be commissioned or in the commissioning process. In the medium term (2015), the SHP sites with feasibility and detailed project reports that could be implemented account for about 23 megawatts of capacity. For the long term, there are about 1,777 megawatts of potential SHP sites under prefeasibility or unknown status, which might be implementable. This implies that by 2035, about 48 percent (that is, 1,794 megawatts) of the total SHP potential (3,500 megawatts) might

**Table L.1 Small Hydropower Installed Capacity**

| *River* | *State* | *Installed capacity (MW)* |
|---|---|---|
| 1. Bagel (I) (II) | Plateau | 1 |
| 2. Kurra | Plateau | 8 |
| 3. Lere (I) (II) | Lere | 4 |
| 4. Bakalori | Sokoto | 3 |
| 5. Tiga | Kano | 6 |
| 6. Oyan | Ogun | 9 |
| **Total** | | **31** |

*Source:* UNIDO 2011.

**Table L.2 Summary of Small Hydro Potential Sites in Nigeria**

| *Status of SHP potential sites* | *Small (MW)* | *Micro (MW)* | *Pico (MW)* | *Total (MW)* |
|---|---|---|---|---|
| Feasibility | 3.72 | 1.03 | | 4.75 |
| Prefeasibility | 1,751.23 | 2.70 | | 1,753.92 |
| Detailed project report (DPR) | 3.00 | 0.74 | | 3.74 |
| DPR available | 13.35 | 1.17 | 0.02 | 14.54 |
| Awaiting commission | | 0.03 | | 0.03 |
| Commissioning | | 0.15 | | 0.15 |
| Not available | 17.80 | | | 17.80 |
| Total | 1,789.10 | 5.82 | 0.02 | 1,794.93 |

*Source:* Calculations based on data sources listed in chapter 14 references.

**Table L.3 Expected Implementation of Small Hydropower in Potential Sites in Nigeria**

| | *Short (2013)* | *Medium (2015)* | *Long (2035)* |
|---|---|---|---|
| SHP | 0.81 MW | 23 MW | 3.5 GW |

*Source:* Calculations based on NASEI data.

be implemented, as shown in table L.2. Based on the above information, the assumed SHP capacity that could be implemented in the short, medium, and long term are 1 megawatt, 25 megawatts, and 3,500 megawatts, respectively. The expected implementation of SHP capacity for the low carbon scenario is provided in table L.3.

APPENDIX M

# Waste-to-Energy (WtE) Potential

The decomposition of waste in landfills is the third largest source of global anthropogenic methane emissions, a greenhouse gases (GHG) agent 23 times more potent than carbon dioxide. In developing countries, cities often spend 20–50 percent of their budget on waste management. Still, as much as 60 percent of urban solid waste can go uncollected—open dumping of waste is the norm. A review of various studies of different landfill gas to energy (LFGE) projects reveals that for an LFG capture project to be viable in terms of LFG generation, the solid waste disposal service (SWDS) must receive at least 200 tonnes per day of waste, must be designed for a minimum capacity of at least 500,000 tonnes, must have a minimum filing height of 10 meters, and the waste in place should not be older than 10 years (USEPA 2010). Thus, any LFGTE project in Nigeria should satisfy these requirements.

In some parts of Nigeria, several waste collection projects have been planned and feasibility studies conducted successfully. However, there is rarely any concrete plan for proper disposal of waste. If proper solid waste disposal is planned and executed, an integrated LFGE system from landfills or dumpsites is possible. Several urban areas (table M.1) in Nigeria have a potential for LFGE projects.

**Table M.1 Typical Solid Waste Generation in Some Cities in Nigeria**

| *City* | *Population* | *Waste production (t/mo)* | *Density (Kg/m$^3$)* | *Daily production (Kg/capita/day)* |
|---|---|---|---|---|
| Lagos | 8,029,200 | 255,556 | 294 | 0.63 |
| Kano | 3,348,700 | 156,676 | 290 | 0.56 |
| Ibadan | 307,840 | 135,391 | 330 | 0.51 |
| Port Harcourt | 1,053,900 | 117,825 | 300 | 0.60 |
| Kaduna | 1,458,900 | 114,433 | 320 | 0.58 |
| Onitisha | 509,500 | 84,137 | 310 | 0.53 |
| Makurdi | 24,900 | 24,242 | 340 | 0.48 |
| Abuja | 159,900 | 14,785 | 280 | 0.66 |
| Nsukka | 100,700 | 12,000 | 370 | 0.44 |

*Source:* USEPA 2010.

The United States Environmental Protection Agency (USEPA) completed a prefeasibility study for a comprehensive integrated LFGE project for four dumping sites in Nigeria (table M.2) including Ibadan (Afofunra, Ajakang, and Awotan) and Abuja (Mpape) (USEPA 2010). According to the report, in the near future, they intend to start the next phases of detailed feasibility and construction, with operation expected to start in 2013 (table M.3).

Another area investigated for potential electricity generation is the city of Lagos. Olusosum solid waste dumpsite is the largest SWDS in Lagos and is fit for an LFGE project (Aboyade 2004). The dumpsite was constructed under a World Bank loan secured in 1988 to use the trench system. However, it might be too late for electricity generation since by 2013 the gas production of the dumpsite will be decreasing. There is potential for a similar LFGE project in Lagos City with huge waste generation potential. If a dumpsite starts 2012, LFGE operation could start after 2015. With an installed capacity of 8 megawatts per internal combustion engine, it would be possible to produce about 70,000 megawatt-hours (Aboyade 2004).

**2011–35 LFGE capacity assumption:** At least four cities, Lagos, Kano, Port Harcourt, and Kaduna, have the potential for large-scale LFGTE projects. The proposed capacity in medium and long term could reach about 10 gigawatts and 40 gigawatts, respectively, assuming that untapped potentials also come online.

**Table M.2 Total Waste in Place in 2013, at Closure of Dumpsites**

| City | Dump site | Expected year of closure | Tons | $CH_4$ generation potential | Power potential size | |
|---|---|---|---|---|---|---|
| | | | | MMCF/year | kW | MWh/year |
| Ibadan | Afofunra | 2013 | 508,000 | 70 | 71 | 625 |
| Ibadan | Ajakang | 2013 | 850,000 | 133 | 126 | 1107 |
| Ibadan | Awotan | 2013 | 575,000 | 83 | 83 | 723 |
| Abuja | Mpape | 2013 | 611,355 | 126 | 96 | 842 |

*Source:* USEPA 2010.

**Table M.3 Typical Solid Waste Generation in Key Cities in Nigeria and Expected Start of Operation**

| City | Population | Installed power capacity (MW) | Generation (GWh/year) | Installed cost ($million) | Start year |
|---|---|---|---|---|---|
| Lagos | 8,029,200 | 8.00 | 70 | 18.55 | 2020 |
| Kano | 3,348,700 | 8.00 | 70 | 18.55 | 2020 |
| Ibadan | 307,840 | 0.28 | 2.5 | 1.53 | 2013 |
| Port Harcourt | 1,053,900 | 8.00 | 70 | 18.55 | 2015 |
| Kaduna | 1,458,900 | 8.00 | 70 | 18.55 | 2025 |
| Onitisha | 509,500 | 0.25 | 2.5 | 1.53 | 2020 |
| Makurdi | 24,900 | 0.015 | 0.42 | 0.50 | 2020 |
| Abuja | 159,900 | 0.096 | 0.84 | 0.70 | 2013 |
| Nsukka | 100,700 | 0.096 | 0.84 | 0.70 | 2020 |
| Total | | 33 | 287 | 79.16 | |

*Source:* USEPA 2010.

**APPENDIX N**

# Biomass Potential

Biomass resources of Nigeria include forestry woods; forage grasses and shrubs; energy trees and crops; animal and human wastes; agricultural, municipal, and industrial wastes; and aquatic biomass. Biomass may be transformed into solid briquettes as well as liquefied or gasified fuels. FGN has indicated that Nigeria should harness and integrate non-fuel wood biomass energy resources with other energy resources, with efficient conversion technologies.

Plant biomass can be utilized as fuel for small-scale industries. It can also be fermented by anaerobic bacteria to produce versatile and cheap fuel biogas (Okafor and Joe-Uzuegbu 2010). A recent low-carbon study for Sub-Saharan Africa (de Gouvello, Dayo, and Thioye 2008) indicates that the CDM project potentials of Nigeria could reach about 11 gigawatts, including 4 gigawatts from agricultural residue, 2 gigawatts from residue from round wood production, 1 gigawatt from residue from wood processing facilities, and 4 gigawatts from jatropha biodiesel-fueled generators.

In the absence of enough information on biomass-electricity-generating biomass power plants, such as small- to medium-scale CHP, biogas digestion, waste incineration, and co-firing, the analysis assumes that biomass plants could generate 0.5 gigawatt in the short term, 1 gigawatt in the medium term, and 2 gigawatts in the long term.

APPENDIX O

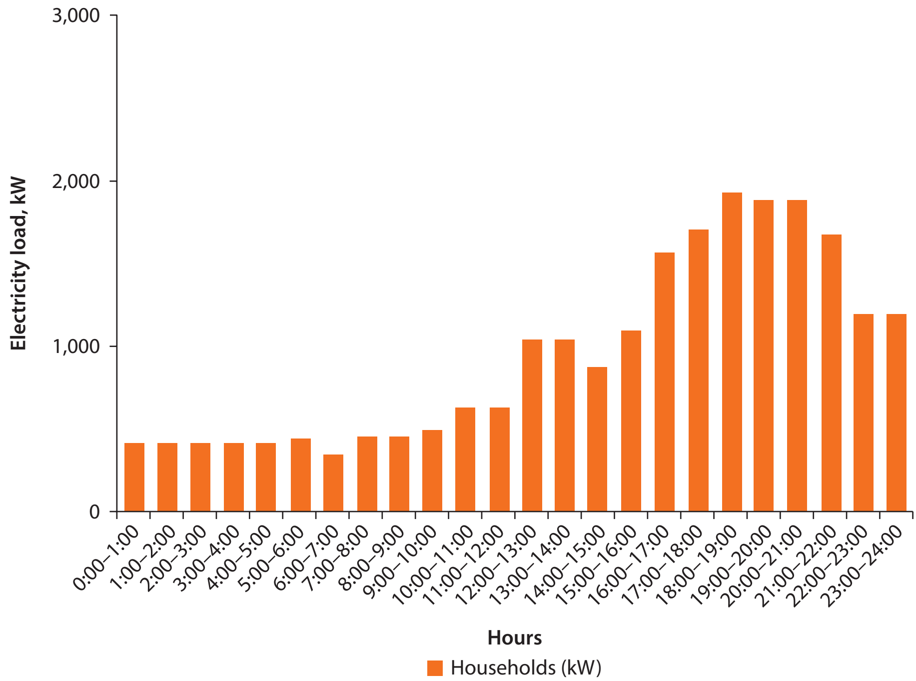
# A Wind-Solar-Diesel Hybrid System Case Study

In 2011 Triple E Systems surveyed household electricity consumption in Egbeda, a collection of nine communities in Southern Nigeria with the results shown in figure O.1. Using the appliances from the household survey used to project Nigeria's household electricity consumption, they estimated the daily electricity load of a representative village of more than 3,000 households.

Triple E Systems estimated the monthly insolation and wind speeds at two representative locations in the North (Jos) and South (Port Harcourt), based on data from NASA and Lahmeyer International, respectively. Using these data, they estimated hybrid renewable energy generation and costs using RETScreen International of Canada. They used the Hybrid Optimization Model for Electric Renewables (HOMER) software developed by NREL to estimate the share of energy from renewables from a hybrid wind-PV-diesel system. The wind-solar share in hybrid systems could reach about 90 percent. Due to expected intermittency, it is assumed that the diesel fraction of hybrid systems is about 20 percent on an energy basis. They found that photovoltaic (PV)-diesel, wind-diesel, and PV-wind-diesel hybrids are more cost-effective than diesel-only systems. They show that the renewable share of electricity production in hybrids is higher in the north than the south, implying that hybrid systems are more attractive in the north.

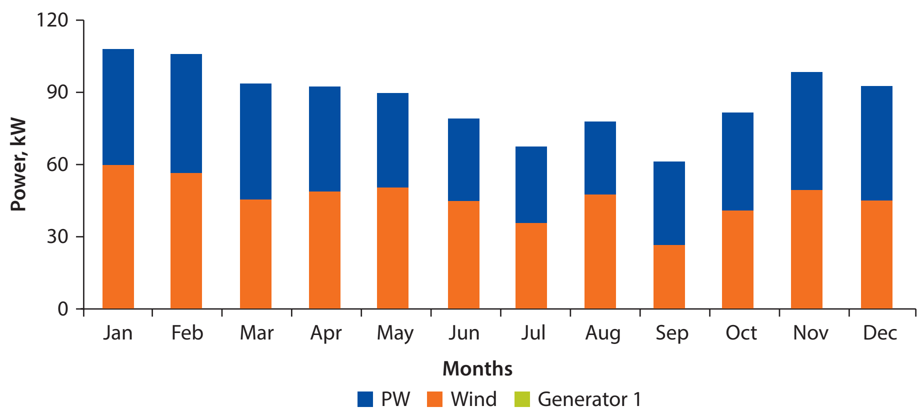
The results show that one village required 200 kilowatts PV and 50 kilowatts of wind turbine, a total of 250 kilowatts. The low-carbon scenario analysis assumes that a total of about 3,900 villages could be electrified using the hybrid system by 2030 with a total installed capacity of hybrid systems of about 11 gigawatts. The feasibility of deployment of PV and hybrid systems on such a scale will depend on the development of technical expertise to install, operate, and maintain them, and the commercial markets to supply them.

**Figure O.1 Egbeda Community Daily Household Electricity Load (kW) of 167 households**



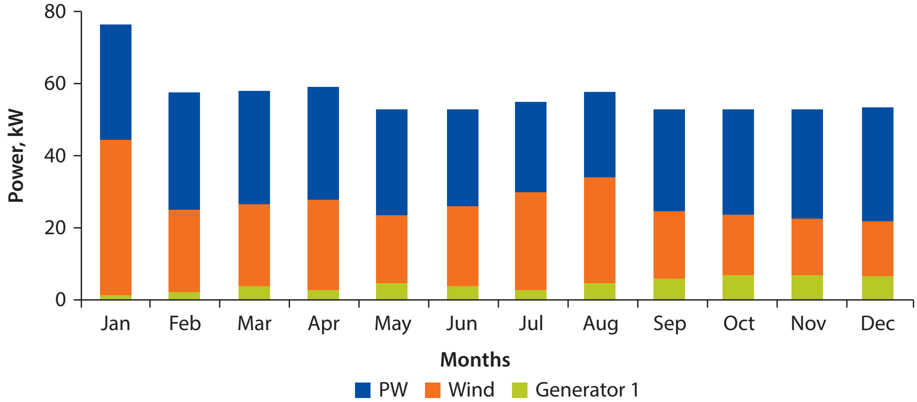

*Source:* Living Earth Foundation, 2011.

**Figure O.2 Monthly Average Electricity Production at Jose, Sokoto State**




*Source:* Calculations based on analysis using HOMER software from NREL.

**Figure O.3 Monthly Average Electricity Production at Port Harcourt, River State**




*Source:* Calculations based on analysis using HOMER.

**APPENDIX P**

# Cost and Performance of Technologies

Cost projections for technologies are based in part on these cost and performance characteristics from EIA 2009 and IEA 2010d.

**Table P.1 Cost and Performance Characteristics of Grid-Connected Technologies in 2009**

| *All costs in 2009$* | *Capital costs $/kW* | *Fixed O&M costs $/kw-yr* | *Variable O&M costs $/MWh* | *Fuel costs $/kWh* | *Unit size MW* | *Heat rate BTU/kWh* | *Efficiency %* | *Plant life Years* | *Capacity factor %* | *LCOE 2009 $/MWh* |
|---|---|---|---|---|---|---|---|---|---|---|
| Single-cycle gas turbine | 816 | 12 | 5.33 | 0.036 | 120 | 10,590 | 32 | 35 | 80 | 57 |
| Combined-cycle gas turbine | 1,246 | 16 | 2.01 | 0.024 | 300 | 7,260 | 47 | 35 | 80 | 50 |
| Subcritical coal | 1,296 | 33 | 1.2 | 0.037 | 114 | 9,900 | 34 | 50 | 83 | 65 |
| Hydropower | 2,080 | 21.9 | 3.2 | 0 | — | 0 | — | 40 | 38 | 88 |
| Biomass | 2,574 | 64 | 6.63 | 0.05 | 80 | 11,000 | 31 | 25 | 70 | 122 |
| Wind | 4,000 | 30 | 7 | 0 | 0.05 | 0 | — | 30 | 30 | 186 |
| Solar thermal | 5,490 | 56 | 4.5 | 0 | 100 | 0 | — | 30 | 33 | 244 |
| Solar PV (Grid) | 4,080 | 11 | 4.5 | 0 | 5 | 0 | — | 30 | 22 | 245 |
| Nuclear | 4,434 | 89 | 0.5 | 0 | 1350 | 10.5 | 32 | 40 | 82 | 101 |
| Supercritical coal with CCS | 4,579 | 63 | 9.1 | 0.032 | 1300 | 8 | 40 | 40 | 86 | 139 |

*Sources:* EIA 2009; IEA 2010d.
*Note:* — = not available.

**Table P.2 Cost and Performance Characteristics of Off-grid Technologies in 2009**

| *All costs in 2009$* | *Capital costs $/kW* | *Fixed O&M costs $/kw-yr* | *Variable O&M costs $/MWh* | *Fuel costs $/kWh* | *Unit size MW* | *Heat rate BTU/ kWh* | *Efficiency %* | *Plant life Years* | *Capacity factor %* | *LCOE 2009 $/MWh* |
|---|---|---|---|---|---|---|---|---|---|---|
| Diesel generators (off-grid A&D) | 408 | 20 | 0 | 0.23 | 0.176 | 9.47 | 36 | 8 | 40 | 251 |
| Diesel generators (off-grid B&C) | 653 | 76 | 27 | 0.18 | 5 | 7.9 | 43 | 20 | 60 | 236 |
| Gasoline generators | 425 | 120.8 | 0 | 0.25 | 0.0016 | 13.3 | 25.6 | 3 | 30 | 324 |
| Combustion turbine | 1,832 | 12 | 3.55 | 0.05 | 5.5 | 12.3 | 27 | 25 | 80 | 96 |
| Solar PV | 5304 | 19.3 | 0.002 | 0 | 0.05 | n.a. | n.a. | 30 | 22 | 310 |
| Hybrid (Wind-PV-Diesel) | 6,120 | 25 | 6.9 | 0.05 | 0.041 | n.a. | n.a. | 30 | 33 | 285 |
| Small hydro | 3,326 | 25.8 | 0 | 0 | 0.001 | n.a. | n.a. | 65 | 33 | 126 |

*Source:* ESMAP 2007; IEA 2011.
*Note:* n.a. = not applicable.

PART 4

# Road Transport Sector

# Acknowledgments

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# Abbreviations

| | |
|---|---|
| BAU | business-as-usual |
| BRT | bus rapid transit |
| CNG | compressed natural gas |
| $CO_2$ | carbon dioxide |
| $CO_2e$ | carbon dioxide equivalent emissions |
| ESMAP | World Bank Energy Sector Management Assistance Program |
| EU | European Union |
| FRSC | Federal Road Safety Corps |
| FGN | Federal Government of Nigeria |
| GDP | gross domestic product |
| GHG | greenhouse gases |
| HCV | heavy commercial vehicle, passenger |
| HDV | heavy duty vehicle |
| HGV | heavy goods vehicle |
| IPCC | Intergovernmental Panel on Climate Change |
| Kg | kilograms |
| km | kilometers |
| kt | kilotonnes |
| l | liter |
| LCV | light commercial vehicle |
| LD | light-duty |
| LNG | liquefied natural gas |
| Mt | million metric tons |
| MW | megawatt |
| ₦ | naira |
| NBS | National Bureau of Statistics (Nigeria) |
| NGO | nongovernmental organization |
| NGC | Nigeria Gas Company |
| NIPCO | Nigerian Independent Petroleum Company |

| | |
|---|---|
| NVLS | National Vehicle Identification Scheme |
| SSA | Sub-Saharan Africa |
| UN | United Nations |
| UNDP | United Nations Development Programme |
| USD | United States dollars |

# Executive Summary

Nigeria's on-road transport sector is a significant and growing contributor to Nigeria's overall carbon emissions. As part of a broader, multisector analysis of low-carbon development opportunities in Nigeria, this book assesses the expected growth in $CO_2$ emissions from on-road transport under a normal business development scenario up to the year 2035 and identifies policy and other mitigation actions at national and local levels that would reduce this growth.

In order to quantify and better understand the likely scale of this growth, the study team projected the evolution in vehicle emissions by considering the key factors driving growth in motorization levels and the demand for transport. These projections show that growth in greenhouse gas (GHG) emissions from this sector is likely to become increasingly important overall as a combination of factors come together to drive a rapid increase in motorization and consequent carbon emissions. Based on the analysis of these factors, potential mitigation measures that might be feasible and achievable within the Nigerian context have been identified.

## The Reference Scenario: Population and Vehicle Growth

Against the backdrop of rapid population and expected GDP growth, a very fast increase is forecast in the number of privately owned vehicles. Currently Africa's most populous country, Nigeria's rank in world population is expected to go from seventh to fourth by 2050. With an expected growth rate over 3 percent per year, Nigeria's population would increase from 158 million to 288 million by 2035, according to the United Nations' *World Population Prospects 2010*.

Sustained economic growth at a projected rate of 9 percent to 2025 and 6 percent for the remainder of the forecast period will increase per capita income. Nigeria currently has a low level of car ownership, with just 29 cars per 1,000 people. However, aspiration for car ownership is high due to the status it conveys; increasing income levels are expected to bring Nigeria in line with other comparable countries in terms of vehicle ownership rates. Based on international experience, a four-and–a-half-fold increase in car ownership—from 4.65 million to over 20 million—is expected over the forecast period.

The growing population will also need more public transport and commercial services. Passengers traveling by public transport are typically served by “paratransit” minibus type vehicles known as *danfo*. These vehicles are usually privately owned and operated to serve the interests of the owner/operator, with intense competition among drivers. Worsening congestion and ever increasing demand for movement in the large cities means that ever greater numbers of vehicles are required to serve the public.

For other commercial vehicle activity, economic growth drives a greater demand for the movement of freight and goods, enhanced by the increasing contribution the freight-intensive manufacturing and services sectors are projected to make to national income. The result is that commercial and passenger transport kilometers are forecast to increase ninefold by 2035.

Nigeria’s vehicle fleet is undergoing a slow evolution as vehicle emissions controls and import regulations come into force. Euro 2 standards were adopted from the end of 2011 for all new and imported vehicles. The import of two-stroke motorcycles was banned from the end of 2011, although the large import of these vehicles in anticipation of the ban means that these high-polluting two-wheelers are widespread in many parts of the country.

The existing vehicle fleet is made up of aging and high-polluting vehicles, the majority imported from western countries only when they approach the end of their economic life (currently allowable are imports of cars up to 8 years old, trucks younger than 15 years, and buses less than 10 years old). Poor routine maintenance and the harsh environment in Nigeria mean that the condition of these vehicles deteriorates quickly. However, the high costs of importation and weak vehicle testing procedures provide the incentive to extend the life of the existing fleet beyond the age and the operating conditions that might be considered desirable for the environment.

Future regulatory tightening of emissions standards was announced, with a move to Euro 3 in 2015. Future emissions regulations are thus forecast to track European standards with the current 15-year lag until the end of the modeled period.

The impact of the government fuel subsidies, which until recently had kept the price of gasoline well below market levels (around 65 naira/liter), has had clear effects on vehicle fleet composition. The proportion of private vehicles that run on diesel is negligible, with commercial vehicle owners also opting to run petrol vehicles wherever possible. Hence the majority of small and medium-size danfo minibuses run on petrol as do even half of the large buses and coaches.

The removal of the subsidy caused the price at the pump to almost double overnight, leading to civil unrest. The latest situation is a partial removal of the subsidy, bringing petrol to around 97 naira/liter), although the anticipated eventual removal will narrow the differential with the cost of diesel (170 naira/liter in 2012). The behavioral response to the elimination of the fuel subsidy terms of vehicle purchase was modeled to bring the Nigerian fleet into line with neighboring countries in terms of the mix between petrol and diesel vehicles.

## A Complex Challenge to Nigeria's Low-Carbon Future

The reference case scenario sees rapid growth in carbon emissions, rising from an estimated 27.6 million metric tonnes of carbon per year (Mt $CO_2e$) to 187 Mt $CO_2e$ by the end of the simulation period (figure ES 4.1). To put this into context, by 2035 emissions levels in Nigeria are projected to far exceed the level generated by the on-road transport sector across Sub-Saharan Africa as a whole (133 Mt in 2008).

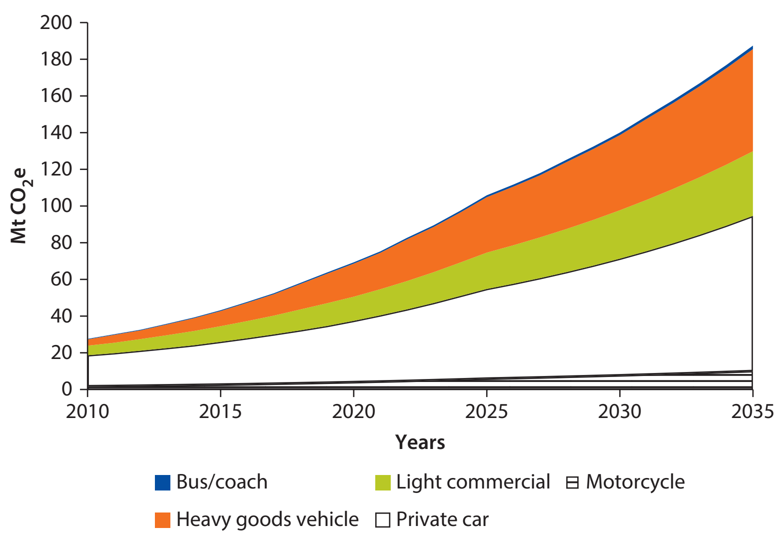
The growth in emissions is driven both by private vehicle use and, in particular, the increase in commercial vehicle activity. Commercial vehicles have typically higher emissions; therefore, the increase in activity has a more-than-commensurate impact on overall emissions levels.

## Potential Mitigation Measures

The main drivers of emissions projections are population growth, rising per-capita incomes, and increasing levels of overall economic activity. Mitigation actions should focus on policy measures that can reduce emissions per capita and/or per unit of GDP.

The options explored in this study focus on measures that can be implemented at the national level, specifically, freight movement, the efficient mass transportation of travelers within the major cities, and how to make greater use of Nigeria's rich natural gas resources.

**Figure ES 4.1 GHG Emissions Forecast from On-Road Transport**




*Source:* Modeled based on vehicle fleet estimates and emissions factors from EFFECT model.

## Movement of Freight

With the decline in the condition and operation of Nigeria's rail network since the 1980s, all but a small fraction of freight is transported by road. Reinstatement of the rail network to its former operating capacity would permit the transfer of some goods to the rail network, particularly aggregates, cement, and other heavy freight.

Taking into account historic freight tonnage statistics, the latest plans for the rail network, and the efficiency levels achieved on the rail networks in neighboring African countries, the study finds that a proportion of freight can be more efficiently transported by rail. The scale of mitigation possible is constrained by the coverage of the rail network, which, even with the proposed expansion, would probably be inadequate to meet a rapidly growing demand for the transportation of goods. Consequently, while rail might be able to carry 5 percent of freight by year 2015, the fraction of total freight subsequently falls as the total annual freight tonnage increases over the projected period.

Recognizing the likelihood that the majority of freight will be carried by road in the medium term, the study team hypothesized that measures to increase the efficiency of freight movements through better logistical planning and fleet management would prove most effective. Reducing empty running and rationalizing freight movements with a move toward using larger freight vehicles were demonstrated to achieve significant savings in operating km and hence emissions levels.

Driver awareness and training have also been demonstrated to play an effective role in reducing fuel consumption and hence emissions levels. A driver training program with coverage of 20 percent of commercial vehicle drivers repeated each decade was modeled, applying observed fuel efficiency gains achieved in similar programs elsewhere.

## More Efficient Private Vehicles

The average age of Nigeria's private vehicle fleet is 14 years; the majority of these vehicles do not conform to the incoming new vehicle emissions regulations introduced in Nigeria and, as a result, are outdated in terms of fuel efficiency and carbon emissions levels. The adoption of European GHG emissions standards as well as the Euro standards for local air pollutants would result in considerable fuel efficiency improvements lower polluting emissions. Over the 25-year projected study timeframe, average vehicle fleet efficiency could be improved by over 30 percent through the implementation of European standards, with a 15-year time lag.

## Better Public Transit

Public transport is currently the only available form of motorized transport for over three-quarters of travelers in the urban environment because most can't afford cars. While public transport typically alleviates urban congestion, the present public transport system—comprising small, privately owned minibuses, taxis, and motorcycle taxis—is actually the source of much disruption, with undisciplined and erratic driving behavior (for example, danfo regularly block two lanes of traffic while trying to board and alight passengers).

Nigeria is characterized by large cities, 10 of which have over 1 million people. Estimates for the population of Lagos vary from 9 million to over 17 million. Up until four years ago it was the only World mega-city without any form or organized public transport. The sheer scale of person movements in the major urban areas cannot adequately be served by an unplanned and unstructured public transport system.

A move to organized mass transit, whether rail, bus rapid transit (BRT) or conventional large bus operations, can significantly enhance the efficiency of transport operations, not only for public transport travelers but for all highway users.

The scenario considered in this study focuses initially on the migration to organized large bus operations because of its replicability in all major cities across Nigeria. Modeling the displacement of just under one-third of existing paratransit operations based on conservative assumptions, it turns out that these vehicles could be replaced with one-fifth the number of large vehicles. The additional potential benefits and reduction in vehicle activity resulting from implementation of BRT along selected high demand corridors has also been considered as applicable in the major cities.

## Natural Gas as Automobile Fuel

In addition to its oil production, Nigeria is also rich in natural gas, produced as a by-product of the oil extraction process. Use of this gas as a means of powering transportation in the form of compressed natural gas (CNG) is in its infancy in Nigeria, although widespread in many other countries worldwide. A trial commenced in 2010 in Edo State, promoted by the Nigerian Independent Petroleum Company (NIPCO) in partnership with Nigeria Gas Company (NGC). As a result of the program, as of 2012 there were six fueling stations—and another two under construction—to serve the state's large buses converted to CNG, and a fleet of 250 CNG taxis. NIPCO aims to roll out the concept and ultimately make CNG available at 5,000 stations across the country.

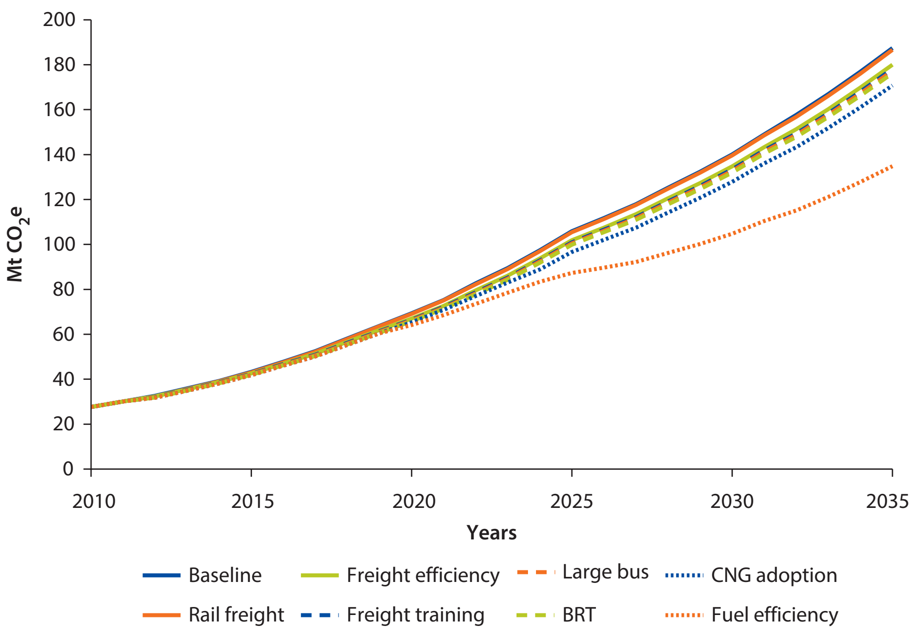
As well as lowering fuel costs by up to 50 percent, although CNG is still a fossil fuel, the levels of GHG pollution are much lower than those of gasoline or diesel.

The modeled scenario considers the successful rollout of CNG to all new large bus vehicles introduced in the mass transit scenario (existing bus vehicles are assumed to remain on standard technology) and adoption of CNG by 50 percent of the national taxi fleet and 15 percent of other private and commercial vehicles.

## Expected Results of Low-Carbon Policies

In total, the combination of $CO_2$ mitigation measures used in the model can achieve a reduction in emissions of 0.88 Mt per year in 2012 (first year of interventions) with increases to over 50 Mt in 2035. In total, this amounts to a reduction of 452 Mt of carbon over the 25-year projected period. Of the identified measures, the greatest emissions savings is achieved through the regulation of vehicle efficiency standards (figure ES 4.2 and table ES 4.1). Freight measures are also demonstrated to play a role in mitigating against the large increase in emissions from this rapidly growing sector.

**Figure ES 4.2 Impact of Mitigation Measures on $CO_2$ Emission Levels**




*Source:* Modeled based on vehicle fleet estimates and emissions factors from EFFECT model.

**Table ES 4.1 Emissions Savings Achievable under Mitigation Scenarios**

| *Annual emissions (Mt CO2e)* | *2010* | *2012* | *2020* | *2030* | *2035* |
|---|---|---|---|---|---|
| Baseline | 27.636 | 32.629 | 69.319 | 140.024 | 187.388 |
| Rail freight | 27.636 | 32.391 | 69.080 | 139.600 | 186.581 |
| Freight efficiency | 27.636 | 32.337 | 66.940 | 134.732 | 179.961 |
| Driver training | 27.636 | 32.146 | 66.482 | 133.392 | 178.116 |
| Large bus | 27.636 | 32.004 | 66.154 | 132.772 | 177.291 |
| BRT | 27.636 | 31.814 | 65.721 | 131.949 | 176.196 |
| CNG | 27.636 | 31.750 | 65.345 | 127.856 | 170.764 |
| Efficiency regulations | 27.636 | 31.750 | 64.109 | 104.713 | 134.859 |
| Total reduction | 0.000 | −0.880 | −5.210 | −35.312 | −52.529 |
| Cumulative reduction | 0.000 | −0.880 | −19.975 | −223.739 | −452.195 |

*Source:* Modeled based on vehicle fleet estimates and emissions factors from EFFECT model.

Although in combination, the measures have the potential to achieve significant emissions savings over the projected period, it remains clear that the growth in carbon emissions from road transport sector will feature increasingly as a major contributor to Nigeria's overall GHG emissions, and an area of significant challenge if Nigeria is to move toward a low-carbon future.

CHAPTER 20

# Study Methodology

The goal of this study is to present an objective assessment of the expected growth in $CO_2$ emissions from on-road transport under a normal business-development scenario into the medium-long term (2035) and to identify policy actions and other mitigation measures at national and local levels that would allow this rate of growth to be reduced. The resulting analysis frames the growing importance of the transport sector in terms of carbon emissions and initiates debate and discussion of possible mitigation measures. This book sets out the data analyzed, the development of the dynamic baseline and the potential mitigation measures to slow the rate of growth of vehicle emissions in Nigeria.

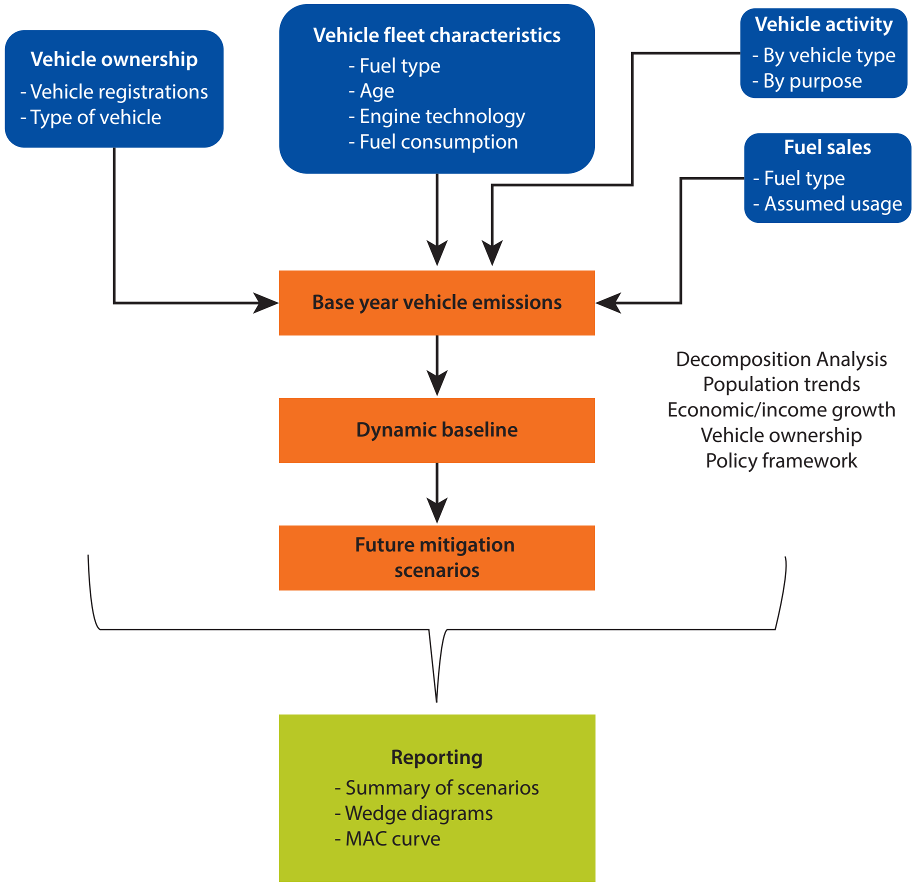
A brief description of the approach and methodology adopted for this study is set out in this chapter. Included is a listing of data the study team compiled for analysis, as well as references for other information for this book. Chapter 21 uses the data to develop the base year vehicle emissions estimate, followed in chapter 22 by projections of vehicle emissions under a dynamic baseline based on the forecast trends in key drivers of emissions levels. Chapter 23 considers the scale of the potential driving factors behind the emissions growth, using decomposition analysis to identify the areas where policy intervention may prove most fruitful, and chapter 24 then presents the potential impact of mitigation scenarios. Finally, chapter 25 draws broad conclusions from the analysis and recommends mitigation measures. Figure 20.1 summarizes the team's study process.

## Data Collection and Modeling

### *Base Year Emissions Modeling*

Available data—including vehicle ownership statistics, fleet composition, and estimates of vehicle activity—were used to construct an estimate of base year vehicle emissions for Nigeria. These estimates were validated against fuel sales data for the country to determine a best estimate of carbon emissions attributable to the on-road transport sector.

**Figure 20.1 Study Methodology**




## *Dynamic Baseline*

The base year emissions estimate were projected forward based on forecast trends in the key drivers of evolution in emissions levels, including population growth, rising income levels, and increasing motorization, which drive increases in vehicle ownership and vehicle activity. Comparison with countries of higher-income levels served as a basis for determining likely convergence in ownership and motorization levels. Evolution in the makeup of the vehicle fleet and vehicle characteristics was projected based on the best available trend data and on assumptions relating to the wider policy framework.

## *Mitigation Scenarios*

Having defined the "business as usual" (BAU), or reference scenario up until 2035, the team then focused on identifying the principal drivers of the increase in emissions using decomposition analysis, which provided the framework for identifying the potential scale of mitigation that might be achieved through policy measures that constrain growth in the main drivers of increased emissions. The team then developed a set of mitigation measures and forecast the scale of potential impacts that might be achieved by each of them over the projected period (see figure 20.1).

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CHAPTER 21

# Base Year Emissions Estimates

The study team produced emissions estimates projecting trends over a 40-year horizon. The base year selected was 2010 and projections were made to 2050. The base year was chosen based on availability of the most up-to-date data and comparability with other projections.

Base year emissions estimates were derived by drawing the required inputs from the data sources presented above. Vehicle emissions factors were sourced from the Emissions module within the EFFECT model, which itself derives values from COPERT.

## Vehicle Types

The following vehicle types form the basis of the Energy Forecasting Framework and Emissions Consensus Tool (EFFECT) model inputs, and for which fuel consumption and emissions factors are available from the model:

- Moped
- Scooter
- Motorcycle
- Minicar
- Small car
- Lower medium car
- Upper medium car
- Large and luxury car
- SUV
- Light commercial vehicle (passenger)
- Light commercial vehicle (goods)
- Heavy commercial vehicle (urban bus)
- Heavy commercial vehicle (coach)
- Heavy commercial vehicle (truck)
- 3-wheeler.

**Table 21.1 Vehicle Table Fleet Estimates Based on Vehicle Population Data**

| *Hfca* | *Growth to 2010* | *Total vehicles 2010 (forecast)* | *Vehicle type* | *Vehicle type in effect model* | *% of total* | *Vehicle numbers* |
|---|---|---|---|---|---|---|
| 7,171,475 | 1,500,000 | 8,671,475 | Motorcycles | Two-wheelers | 38.32 | 3,322,888 |
| | | | Saloon/station wagon | Cars | 53.63 | 4,650,509 |
| | | | Van, pickup and kitcar | LCV-Goods | 1.11 | 96,314 |
| | | | Lorry/truck | HCV Truck | 1.35 | 117,424 |
| | | | Minibus | LCV Goods[a] | 5.32 | 460,987 |
| | | | Omnibus | HCV Coach | 0.12 | 10,687 |
| | | | Tanker | HCV Truck | 0.01 | 1,055 |
| | | | Tractor | HCV Truck | 0.01 | 1,121 |
| | | | Trailer | HCV Truck | 0.04 | 3,232 |
| | | | Tipper | HCV Truck | 0.08 | 7,257 |

*Source:* Estimate based on State Licensing Authority vehicle registration data (SLA 2005) uplifted and disaggregated by vehicle classification using Lagos State Newly Registered Motor Vehicles by Type of Vehicle and Year of Registration (1990–2005) (SLA 2010).
a. Minibus vehicles were assigned to LCV goods as high proportion are assumed to be danfo which are typically are petrol, which does not feature within HCV Coach.

Within each vehicle category are different engine technologies disaggregated by fuel type, engine size, and emissions standard (for example, Euro standard).

The vehicle data to be input into the transport table of the EFFECT model were derived from files from the World Bank and other data sources listed in chapter 20. Key data were the total number of vehicles in 2006 and the split between the vehicle types. Table 21.1 shows how the agglomerated data were translated into data that can be used in the model. Growth to 2010 was forecast at 1.5 million vehicles based on historic registration trends.

Information on the vehicle fleet from the registration data is limited beyond that presented in the table 20.1 breakdown. However, a targeted vehicle population survey was conducted at various locations in Nigeria to better understand the composition and characteristics of Nigeria's vehicle fleet. The emerging results of this survey were used to assist in making an informed judgment about the vehicle population as set out in the next section.

## Nigeria Vehicle Population Survey Review

A survey of vehicle types across Nigeria provided a broad geographic spread and a range of different environments. A survey of 3,000 vehicles was conducted across survey sites in each of the four cities: Abuja, Kaduna, Lagos, and Ondo.

Drivers were questioned about the make, model, engine type, and age of vehicles, with further questions on purchase, type of use, annual km, and fuel consumption. Key observations were as follows.

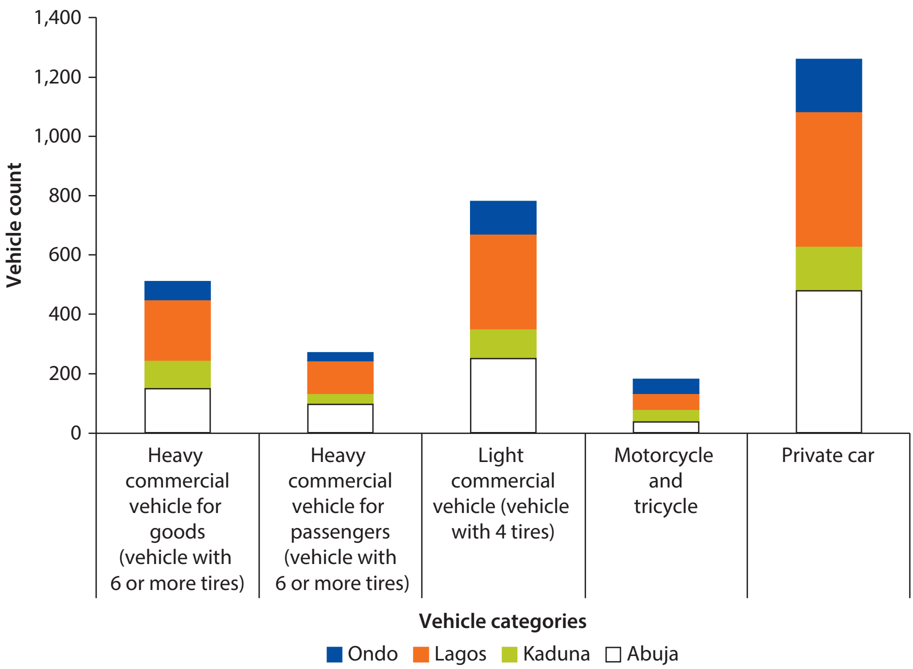
## Vehicle Classification

The surveys collected data relating to all vehicle classifications observed at the sites, without being specifically stratified. Figure 21.1 summarizes the sample split across the broad vehicle classifications.

As the figure shows, the sample size within each broad vehicle category ranges from approximately 200 to over 1,200, providing reasonable sample sizes across all categories.

The vehicle classifications was applied to the COPERT (Computer Programme to calculate Emissions from Road Transport) disaggregation by means of the transposition in table 21.2.

**Figure 21.1 Vehicle Survey Sample by Broad Vehicle Classification and Location**




*Source:* World Bank vehicle population survey 2012.

**Table 21.2 Transposition of Survey Classifications to COPERT Fields**

| *Survey categories* | *COPERT classification* |
|---|---|
| Motorcycle and tricycle | Two-wheelers/three-wheelers |
| Private car | Car |
| Light commercial vehicle (LCV) | LCV-Goods |
| Heavy passenger commercial vehicle (HCV) | HCV-Bus (split between coach and urban bus) |
| Heavy goods commercial vehicle (HCV) | HCV-Truck |

*Source:* World Bank data.

The observed characteristics are summarized in five major vehicle categories as follows.

***Motorcycle and Tricycle***

The following observations can be made from the two-wheelers and three-wheelers surveyed:

- All two-wheelers and three-wheelers surveyed were petrol powered.
- All motorcycles were two-stroke.
- 25 percent of three-wheelers were four-stroke.
- Average vehicle age is five years old.

***Private Car***

The private car subcategory includes cars, jeeps, SUVs, pick-ups, MPV, and wagons. Of these vehicles, the split observed from the surveys is as follows:

- Car—69 percent
- Jeep—10 percent
- Pick-up—2 percent
- Multipurpose vehicle (family car, MPV)—9 percent
- SUV—1 percent
- Wagon—9 percent.

With the largest sample size, the information on private cars provides a good overview of fleet technology:

- 98 percent of private car vehicles are petrol, of which 45 percent are carburated and 55 percent fuel injection.
- The average vehicle age within the private car category is 14 years.
- The large majority within this category were for private use (88 percent), while 9 percent were for official use and the remaining 3 percent commercial.

***Light Commercial Vehicle (4 tires)***

The LCV category incorporates light commercial, four-tired vehicles including taxis, lorry/goods vehicles, and the minibus vehicles that provide the majority of public transport. The main observations from the survey data are as follows:

- Just one of nearly 500 light commercial vehicles surveyed was diesel powered.
- Average vehicle age within this category is 24 years.
- 75 percent of petrol based vehicles are carburated, with 25 percent fuel injected.

***Heavy Commercial Passenger Vehicle (6 or more tires)***

Large passenger-carrying vehicles within this category feature large intra-city bus vehicles and interstate buses. The surveys indicate that:

- Only 50 percent of the large bus vehicles run on diesel, with the remaining half petrol fueled.
- The average vehicle age of the large buses is 16 years.

***Heavy Goods Vehicle (6 or more tires)***
The HGV category comprises 3, 5, and 15 tonne goods vehicles, trucks and trailers. These are split as follows:

- 3 tonne HGV—11 percent
- 5 tonne HGV—6 percent
- 15 tonne HGV—12 percent
- Heavy truck—32 percent
- Trailer—40 percent.

In terms of vehicle characteristics:

- Average HGV vehicle age is 18 years.
- 89 percent are diesel fueled.

## Modeled Vehicle Fleet

A review of the vehicle type survey data provides a basis for disaggregating by vehicle type and technology within the broad vehicle classifications reflected in the vehicle registration statistics. The disaggregation of the above vehicle classifications was applied as follows and shown in table 21.3.

**Table 21.3 Disaggregated Vehicle Split Used In Baseline Emissions Estimates**

| *Vehicle type* | *Classification* | *Emission norm* | *Fuel system* | *Fuel type* | *CC class* | *Split (%)* |
|---|---|---|---|---|---|---|
| Motorcycle | scooters | no norms | 2 stroke | petrol | > 50cc | 40 |
| | motorcycles | no norms | 2 stroke | petrol | > 50cc | 50 |
| | motorcycles | no norms | 4 stroke | petrol | < 250cc | 5 |
| | motorcycles | Euro I | 4 stroke | petrol | < 250cc | 5 |
| Cars | lower medium | no norms | diesel pump | diesel | < 2.0L | 1 |
| | lower medium | no norms | carburetor | petrol | < 2.0L (carb) | 15 |
| | lower medium | no norms | fuel injection | petrol | < 2.0L | 25 |
| | upper medium | no norms | carburetor | petrol | < 2.0L (carb) | 15 |
| | upper medium | Euro II | fuel injection | petrol | < 2.0L | 15 |
| | SUV | no norms | carburetor | petrol | < 1.4L (carb) | 15 |
| | SUV | Euro I | carburetor | petrol | < 1.4L (carb) | 14 |
| Light duty vehicle (LDV) | minivan/truck | no norms | carburetor | petrol | < 3.5t | 75 |
| | minivan/truck | Euro I | fuel injection | petrol | < 3.5t | 25 |
| Bus | light bus | no norms | diesel pump | petrol | 3.6t | 50 |
| | medium bus (LD) | no norms | diesel pump | diesel | 16t | 50 |
| Heavy goods Vehicle (HGV) | light truck | no norms | diesel pump | diesel | 5t | 17 |
| | medium truck | no norms | diesel pump | diesel | 16.2t | 12 |
| | heavy truck | no norms | diesel pump | diesel | 25t | 31 |
| | prime mover | Euro I | diesel pump | diesel | 40t | 40 |

*Source:* Estimate derived from Nigeria Vehicle Population Survey 2012.

## Vehicle Activity

Estimates of vehicle activity were derived from a number of different sources, as follows.

### *UITP Report*

The UITP and UATP (2010) report on the statistical indicators of public transport provides vehicle activity estimates relating only to the Lagos vehicle fleet, with estimates shown in table 21.4.

### *UN Report*

A United Nations Report on transport in Africa finds that commercial vehicle utilization in Africa is low compared to other parts of the developing world due to the combination of poor roads and vehicle condition. Typical annual km for commercial vehicles operating in Africa are estimated to be 65,000 kilometers per year (UNESCO 2009).

### *WB Nigeria Vehicle Survey*

Annual km traveled by vehicle type was recorded in the Nigeria vehicle population survey conducted in 2012 (Nigeria Vehicle Population Survey 2012). Table 21.5 summarizes the results collected, disaggregated by vehicle type.

Average vehicle activity levels are very high for private vehicles, at upwards of 30,000 kilometers per year for most subcategories. As an estimate of average vehicle activity, these levels appear very high and may reflect the inherent response bias in this type of survey (with little used vehicles less likely to be captured in the survey sample). Conversely, the activity levels for commercial passenger and goods vehicles are somewhat lower than might be expected (compared to the sources presented above) for vehicles typically used intensively for commercial gain, with passenger buses averaging under 30,000 kilometers and goods vehicles showing similar low activity levels.

**Table 21.4 Transport Indicators for Lagos**

| *Indicator* | *Private car* | *PT (large bus)* | *PT (minibus)* |
|---|---|---|---|
| Fleet | 800,000 | 755 | 80,000 |
| Capacity (people/vehicle) | 5 | 80 | 30 |
| Annual km per unit | 4,260 | 73,920 | 72,000 |
| Average occupancy | 1.8 | 43 | 18 |
| Annual passengers | 999,499,456 | 126,000,000 | 2,140,000,000 |
| Daily unit trips | 2 | 12 | 8 |
| Average speed on road network | 23 km/h | | |

*Source:* UITP and UATP 2010.

**Table 21.5 Average Annual Travel per Vehicle, from WB Nigeria Vehicle Survey**
*Kilometers*

| *Vehicle type* | *Private* | *Commercial—Passenger* | *Commercial—Goods* |
|---|---|---|---|
| Car | 29,595 | 18,587 | 12,313 |
| Wagon | 28,921 | 33,044 | 12,233 |
| Jeep | 40,604 | | |
| Space bus | 33,256 | 39,167 | |
| Sports car | 25,240 | | |
| SUV | 36,111 | | |
| Pick-up | 10,923 | | 20,604 |
| Bus | 18,192 | | |
| Motorcycle | 7,659 | | |
| Tricycle (three-wheeler) | 24,933 | | |
| Minibus 10–14 passenger (Urban Bus) | | 14,876 | |
| Mid-bus 18–35 (urban bus) | | 28,743 | |
| Big bus 50–60 passenger (urban bus) | | 23,024 | |
| Minibus 10–14 passenger (long-distance bus) | | 17,451 | |
| Mid-bus 18–35 passenger (long-distance bus) | | 32,828 | |
| Big bus 50–60 passenger (long-distance bus) | | 49,313 | |
| 3 ton canter | | | 25,737 |
| 5 ton canter | | | 29,327 |
| 15 ton canter | | | 34,291 |
| Heavy truck | | | 37,533 |
| Trailer | | | 42,786 |

*Source:* World Bank data.

**Table 21.6 Vehicle Activity Levels Used in Emissions Calculations**

| *Vehicle type in effect model* | *Annual (km)* |
|---|---|
| Two-wheelers[a] | 7,000 |
| Car[b] | 17,000 |
| LCV-goods[c] | 30,000 |
| HDV-Ubus | 30,000 |
| HDV-coach[d] | 45,000 |
| HCV-truck[d] | 33,500 |

*Source:* Estimate based on Nigeria Vehicle Population Survey 2012 and UITP/UATP 2010, balanced against fuel sales data from World Bank Development Indicator Index.
a. Motorcycle usage is assumed to be relatively high, due to intensive usage of a proportion of the vehicle fleet as Okada.
b. Private car vehicle activity was reduced from levels observed in vehicle survey to reflect potential response bias, but remains high relative to other sources.
c. LCV goods includes danfo minibus vehicles.
d. Truck and coach activity adjusted to balance with diesel sales data.

Informed by the evidence sources in the tables, vehicle activity levels were estimated for each vehicle type. They were reviewed against fuel sales data and adjusted to ensure that fuel consumption by fuel type broadly reflected the levels observed in the fuel sales data. The estimated resulting vehicle activity levels are shown in table 21.6.

## Emissions Factors

The emissions factors used for the baseline carbon emission forecasts were taken from the EFFECT model, within which the Emissions Factors module takes its values from COPERT.

The following inputs were used as inputs to the emissions factor calculations:

- Ambient temperature (see table 21.7)—average daily high temp (C), average daily low temp (c)
- Vehicle fuel density (gasoline, diesel)—no information available, default EFFECT values retained (grams per liter)
  - Gasoline 720
  - Diesel 850
- Ethanol share by volume into gasoline—no information available, assumed negligible
- Biodiesel blend share by volume into diesel—no information available, assumed negligible
- Fuel prices (price per kg without duties)
  - Petrol: US$/l super grade gasoline = 0.4 (source: World Development Indicators)
  - Diesel: US$/l diesel = 0.8 (source: World Bank, World Development Indicators)
- LPG—assumed negligible
- CNG—assumed negligible (small scale trial currently underway in one state)
- Vehicle speed and trip length—assumptions are shown in table 21.8.

**Table 21.7 Ambient Temperature for Emissions Calculations**

| | *Jan* | *Feb* | *Mar* | *Apr* | *May* | *Jun* | *Jul* | *Aug* | *Sep* | *Oct* | *Nov* | *Dec* |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Average daily high temperature (°C) | 32 | 33 | 33 | 32 | 31 | 29 | 28 | 28 | 29 | 30 | 31 | 32 |
| Average daily low temperature (°C) | 22 | 23 | 24 | 23 | 23 | 22 | 22 | 22 | 22 | 22 | 23 | 22 |

*Source:* http://www.weather.com/weather/wxclimatology/monthly/graph/NIXX0012.

**Table 21.8 Vehicle Speed and Trip Length Assumptions**

| | *Speed (kph)* | | | |
|---|---|---|---|---|
| | *Urban* | *Rural* | *Highway* | *Average trip length (km)* |
| MC | 20 | 60 | 100 | 5 |
| 3W | 20 | 60 | 100 | 5 |
| Car | 20 | 60 | 100 | 8.8 |
| LCV-Passenger | 20 | 60 | 100 | 8.8 |
| LCV-Goods[a] | 20 | 60 | 100 | 8.8 |
| HDV-Ubus | 20 | 60 | 100 | 8.8 |
| HDV-Coach | 20 | 60 | 100 | 8.8 |
| HDV-Truck | 20 | 60 | 100 | 8.8 |

*Source:* Estimates based on data sources listed in chapter 21.
a. Average loading for goods vehicles is taken to be 50 percent.

## Base Year Summary Results

Based on the above inputs, the team calculated aggregate vehicle fleet statistics, vehicle activity, fuel consumption, and $CO_2$ emissions. These results are summarized in the following tables and figures.

## Base Year Vehicle Fleet and Activity

Vehicle fleet composition and total annual vehicle activity levels are presented in table 21.9.

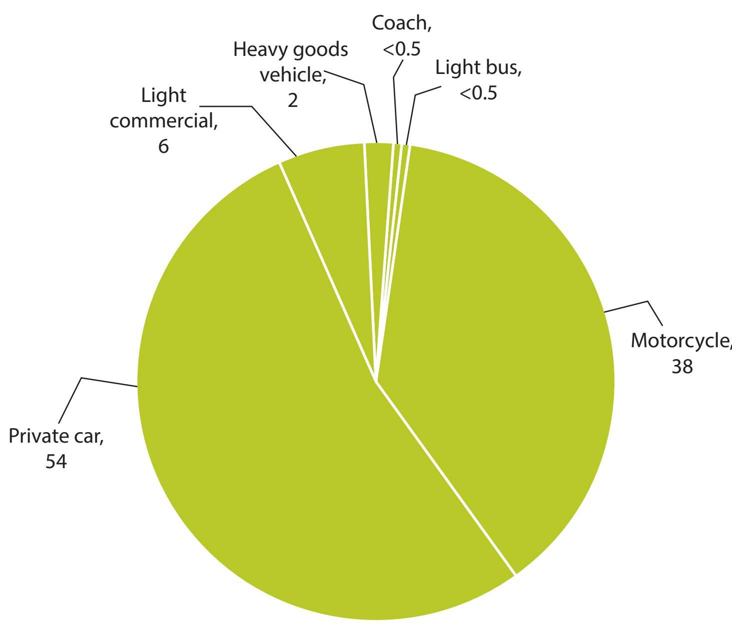
As indicated in figures 21.2 and 21.3, private car use accounts for by far the greatest share of vehicle activity, followed by motorcycle (both mainly for

**Table 21.9 Base Year Vehicle Fleet and Activity Levels**

| *Vehicle type* | *Vehicle fleet* | *Veh/km (Millions)* |
|---|---|---|
| Motorcycle | 3,322,888 | 23,260 |
| Car | 4,650,509 | 79,059 |
| Light goods vehicle | 557,301 | 16,719 |
| Heavy goods vehicle | 130,089 | 4,358 |
| Urban bus | 5,344 | 160 |
| Long-distance coach | 5,344 | 240 |
| Total | 8,671,474 | 123,797 |

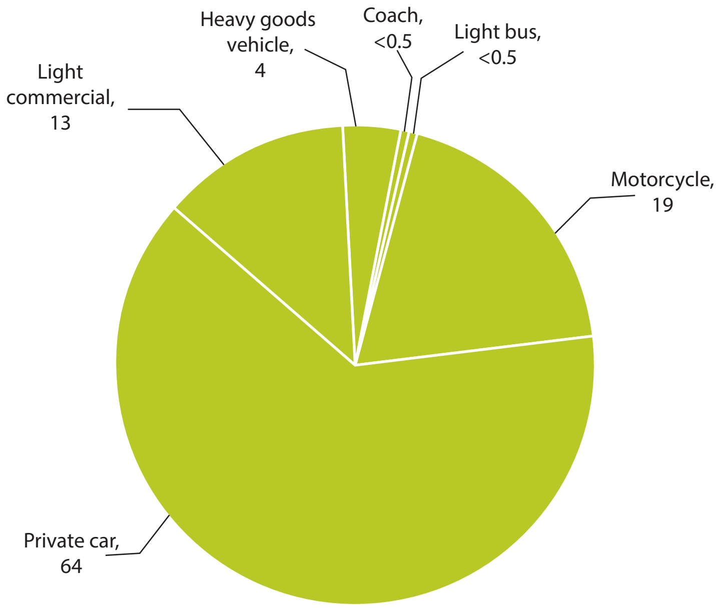
*Source:* Calculation based on vehicle activity and vehicle population estimates in tables 21.3–21.6.

**Figure 21.2 Vehicle Fleet Composition**
*Percent*




*Source:* World Bank commissioned survey, 2012, based on State Licensing Authority vehicle registration data (SLA 2005).

**Figure 21.3 Vehicle Fleet Activity**
*Percent annual kilometers, millions*




***Source:*** World Bank commissioned survey, 2012, based on State Licensing Authority vehicle registration data (SLA 2005).

commercial activity), and then light goods vehicles, including minibus (danfo) activity.

Public transport movements account for around a third of vehicle activity in the large cities like Lagos, with private car representing a similar proportion. Taxis typically account for up to 15 percent of movement, with the remainder made up of motorcycles and goods. However, this varies from city to city, with Kano, for example, demonstrating a much higher proportion of motorcycle activity.

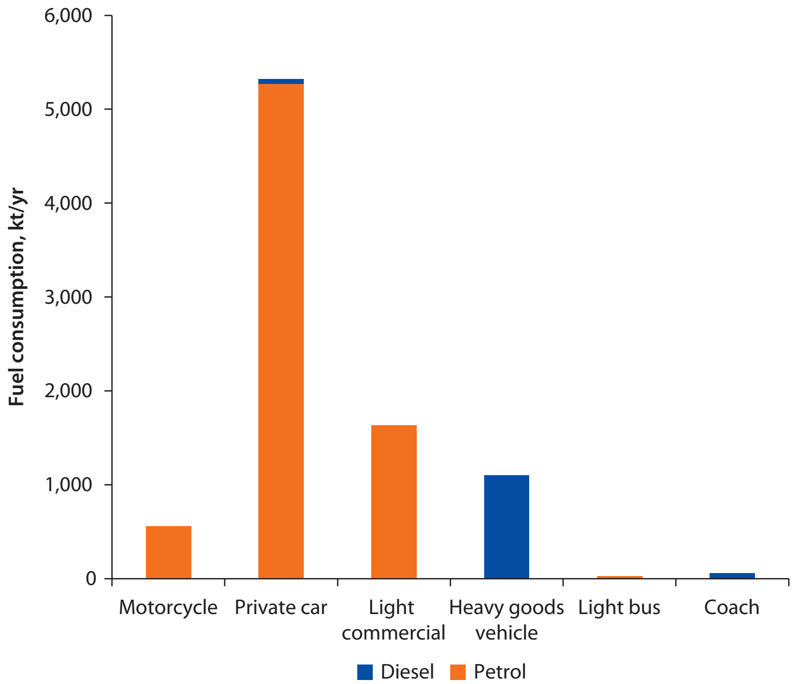
## Fuel Consumption

Using the COPERT fuel consumption factors for the vehicle subcategories, estimates of total fuel consumption based on the baseline vehicle fleet and activity levels were made. They are summarized in figure 21.4 disaggregated by fuel type.

Petrol is the fuel of choice for the vast majority of vehicles operating in Nigeria, due to the preferential cost of petrol attributable to the fuel subsidy and the general availability of diesel. For this reason, almost all private vehicles and a large number of commercial vehicles have gasoline engines.

The road vehicle fuel consumption estimates (see table 21.10) can be compared against fuel sales data as a source of validation. Table 21.11 provides the most up-to-date fuel sales data for Nigeria.

**Figure 21.4 Base Year Fuel Consumption (kt) by Vehicle and Fuel Type**




*Source:* Calculated using vehicle fleet estimates with EFFECT model fuel consumption factors.

**Table 21.10 Base Year (2010) Fuel Consumption by Vehicle Type**

| | *Fuel consumption (kt)* | |
|---|---|---|
| *Vehicle type* | *Petrol* | *Diesel* |
| Motorcycle | 559 | 0 |
| Car | 5,268 | 51 |
| Light goods vehicle | 1,631 | 0 |
| Heavy goods vehicle | 0 | 1,099 |
| Light bus | 30 | 0 |
| Coach | 0 | 61 |
| Total | 7,487 | 1,211 |

*Source:* Calculated using vehicle fleet estimates with EFFECT model fuel consumption factors.

**Table 21.11 Nigerian Fuel Sales Data**

| | *Fuel consumption (kt/year)* | |
|---|---|---|
| *Fuel sales data sources* | *Petrol/Gasoline* | *Diesel* |
| Road; fuel used in road vehicles and agricultural and industrial highway (excludes military consumption) | 7,496 | 1,227 |

*Source:* Private communication by John Rogers of World Bank.

Taking the estimated usage for transport vehicles as the nearest estimate to base year consumption figures for validation, the estimated base year fuel consumption calibrates closely with the fuel sales data.

### *Base Year $CO_2$ Emissions*

The forecast $CO_2$ emissions from the road transport sector are shown in table 21.12.

Overall, the team estimated that the road sector accounts for 27.6 Mt of $CO_2$ emitted at 2010 activity levels.

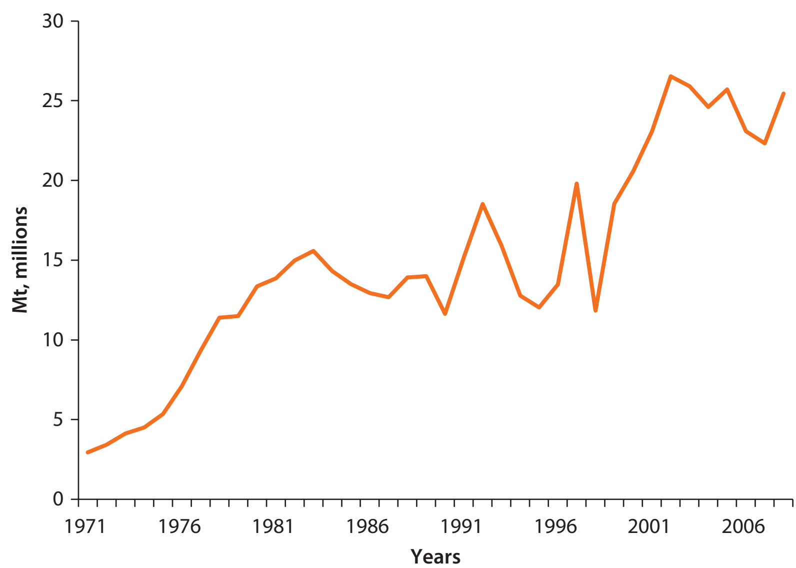
The World Bank World Development Indicators dataset provides an estimate of $CO_2$ emissions from the transport sector. The full data series available was plotted in figure 21.5. The latest carbon emissions estimate relating to

**Table 21.12 Base Year $CO_2$ Emissions Estimate**

| *Base year 2010* | *$CO_2$ Emissions (Mt/year)* |
|---|---|
| Motorcycle | 1.778 |
| Car | 16.930 |
| Light goods vehicle | 5.192 |
| Heavy goods vehicle | 3.449 |
| Urban bus | 0.095 |
| Coach | 0.192 |
| Total | 27.636 |

*Source:* Calculated using vehicle fleet estimates with EFFECT model emissions factors.

**Figure 21.5 Transport Sector $CO_2$ Emissions Time Series**




*Source:* World Bank Development Indicator dataset.

the transport sector in Nigeria is *25.5 Mt of* $CO_2$ *in 2008*. The World Bank data are taken from IEA statistics and includes emissions from the combustion of fuel for all transport activity, regardless of sector, except for international marine bunkers and international aviation.

The emissions estimate for 2010 is of a similar order of magnitude to the World Bank estimate, with the slightly higher value sitting in line with the recent trend in emissions as observed in figure 21.5.

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CHAPTER 22

# Dynamic Emissions Estimates

Over the coming years, a number of cumulative factors are likely to lead to increasing levels of greenhouse gas (GHG) emissions from the transport sector. Evolving trends in the following are likely to drive these changing levels:

- Population
- National income
- Household income
- Vehicle fleet composition.

## Population Growth

Nigeria at over 160 million people is the most populous country in Africa, ranking seventh largest in the world and forecast to become fourth largest by 2050 (figure 22.1).

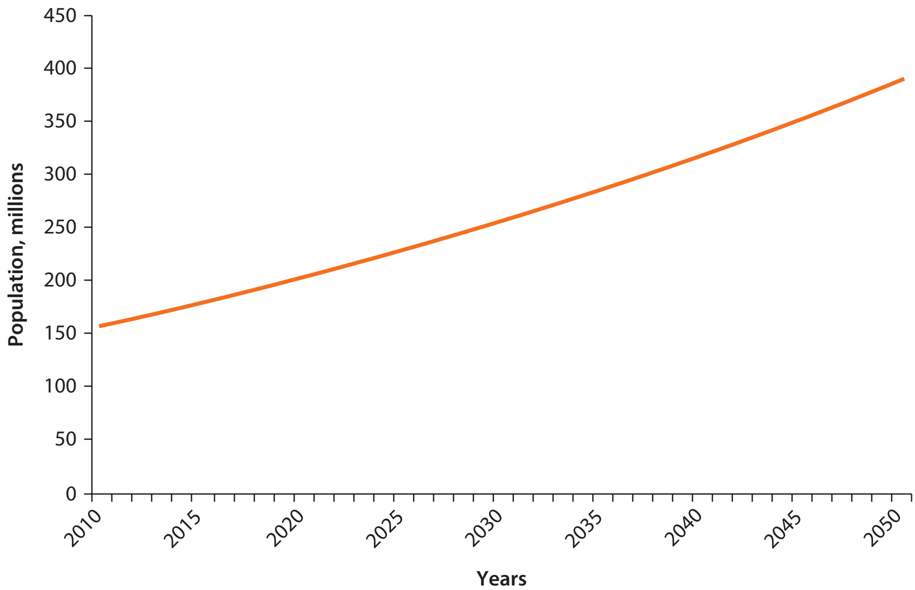
Nigeria's population is comparatively young, with 55 percent under 20 in the base year. In future years, the population will age as youth mature, although relatively high birth rates will help to retain a relatively youthful population over the forecast period. By 2050, 44 percent of the population will be under 20 years of age (figure 22.2).

The composition of the population is directly related to the potential pool of future car owners. All other things equal, increasing the population of driving age might be expected to effect a pro-rata increase in vehicle ownership and usage. The UN data on growth in total population were used as a growth factor for the vehicle fleet (UN 2010).

## National Income

The prosperity and productivity of a country has an intrinsic link to mobility, as the demand for travel is a derived demand. Economic growth drives both personal and commercial travel demand. It is equally true that the ability to move goods and people is a requisite to achieving economic growth. Therefore, it is widely recognized that an efficient transport system is an essential element of a strongly performing economy.

**Figure 22.1 Nigeria Population Projections to 2050**




*Source:* UN 2010

Nigeria's economy is growing rapidly. Nigeria's real rate of gross domestic product (GDP) growth over the last decade is shown in figure 22.3.

Taking into account the other economic sectors studied for this project, the assumed rate of economic growth over the forecast period is taken to be 9 percent growth/year until 2025 and 6 percent growth thereafter.

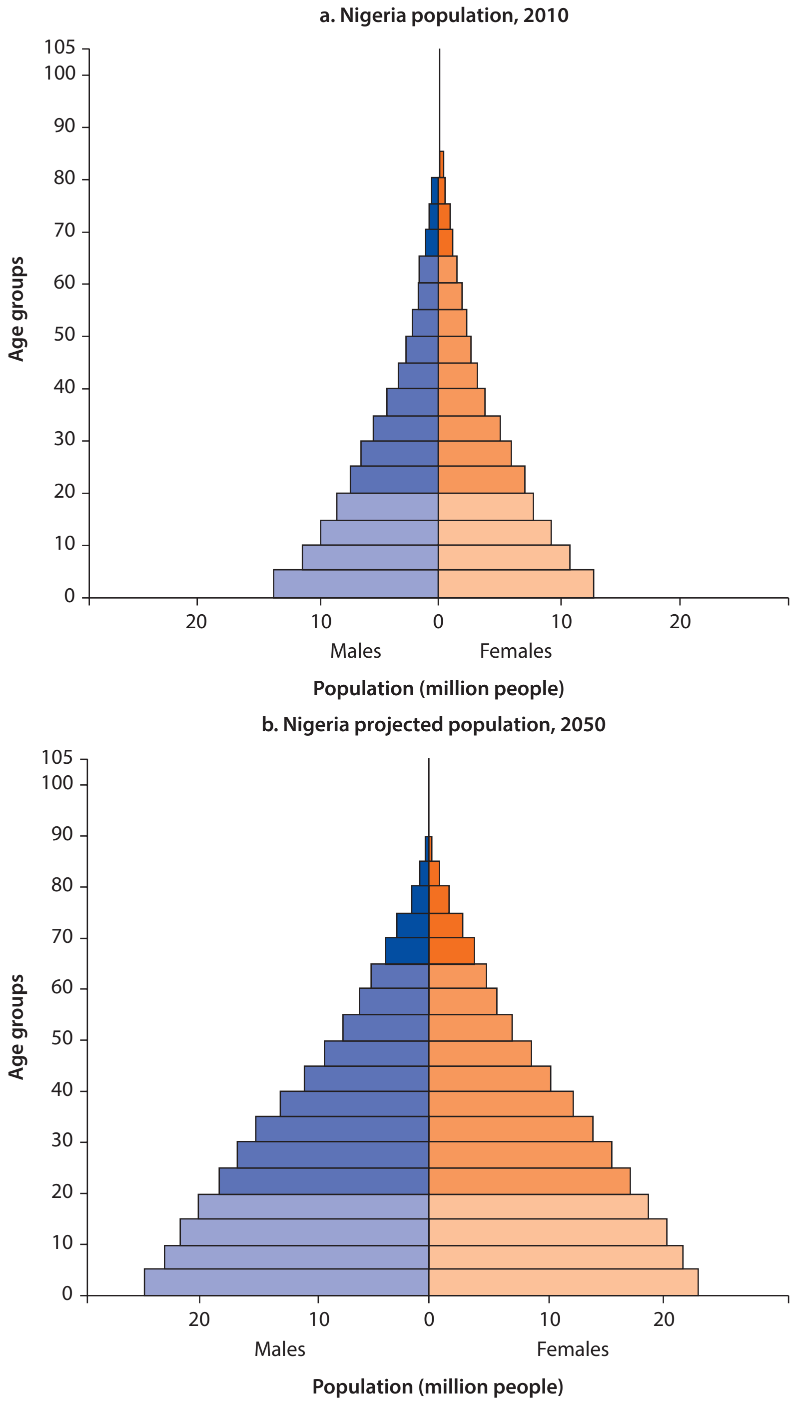
National economic growth drives commercial activity. Nigeria's economy currently exhibits a bias toward oil and gas extraction industries and agriculture. While these industries are likely to remain of significant importance to the Nigerian economy, projections point to an increasing shift to manufacturing and service sectors as the economy develops and matures. This evolution is illustrated in table 22.1.

Manufacturing and services are more freight-intensive than oil and gas extraction, therefore, the growth in these sectors is expected to lead to faster growth in freight demand than would otherwise be expected.

Typically, the elasticity of freight activity in relation to GDP was estimated to be greater than 1 for developing counties, while industrialized countries have seen a soft decoupling of freight to economic growth leading to elasticity values falling below 1. For the purpose of freight forecasts, *a conservative elasticity value of unity was adopted*. This was applied to commercial public transport vehicle growth and also that of light goods vehicles.

However, to account for the increasing share that manufacturing and services will have in the Nigerian economy, and their greater freight intensity, growth in heavy goods vehicle numbers was increased pro rata to the growth in these industries rather than GDP as a whole.

**Figure 22.2 Nigeria Population Pyramids for 2010 and 2050**




*Source:* UN 2010.

**Figure 22.3 Nigeria Real Rate of GDP Growth 1999–2009**


*Source:* Indexmundi. http://www.indexmundi.com/g/g.aspx?c=ni&v=66.

**Table 22.1 Projected Macro-Sectorial Shares for Value Added in Nigeria**
*Percent*

| *Year* | *Agriculture* | *Manufacturing* | *Mining* | *Services* |
|---|---|---|---|---|
| 2010 | 43 | 1 | 36 | 19 |
| 2015 | 32 | 5 | 33 | 29 |
| 2020 | 25 | 12 | 25 | 38 |
| 2025 | 23 | 17 | 21 | 39 |
| 2030 | 21 | 18 | 21 | 39 |
| 2035 | 21 | 19 | 21 | 39 |

*Source:* Private communication by John Rogers of World Bank.

## Household Income

In developing countries, rising income levels are the principal driver behind increasing levels of car ownership. In Nigeria and other West African countries where car ownership is currently low, the aspiration for car ownership is particularly strong as a sign of status and wealth.

Comparison of car ownership rates across the developing and developed world was undertaken using the World Bank Development indicator dataset. A Gompertz function was chosen as most appropriate in explaining the relationship. This S-shaped curve reflects the initial slow increase in car ownership until a threshold was reached, after which car ownership increases rapidly before finally reaching saturation levels at around 450 cars per 1,000 population.

Taking the resulting relationship between per capita GDP and car ownership levels (per 1,000 population), the increase in car ownership can be projected based on income level increases expected over the forecast period.

## Vehicle Fleet Evolution

Despite sparse information on Nigeria's current vehicle population, registration data were used to provide a base year estimate of vehicle fleet composition. Much of the current fleet self-evidently consists of very old and poorly maintained vehicles. The average age of commercial vehicles is estimated to be more than 20 years, while many private vehicles are kept on the road despite approaching the end of their serviceable lives.

### *Import Regulations*

The use of old and polluting vehicle technology (such as two-stroke motorcycle engines and vehicles without catalytic converters) poses significant disbenefits to society through pollution. The poor condition of vehicles also poses great safety issues.

The FGN has taken action in setting regulatory policies aimed at tackling the problems of poor quality of the vehicle fleet. The FGN recently set import regulations with the following limits on age of imported vehicles:

- Buses—maximum 10 years old
- Trucks—maximum 15 years old
- Cars—maximum 8 years old.

Furthermore, to tackle pollution levels, regulation relating to engine technology was also introduced, including the following limitations:

- The import of two-stroke motorcycles was prohibited from end 2011.
- Euro II standards to were adopted as a minimum for all vehicles imported/sold from end 2011.
- In 2015 FGN plans to adopt Euro III emissions standards for newly purchased vehicles.

While these regulations will not have an immediate impact on the vehicle population, over time the vehicle fleet will evolve to reflect these regulations as new vehicles are imported and old vehicles reach the end of their useful lives. Many vehicles are imported from Europe, which is well advanced in terms of emissions standards (table 22.2).

**Table 22.2 European Passenger Car Emissions Standards Implementation Dates**

| *Emissions standard* | *EU implementation dates* |
|---|---|
| Euro I | July 1992 |
| Euro II | January 1996 |
| Euro III | January 2000 |
| Euro IV | January 2005 |
| Euro V | September 2009 |
| Euro VI | September 2014 |

*Source:* Transportpolicy.net http://transportpolicy.net/index.php?title=EU:_Light-duty:_Emissions.

Nigeria is lagging about 15 years behind Europe in terms of emissions standards. The study team took this into account when considering the likely technology of vehicles imported into Nigeria. They forecast vehicle fleet evolution based on the lagged introduction of vehicles conforming to the newer regulations, in line with import regulations. By 2035, all new vehicles in Nigeria must conform to Euro V as a minimum standard.

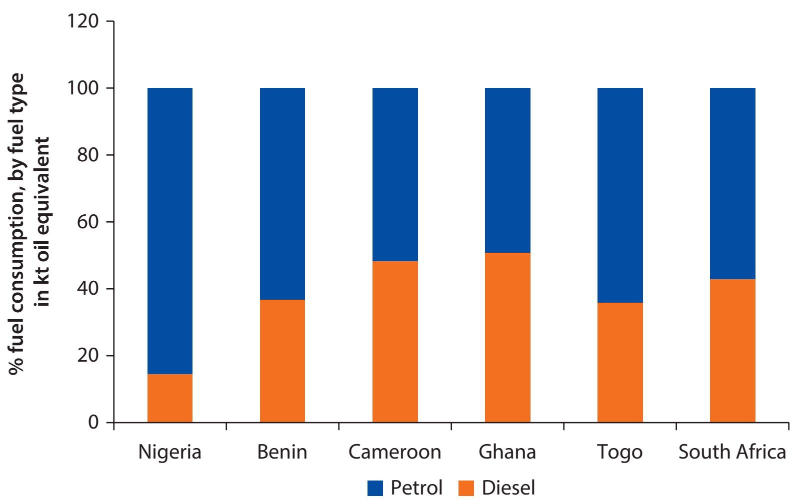
### *Fuel Type*

The composition of Nigeria's vehicle fleet is currently weighted heavily toward petrol engine vehicles, due principally to the fuel subsidy which has kept gasoline prices significantly below market levels since its introduction in the 1980s. In early 2012, the government attempted to remove the fuel subsidy to bring fuel prices in line with market rates, thus greatly reducing the discrepancy between the cost of petrol and diesel. Although the subsidy was particularly reinstated due to public pressure, the likelihood is that at some point in the future the subsidy will be removed.

Although no specific information on fuel usage was sourced, anecdotal evidence suggests that adjacent countries have a greater proportion of diesel vehicles within their fleet and the trend toward use of diesel vehicles is likely to be pronounced in Nigeria following the removal of the fuel subsidy. Indirect evidence on the split between petrol and diesel usage can however be observed through road fuel consumption estimates.

Figure 22.4 shows how fuel consumption is split by fuel type in Nigeria and its neighboring countries (note that this does not equate to the split of vehicles by fuel type). Nigeria may be expected to come into line with its neighbors following the removal of the fuel subsidy.

**Figure 22.4 Road Sector Fuel Consumption in 2008**




*Source:* World Bank Development Indicators.

**Table 22.3 Proportion of Cars and LGVs in United Kingdom Using Petrol or Diesel by Vehicle** *Kilometers, %*

| | Cars | | LGVs | |
|---|---|---|---|---|
| *Year* | *Petrol* | *Diesel* | *Petrol* | *Diesel* |
| 2002 | 78.1 | 21.9 | 14.1 | 85.9 |
| 2003 | 75.6 | 24.4 | 13.3 | 86.7 |
| 2004 | 73.3 | 26.7 | 11.1 | 88.9 |
| 2010 | decreasing to 59.8 | increasing to 40.2 | 5.5 | 94.5 |
| 2015 | decreasing to 51.0 | increasing to 49.0 | 3.8 | 96.2 |
| 2020 | decreasing to 47.6 | increasing to 52.4 | 2.3 | 97.7 |
| 2025 onwards | decreasing to 47.4 | increasing to 52.6 | 1.5 | 98.5 |

*Source:* UK Department for Transport, TAG Unit 3.5.6, Table 12.

Furthermore, most forecasts suggest a move toward diesel vehicles over time. Table 22.3 is taken from the UK Department for Transport Guidance, suggesting that for the period 2010–25, the proportion of diesel cars in the United Kingdom will grow from 20 percent to over 50 percent.

It is estimated that by 2035, 40 percent of cars imported to or bought in Nigeria are diesel, based on the vehicle fleet composition forecast in the main export markets to Nigeria. The proportion of diesel fuel used by road vehicles is predicted to reach 46 percent of sales in 2035. This brings Nigeria into line with its neighboring countries in terms of fuel usage.

## Dynamic Baseline Results

The outputs for this study are summarized in this section, representing the likely scale of emissions increases resulting from the reference scenario.

Driven by population growth and increasing income levels, private car ownership increases dramatically over the modeled period. GDP per capita increases from $1,222 in 2010 to $4,386 in 2035. The impact of increasing income levels on car ownership is shown in figure 22.5, with Nigeria moving from 29 cars per 1,000 population in 2010 (green) to 72 cars per 1,000 in 2035 (orange).

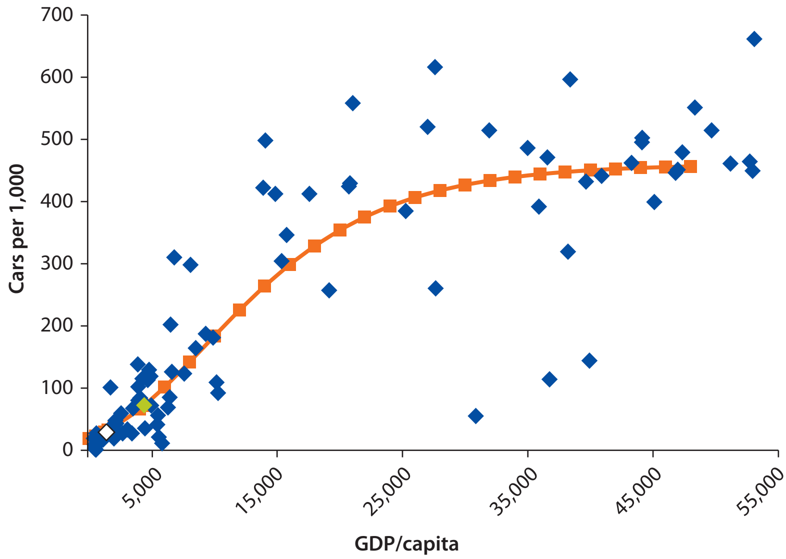
While ownership levels still remain low in international terms throughout the forecast period, the significant increase in ownership from a very low base, compounded with a fast growing population, leads to an 11-fold increase in private vehicle numbers over the modeled period.

Commercial vehicle numbers are forecast to increase in line with economic activity. The impact of the economic and demographic drivers on the Nigeria's vehicle fleet is summarized in table 22.4.

### *Vehicle Activity Levels and Fuel Consumption*

Increasing vehicle numbers lead to an associated rise in vehicle activity and fuel consumed. The evolving vehicle fleet means that the relationship is not necessarily linear, and as discussed earlier, there is a move to diesel over time. Tables 22.5 and 22.6 summarize vehicle activity and fuel consumed.

**Figure 22.5 Car Ownership vs. Income in Various Countries (blue): Nigeria in 2010 (green) and 2035 (orange)**




*Source:* World Bank 2010: World Development Indicators (GDP/Capita, Passenger Cars per 1,000 population).

**Table 22.4 Forecast Nigeria Vehicle Composition, 2010–35**

| *Vehicle Type* | *2010* | *2020* | *2030* | *2035* |
|---|---|---|---|---|
| Motorcycle | 3,322,888 | 7,159,073 | 13,667,052 | 17,781,132 |
| Private car | 4,650,509 | 8,374,026 | 15,657,807 | 20,844,373 |
| Light commercial | 557,301 | 1,319,334 | 2,716,543 | 3,635,348 |
| Heavy goods vehicle | 130,089 | 769,920 | 1,807,225 | 2,460,904 |
| Light bus | 5,344 | 12,650 | 26,047 | 34,856 |
| Coach | 5,344 | 12,650 | 26,047 | 34,856 |
| **Total** | **8,671,474** | **17,647,653** | **33,900,720** | **44,791,470** |
| cars/1,000 | 29 | 41 | 61 | 72 |

*Source:* Adapted within this study from SLA 2005, uplifted and disaggregated by vehicle classification.

**Table 22.5 Vehicle Activity by Vehicle Type (millions of vehicle km), 2010–35**

| *Vehicle type/km travelled* | *2010* | *2020* | *2030* | *2035* |
|---|---|---|---|---|
| Motorcycle | 23,260 | 50,114 | 95,669 | 124,468 |
| Private car | 79,059 | 142,358 | 266,183 | 354,354 |
| Light commercial | 16,719 | 39,580 | 81,496 | 109,060 |
| Heavy goods vehicle | 4,358 | 25,792 | 60,542 | 82,440 |
| Light bus | 160 | 380 | 781 | 1,046 |
| Coach | 240 | 569 | 1,172 | 1,569 |
| Total | 123,797 | 258,793 | 505,844 | 672,937 |

*Source:* Estimate based on Nigeria Vehicle Population Survey 2012 and UITP/UATP 2010, balanced against fuel sales data from World Bank Development Indicator Index.

**Table 22.6 Fuel Consumption (kt) by Vehicle and Fuel Type, 2010–35**

| *Vehicle type/fuel consumption, kt/yr* | *2010* | | *2020* | | *2030* | | *2035* | |
|---|---|---|---|---|---|---|---|---|
| | *Petrol* | *Diesel* | *Petrol* | *Diesel* | *Petrol* | *Diesel* | *Petrol* | *Diesel* |
| Motorcycle | 559 | — | 1,266 | — | 2.431 | — | 3,164 | — |
| Private | 5,268 | 51 | 9,357 | 1,161 | 16,010 | 4,023 | 20,146 | 6,511 |
| Light commercial | 1,631 | — | 9,357 | 495 | 6,373 | 1,934 | 8,423 | 2,674 |
| Heavy goods vehicle | — | 1,099 | — | 5,746 | — | 13,048 | — | 17,742 |
| Light bus | 30 | — | 8 | 62 | 1 | 157 | 1 | 214 |
| Coach | — | 61 | — | 140 | — | 286 | — | 383 |
| Total | 7,487 | 1,211 | 14,266 | 7,603 | 24,815 | 19,448 | 31734 | 27525 |

*Source:* Calculated using vehicle fleet estimates with EFFECT model fuel consumption factors.
*Note:* — = not available.

**Table 22.7 $CO_2$ Emissions (kt) by Vehicle Type, 2010–35**

| *Vehicle type/Emissions, Mt $CO_2e$* | *2010* | *2020* | *2030* | *2035* |
|---|---|---|---|---|
| Motorcycle | 1.778 | 4.030 | 7.738 | 10.07 |
| Private car | 16.930 | 33.427 | 63.586 | 84.56 |
| Light commercial | 5.192 | 13.126 | 26.355 | 35.21 |
| Heavy goods vehicle | 3.449 | 18.028 | 40.941 | 55.67 |
| Light bus | 0.095 | 0.270 | 0.509 | 0.68 |
| Coach | 0.192 | 0.438 | 0.896 | 1.20 |
| Total | 27.636 | 69.319 | 140.024 | 187.388 |

*Source:* Calculated using vehicle fleet estimates with EFFECT model emissions factors.

Fuel consumption is projected to increase by 680 percent over the forecast period, driven by a fivefold increase in total vehicle kilometer. The more than commensurate increase in fuel consumption is accounted for by the greater level of growth observed in the commercial vehicle fleet, which has higher average fuel consumption levels.

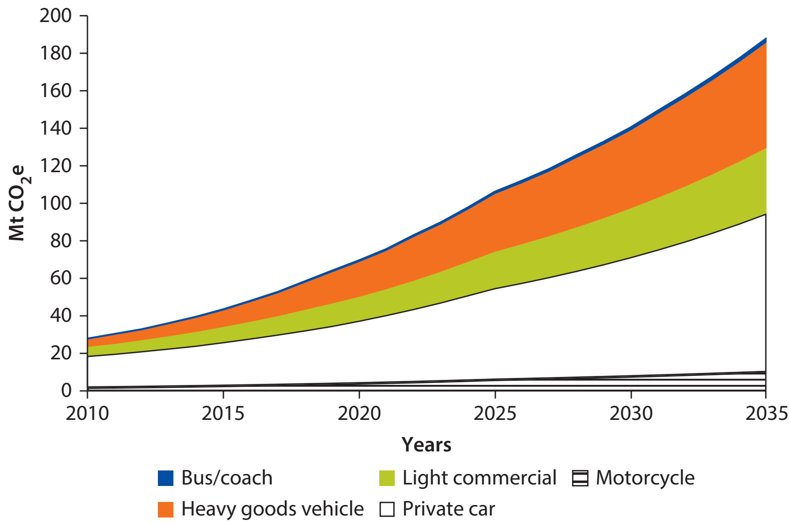
Diesel consumption accounts for 46 percent of the total fuel consumed in 2035, compared to 14 percent in 2010.

### *Carbon Emissions Levels*

The resulting growth in $CO_2$ emissions levels are shown in table 22.7. Carbon emissions are forecast to increase significantly over the forecast period, driven by increasing population, economic activity, and wealth, reaching over 145 million metric tonnes by 2035.

This exponential growth is illustrated in figure 22.6. Light commercial, which includes the danfo minibuses, and heavy goods vehicles, which already generate a significant proportion of carbon emissions in the base year, can be seen to contribute increasingly to overall vehicle emissions, driven by the fast pace of economic growth predicted for the country.

**Figure 22.6 $CO_2$ Emissions Over Forecast Period, 2010–35**




*Source:* Modeled based on vehicle fleet estimates and emissions factors from EFFECT model.

## Conclusions

The BAU projections set out a bleak scenario on the pressure that demographic and economic growth will place on greenhouse gas emissions for Nigeria. To put the numbers in context, the 187 Mt of carbon emitted by the road sector in Nigeria by 2035 represents over 40 percent more than the current emissions estimated for Sub-Saharan Africa as a whole—forecast at 133 Mt in 2008 (World Bank World Development Indicators).

Against the backdrop of rapid population growth, increasing mobility levels, and greater commercial activity, the development of policy interventions to constrain emissions growth is most challenging.

Decomposition analysis is presented in the next chapter, assessing the scale of impact of the contributing factors to current and forecast emissions levels to identify the areas that may afford the greatest opportunity for targeted and effective intervention.

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CHAPTER 23

# Decomposition Analysis

The baseline emissions levels were projected over the forecast period, with the resulting $CO_2$ estimates exhibiting and significant and sustained growth. This is driven by a number of factors which in combination lead to the exponential growth observed. These factors are listed again below:

- Population growth and demographic change
- Economic growth
- Increasing income levels
- Increasing car ownership
- Increasing mobility levels
- Increasing commercial activity
- Fleet evolution (driven by)
- Regulatory restrictions (age, engine types, emissions regulations)
- Fuel prices
- New technology.

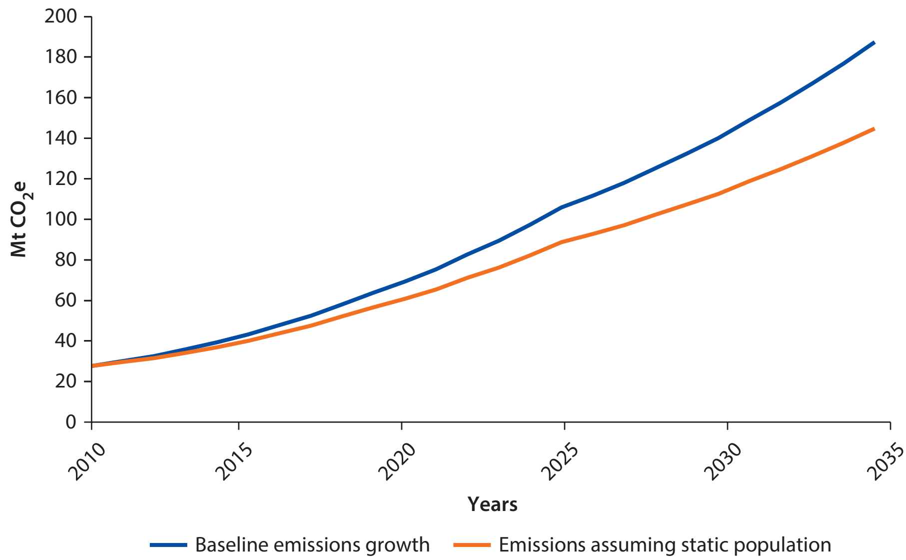
Gaining an understanding of the relative importance of each of these influences is important when considering how policy measures may mitigate against the growth in emissions levels. This can assist in highlighting areas of intervention that might have the greatest impact.

The impact of each of the above factors in relation to overall projected growth in emissions is considered in isolation in this chapter.

## Population Growth

Population growth was forecast to have a pro rata impact on vehicle numbers, and hence other things aside, on vehicle activity and vehicle emissions levels. The scale of this impact in relation to overall projections is plotted in figure 23.1.

**Figure 23.1 Impact of Population Growth on Emissions Levels**




*Source:* Modeled based on UN2010 population growth estimates.

## Economic Growth

Economic growth drives both private and commercial vehicle activity, through a number of different mechanisms. Factors considered in this study included household income, national income, and projected fleet evolution.

### *Household Income*

Increasing household income opens up the possibility of car ownership, which for the majority of Nigerians is a symbol of status out of reach with present household wealth.

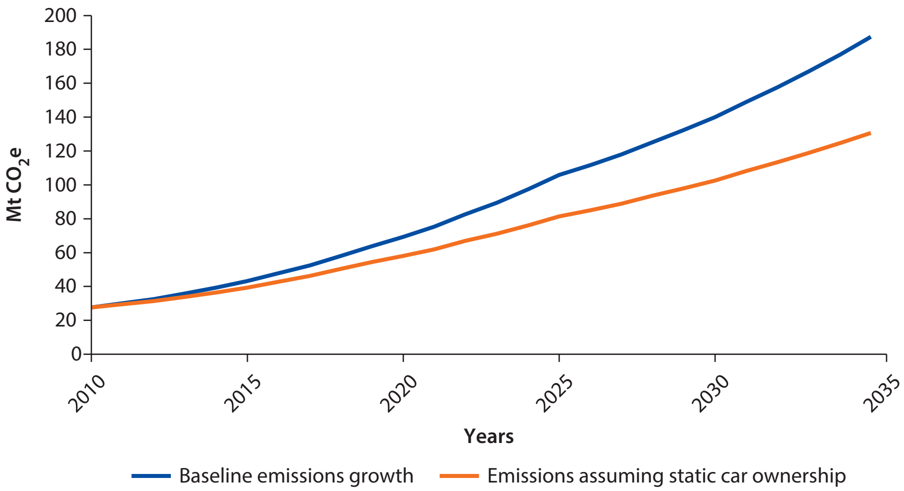
Car ownership is forecast to rise from the current level of 29 cars per 1,000 population to 72 by 2035. Even at 2035 levels, this level of car ownership remains well below the levels observed in developed countries, which typically reach saturation at around 400–500 vehicles per 1,000 people.

Increasing income levels also have an impact on mobility (the number and length of trips made). This has not been explicitly modeled because there is overlap between growth in vehicle activity and mobility, and also because of the increasing public transport km, which are estimated as a function of economic growth. There is a risk of double counting if mobility is considered as a multiplicative function.

The impact of total suppression of growth in car ownership on emissions levels is shown in the figure 23.2.

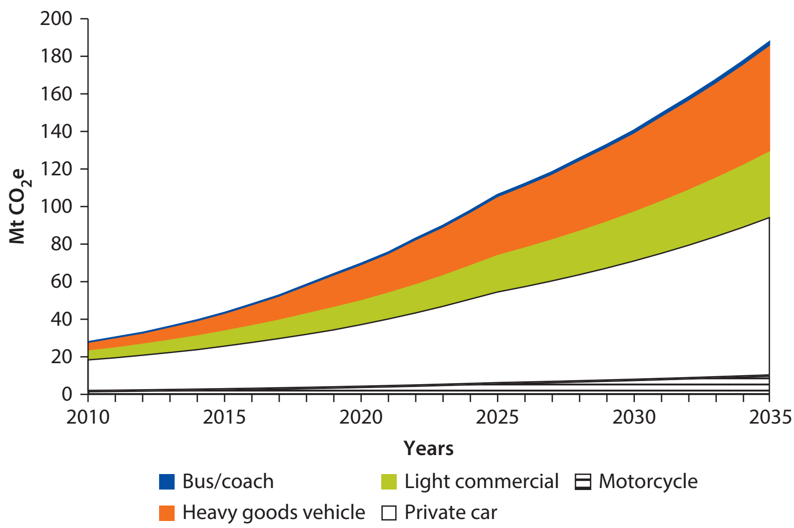
Private vehicle ownership growth is very large over the forecast period, car numbers increasing from 22.6 million to over 20 million. As such, these vehicles account for a significant proportion of total vehicle activity, as shown in figure 23.3. Limiting growth in private vehicle numbers and applying emissions

**Figure 23.2 Impact of Increasing Car Ownership on Emissions Levels**




*Source:* Modeled based on car ownership projections derived within this study.

**Figure 23.3 Contribution to Emissions Levels by Vehicle Type**




*Source:* Modeled emissions based on vehicle fleet estimates and emissions factors from EFFECT model.

regulations which will lead to choosing more efficient types of vehicle therefore has the potential to make a significant impact on emissions levels.

### *National Income*

Commercial vehicle activity (including public transport) makes up an increasing proportion of overall emissions. This growth is significantly in excess of their relative proportion of vehicle numbers—commercial vehicles increase from 8 percent of vehicle fleet in 2010 to 14 percent in 2035—but accounting for over 32 percent of emissions in the base year rising to out 50 percent in 2035.

Commercial vehicle activity is driven by economic growth. An elasticity of unity (1) was taken as a conservative factor, with the decoupling of freight growth and GDP that was observed in some developed countries considered unlikely to occur within the timeframe of this exercise. However, allowance was made for the increasing importance of manufacturing and services as a share of GDP, and the resulting increase in freight intensity, by increasing heavy freight in line with the growth in these sectors.

The same elasticity was applied to the light goods vehicle class, which due to the current petrol engine vehicles used, falls within the light goods classification. Public transport demand for these vehicles is mainly driven by population growth, although increasing mobility due to increasing income and potential to travel also is a factor.

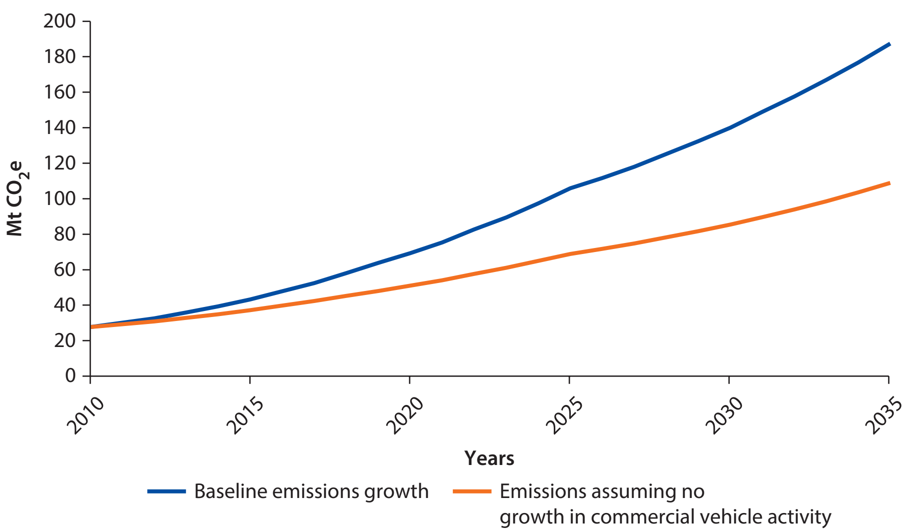
The scale of commercial activity growth on emissions is highlighted in figure 23.4.

The scale of the commercial sector's contribution to emissions levels is sizable, despite the smaller vehicle fleet size, and can be attributed to two factors:

- More intensive vehicle usage related to commercial activity
- Higher emissions levels associated with larger vehicles.

These factors result in commercial vehicles generating a large proportion of vehicle emissions despite their small relative numbers within the total vehicle fleet. The scale of growth in both vehicle numbers and in emissions levels make the commercial vehicle fleet a prime focus for possible mitigation measures.

**Figure 23.4 Impact of Commercial Vehicle Activity Growth of Emissions Levels**




*Source:* Modeled commercial vehicle activity growth based on GDP growth.

### Fleet Evolution

The evolution in the type and characteristics of the vehicle fleet in Nigeria was modeled through informed judgment, paying due regard to the following factors:

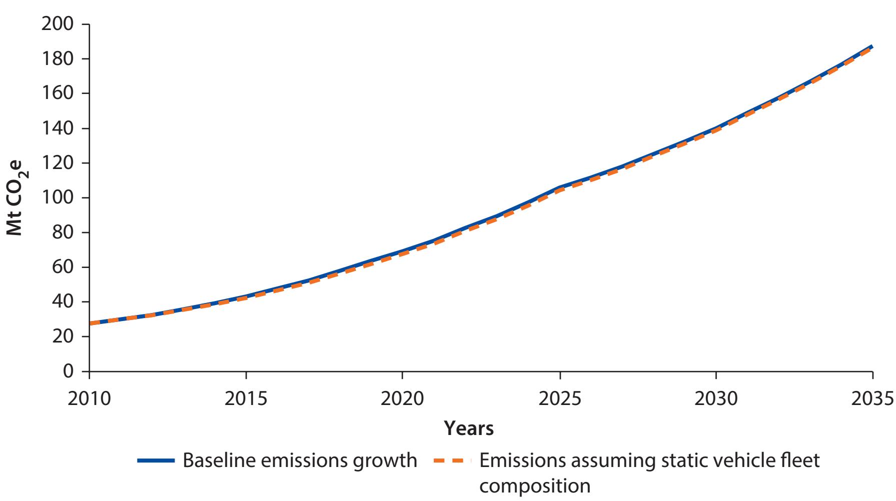
- Vehicle import regulations (setting age limits on imported vehicles)
- Vehicle emissions regulations current and future (taking into account announced future policy and also projecting further into the future based on Nigeria's current position relative to EU regulations)
- A move to diesel-fueled vehicles as the fuel subsidy on gasoline is removed, bringing Nigeria's fleet composition into line with neighboring countries with respect to fuel type used.

Figure 23.5 shows the impact of this evolution on emissions, by holding vehicle composition constant—that is, renewing the old fleet and importing "new" vehicles with the same emissions standards/fuel consumption levels as the current fleet.

As the figure shows, despite the fact that over time the vehicle fleet composition changes significantly—with the move to Euro V standards and beyond—the scale of the impact on overall emissions levels seems to be relatively small.

The scale of impact of vehicle technology improvements suggests that targeted policy measures relating to vehicle emissions standards, while likely to have significant benefits in relation to local air pollution levels, may have limited impact on reducing carbon emissions levels. Regulations relating to fuel efficiency and vehicle size could be expected to play an important role here.

**Figure 23.5 Impact of Evolving Fleet Composition on Emissions Levels**




*Source:* Modeled based on vehicle fleet estimates and emissions factors from EFFECT model.

### *Summary and Conclusions*

The relative contribution of evolving factors over the period of the projections to emission levels was set out in this chapter. This analysis enables a clearer picture of the drivers of emissions growth and hence the most fertile areas of focus for mitigation measures.

The growth in private vehicle ownership levels is shown to play a major role in the increase in vehicle kilometer. This is driven in part by a growing population and in part by increasing levels of household income which bring car ownership into the grasp of more people. It is unlikely that policies would be enacted to constrain these factors.

However policies are favored that will suppress either the increase in private vehicle ownership levels or the uses of private vehicles, which are therefore considered vital to securing a low-carbon future. Such reductions can be achieved by the following measures:

- Efficient and attractive public transport service provision
- Prioritization of public transport over private travel modes
- High duties on private vehicle ownership
- A move to more efficient, smaller private vehicles can also play a role in reducing the impact of the growth in private vehicles on emissions levels.

The following scenario should be considered:

- Apply fuel efficiency/carbon emission standards as adopted in Europe, with a maximum 15-year time lag
- Incentivize alternative fuel technology options, in particular CNG to benefit from Nigeria's reserves of natural gas.

**The following intervention measures to promote the use of public transport are considered in the next chapter:**

- Greater efficiency in public transport operations through a migration to large regulated bus vehicles
- Enhanced public transport provision delivered by mass transit operations (bus or rail based; bus rapid transit is considered initially).

Increasing commercial vehicle numbers and activity has also been shown to play a significant role in growth in emissions levels. Economic growth is a major policy objective and essential to secure the prosperity of the growing nation. The ability to efficiently move people and goods by providing a high-quality transport network is a key element in promoting a vibrant and successful economy. However, economic growth, and the associated demands relating to the movement of goods and people, is energy intensive and typically comes at a cost of greater fossil fuel use.

Existing commercial activity in Nigeria is greatly inefficient in many ways, and policy measures to encourage more efficient movement of goods has great potential, given the scale of the sector in carbon emitted.

The following measures are put forward for consideration:

- A shift to rail-based freight movements as a more efficient form of freight transportation
- Improved organization in the freight sector leading to better logistics and greater efficiency in the movement of goods
- Improved driver training to promote efficient driving behavior and reduce fuel consumption.

The next chapter examines the scale of impact possible, given concerted policy interventions as set out in this chapter.

## Reference

SLA (State Licensing Authority). 2005. *Newly Registered Motor Vehicles by Type of Vehicle and by Year of Registration: 1990–2005*. Lagos, Nigeria: Lagos State Licensing Office and Lagos State Central Statistics Office.

**CHAPTER 24**

# Mitigation Measures

This chapter considers the scale of impact of potential mitigation measures on the growth in emissions. Based on the decomposition analysis, the main areas of focus for intervention measures are the growth in freight movement, public transport vehicle activity, and private vehicle use.

The following intervention measures were identified directly targeting these areas of growth, with the aim of improving efficiency of movements and minimizing the emissions generated by movements that will continue to take place.

***Freight Measures***

- Reassignment of a proportion of freight to rail
- Improving the efficiency of freight movements through better logistics
- Driver training to improve driving efficiency, reducing fuel consumption, and hence emissions levels.

***Public Transport Measures***

- Migration to timetabled large bus operations
- Implementation of mass transit modes
- Bus rapid transit
- Rail transit.

***Vehicle Technology***

- Increased efficiency of the vehicle fleet
- Use of alternative fuels in public transport operations and adoption within the general vehicle fleet.

## Freight Policy Measures

### *Rail Freight Potential*

Nigeria's railways in the past played a much greater role in the transportation of freight as well as passengers. In the 1960s, 3 Mt of freight and over 11 million passengers were transported, but in past decades the railway infrastructure has fallen into disrepair. It is estimated that 98 percent of freight is now carried by road (FGN 2009). Up until the 1960s, rail carried 60 percent of freight but by 2000, freight carried by rail had fallen to just 300,000 tonnes.

The Nigerian Railway Corporation is currently rehabilitating and renovating rail infrastructure. Nigeria's Vision 20: 2020 sets out to increase the rail network coverage from its current 38 km/10,000 $m^2$ (currently 3,500 kilometers narrow gauge and 50km normal gauge) to 184 km/1,000 $m^2$ by 2020, with priority on linking the major ports to the rail network.

The following statistics provide the basis for modeling the potential impact of increasing the amount of rail freight carried:

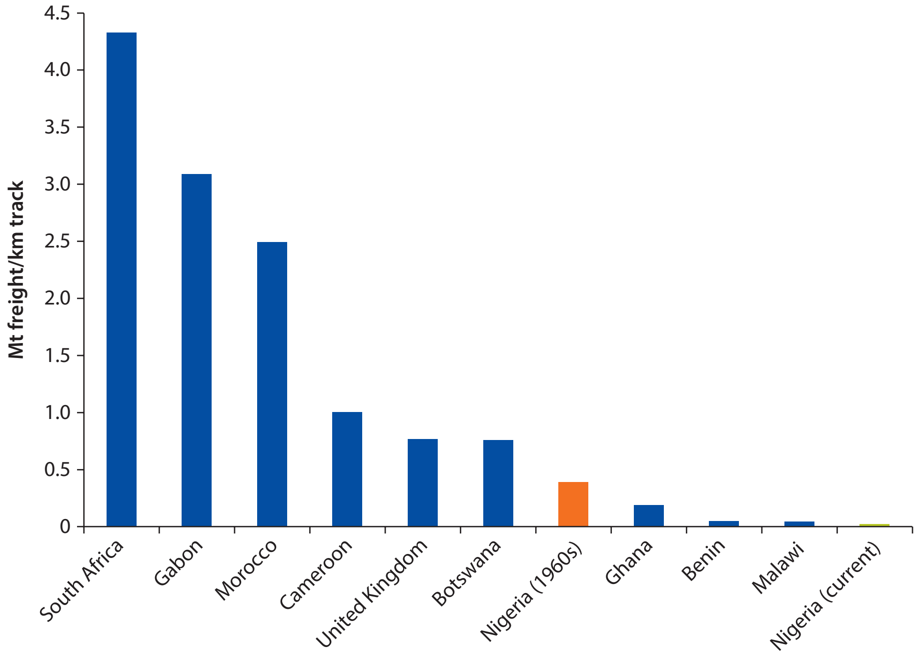
- Road freight vehicle activity: 4,358 million freight vehicle kilometer in 2010 (modeled heavy goods activity)
- Estimate of freight tonnes carried by road: 51,674 Mt km
- Highest freight volume carried by rail in 1977: 2.4 Mt, according to Federal Ministry of Transport
- Freight (kt/km) carried by rail in Nigeria: 77 Mt/km in 2005, from a previous high of 1,400 Mt in the early 1980s, which is as far back as the indicator goes (World Bank Development Indicators)
- Cargo through Nigeria's ports (2011): 82.7 Mt, of which 22 Mt is liquefied natural gas, 21.5 Mt refined petroleum, 13.2 Mt general cargo, and 12.9 Mt dry bulk goods
- Vehicle movements traffic at Nigerian ports for 2011 totaled 231,400 units; only Port Harcourt and Apapa are currently connected to the rail network
- Current rail network length: 3,550 kilometers
- New rail line: 320 kilometers project under way (Ajoakuto to Warri), with a future total network coverage of over 17,000 kilometers targeted in Vision 20: 2020.

Accurate data on road freight tonnage carried is hard to come by. However, straightforward assumptions relating to the potential for transfer of freight to rail can be developed.

The estimates listed suggest that rail freight currently accounts for just 0.1 percent of freight carried, based on the estimate of 77 Mt/km. It is known that this could be increased to at least 1,400 Mt/km, given services operating as they did in the 1960s (2.7 percent). However, even at this level, the intensity of infrastructure usage is relatively low at just 0.39 Mt of freight per km of track, as figure 24.1 shows.

Assuming an improved intensity of usage to around the level of Botswana (0.76 Mt/km) would facilitate the carrying of 2,700 Mt/km, or 5.2 percent. If the rail network expansion outlined in Vision 20: 2020 and the 25-year strategic rail plan are implemented, the growth in the network would facilitate potentially freight movement totaling 13 Mt/km (based on equivalent intensity of network use).

**Figure 24.1 Annual Freight Mt per km of Rail Track**




*Source:* World Bank Development Indicators.

The study team modeled a rail freight scenario that increases the share of freight carried by rail based on the following assumptions:

- Rehabilitation of the network achieved by 2015, with (freight efficiency benefits starting from this point)
- Linear growth in network length to achieve the target network expansion by 2030 (over 20 years rather than the 10 year horizon of Vision 20: 2020)
- Transfer of goods to freight applied from heavy goods vehicle class.

The impact of the move to rail-based freight in terms of reduction in road vehicle emissions is shown in figure 24.2.

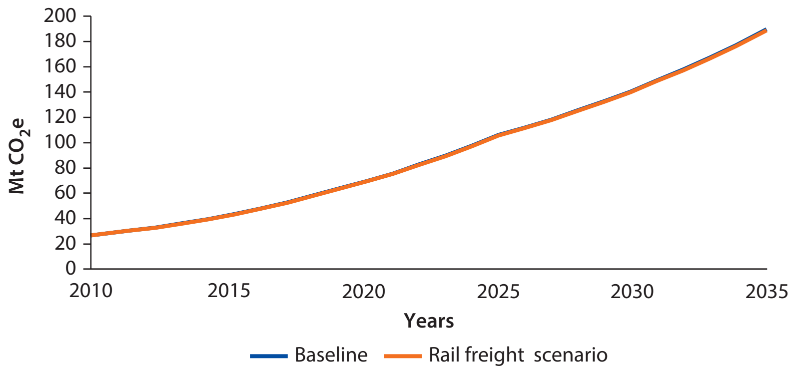
By 2020, increased intensity of usage of the existing rail network for freight carriage, with further rail network expansion could potentially reduce forecast heavy goods vehicle kms by almost 5%, as shown in table 24.1. However, by 2035, with the scale of growth in freight movement, the abstraction to rail falls to 3.7%, as expansion of the rail network cannot keep pace with growth in freight demand.

In terms of overall emissions reduction, the impacts of freight modal shift to rail are small, amounting to a cumulative 10 Mt $CO_2$e by 2035, as summarized in table 24.2.

The scale of $CO_2$ reduction over the 25-year horizon is *9.9 Mt of* $CO_2$.

Of course, transporting goods by rail does not eliminate emissions. The majority of the Nigerian rail network will remain nonelectrified over the medium term.

**Figure 24.2 Rail Freight Scenario Results**




*Source:* Modeled based on data sources listed in chapter 20 and previous model assumptions.

**Table 24.1 Rail Freight Scenario: Change in Model Statistics**

| *Rail freight scenario* | | *2010* | *2020* | *2030* | *2035* |
|---|---|---|---|---|---|
| Heavy goods km | Before | 4,357.98 | 25,792.32 | 60,542.04 | 82,440.29 |
| (annual km, millions) | After | 4,357.98 | 24,543.50 | 57,526.83 | 79,403.23 |
| | % change | 0% | –4.84% | –4.98% | –3.68% |
| Heavy goods emissions | Before | 3.45 | 18.03 | 40.94 | 55.67 |
| (Mt $CO_2$ e) | After | 3.45 | 17.16 | 38.90 | 53.62 |
| | % change | 0% | –4.84% | –4.98% | –3.68% |

*Source:* Modeled based on data sources listed in chapter 20 and previous model assumptions.

**Table 24.2 Rail Freight Scenario: Impact on $CO_2$ Emissions**

| *Annual emissions (Mt $CO_2$e)* | *2010* | *2020* | *2030* | *2035* |
|---|---|---|---|---|
| Annual $CO_2$ emissions: baseline | 27.64 | 69.32 | 140.02 | 187.39 |
| Annual $CO_2$ emissions: rail freight scenario | 27.64 | 69.08 | 139.60 | 186.58 |
| Emissions savings | 0 | −0.24 | −0.42 | −0.817 |
| Cumulative savings | 0 | −2.15 | −6.20 | −9.86 |

*Source:* Modeled based on data sources listed in chapter 20 and previous model assumptions.

The UK Strategic Rail Authority used 20 grams $CO_2$ per tonne per kilometer of freight carried by rail, which compares to a typical 70 grams carbon per tonne per kilometer for a modern lorry. Allowing for the greater level of electrification of the UK network, it can be safely assumed that at least half of the emissions savings shown in table 24.2 would represent global savings through greater efficiency of travel.

## Improved Freight Road Transport Management

The rail scenario highlights the limitations of a move to rail-based freight transportation, given the constraints of the network set against the scale of growth in freight movements.

However, while the great majority of freight is likely to be carried by road over the projected period, measures are recommended to ensure that the growth in the freight is carried in the most efficient way so as to minimize emissions generated from road haulage. Improving the organization and management of the logistics sector can bring savings by the following actions:

- Reconfiguration of logistics networks to reduce heavy goods miles traveled
- Improved scheduling and efficient deployment of freight fleets, matching capacities on routes to demand levels
- Reduced "empty running" through careful route planning.

Trials and national schemes that target realization of these efficiency savings have demonstrated potential reductions in heavy goods vehicle km traveled and vehicle emissions. Examples include Volvo Group, which achieved 22 percent efficiency savings through more efficient use of cargo capacity, larger vehicles, and through driver training (considered below) and Tesco, whose target is to reduce the carbon emissions of each case of goods delivered by 50 percent through reducing empty running, use of larger vehicles, and alternative fueled vehicles for local deliveries.

The improved freight transport management scenario considered in this book focuses on achieving emissions reductions through the rationalization of the currently inefficient logistics network, and best practice measures leading to the improved management of the movement of goods.

The logistic efficiency improvements which could be achieved through better management were applied to the levels of activity as follows:

- Reduction in small and medium freight vehicle activity levels from 2012, achieving a reduction of 20 percent compared to baseline levels by 2020
- Reduction in heavy freight vehicle km from 2012, increasing to 10 percent reduction by 2020. The lower level of reduction reflects the move from smaller to larger freight movements, which form a central part of the move to more efficient freight management.

The impact of the freight efficiency improvements are shown in figure 24.3.

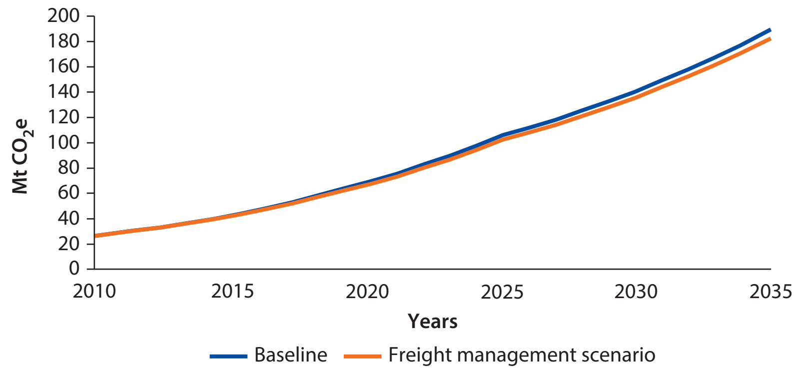
The impact of efficiency improvements ramps up from 2012 to achieve annual savings of over 3.1 percent of overall $CO_2$ emissions by 2020, the year of full efficiency gains.

Cumulative emissions savings over the forecast period amount to *73.3 Mt* $CO_2$ by 2035, as shown in table 24.3, demonstrating the sizable savings that can be achieved through measures aimed at improving the efficiency of the rapidly growing freight sector.

### *Driver Training for Freight Market*

The driving characteristics of truck drivers have a strong influence on engine intensity and hence fuel consumption. Training programs that teach drivers about

**Figure 24.3 Road Freight Efficiency Improvement Scenario Results**




*Source:* Modeled based on estimated efficiency gains and freight vehicle activity levels calculated previously.

**Table 24.3 Road Freight Efficiency Improvement Scenario: Impact on $CO_2$ Emissions**

| *Annual emissions (Mt $CO_2$e)* | *2010* | *2020* | *2030* | *2035* |
|---|---|---|---|---|
| Annual $CO_2$ emissions: baseline | 27.64 | 69.329 | 140.02 | 187.39 |
| Annual $CO_2$ emissions: road freight efficiency scenario | 27.64 | 67.18 | 135.16 | 180.77 |
| Emissions savings | 0 | –2.140 | –4.87 | –6.62 |
| Cumulative savings | 0 | –7.303 | –43.74 | –73.31 |

*Source:* Modeled based on data sources listed in chapter 20 and previous model assumptions.

the impact they have on vehicle wear and tear and operating costs were shown to reap rewards during many pilot studies undertaken in the African region. Through less intensive acceleration and braking and maintaining a constant efficient speed, reductions in fuel consumption of 20 percent or more are typically reported from the training programs. With this scale of potential improvement, enhanced driver training for even a small portion of the goods vehicle drivers can reap strong rewards in term of $CO_2$ reduction, improved commercial performance, as well as safety. The study team developed a scenario based on the following assumptions:

- Training program covering 20 percent of heavy goods drivers in 2012 (representing 30,000 drivers)
- 20 percent improvement in fuel consumption levels for those drivers/vehicles following training
- Repeat training every five years for a similar proportion of drivers.

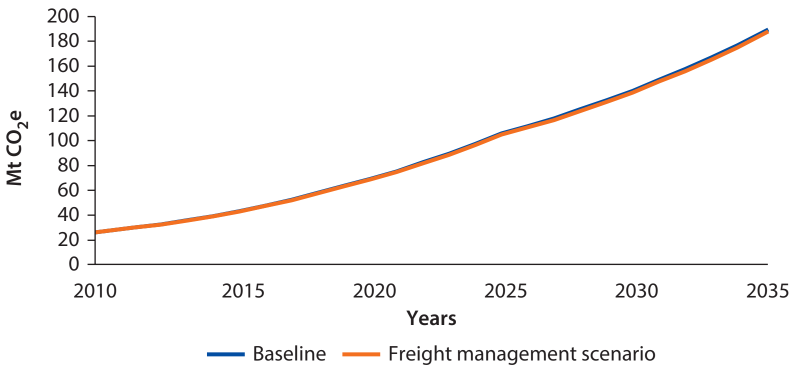
The training of a proportion of freight drivers results in a reduction in fuel consumption of an average of 4 percent across the heavy goods fleet in the training years (2012, then every five years), with a commensurate impact on emissions. The scale of benefits are diluted as the freight fleet grows in the intermediate years between training sessions, but are recaptured following further training exercises. The impact of the measure on annual modeled statistics are presented in figure 24.4 and table 24.4.

Freight growth in the first decade of the projected period is faster, leading to a quicker trailing off of the benefits of the scheme in percentage terms than in later years.

The impact of increasing driver training on overall road sector carbon emissions is shown in table 24.5.

The impacts of the training program are positive, although again relatively small scale. The impacts amount to a reduction in overall $CO_2$ emissions levels of up to 3.3 percent, tailing off over the 5 years between training programmers. The overall impact over the projected period is *9.856 Mt of* $CO_2$ saved.

**Figure 24.4 HGV Driver Training Scenario**




*Source:* Modeled based on data sources listed in chapter 20 and previous model assumptions.

**Table 24.4 Freight Driver Training Scenario: Change in Model Statistics**

| *Driver training scenario* | | *2010* | *2020* | *2030* | *2035* |
|---|---|---|---|---|---|
| Heavy goods fuel consumed | Before | 1,099.26 | 5,745.81 | 1,3048.46 | 17,742.16 |
| (Diesel, liters, millions) | After | 1,099.00 | 6.60 | 12,621.00 | 17,154.00 |
| | % change | 0 | −2.5 | −3.3 | −3.3 |
| Heavy goods emissions | Before | 3.449 | 18.028 | 40.941 | 55.668 |
| (Mt $CO_2$e) | After | 3.449 | 17.570 | 39.601 | 53.823 |
| | % change | 0 | −2.5 | −3.3 | −3.3 |

*Source:* Modeled based on data sources listed in chapter 20 and previous model assumptions.

**Table 24.5 Freight Driver Training Scenario: Impact on $CO_2$ Emissions**

| *Annual emissions (Mt $CO_2$e)* | *2010* | *2020* | *2030* | *2035* |
|---|---|---|---|---|
| Annual $CO_2$ emissions: baseline | 27.64 | 69.329 | 140.02 | 187.39 |
| Annual $CO_2$ emissions: driver training scenario | 27.64 | 69.08 | 139.60 | 186.58 |
| Emissions savings | 0 | −0.24 | −0.42 | −0.81 |
| Cumulative savings | 0 | −2.15 | −6.20 | −9.86 |

*Source:* Modeled based on data sources listed in chapter 20 and previous model assumptions.

## Public Transport Policy Measures

A significant share of the commercial vehicle activity forecast over the projected period is attributable to public transport activity offered by the paratransit minibus vehicles. Typically carrying 8–18 passengers, these vehicles carry almost 90 percent of person trips in the major cities. Despite this impressive claim, these public transport vehicles are observed to cause significant disruption to other road users due to undisciplined stopping behavior, with boarding and alighting of passengers often taking place in the main carriageway. The network is typically arranged to the benefit of the operator rather than the traveler, with multiple interchanges required and short distance routes to maximize fare revenues and avoid congestion.

### *Large Bus Operations*

Migration to an organized and regulated public transport network was shown to offer significant advantages both in term so passenger experience and in travel efficiency. Given the scale of demand observed in the major cities, large bus operations can be used to carry travelers more efficiently along high demand corridors, reducing the number of vehicles in operation and improving traffic conditions for all road users.

The potential impact on road sector emissions impact can be summarized as follows:

- Reduction in the number of bus vehicles required to carry the observed demand along the corridor due to larger capacity vehicles. This would lead to a reduction in the number of public transit vehicle km operated.
- Replacement of old inefficient public transport vehicles with fewer new, more modern bus vehicles with improved emissions levels
- Improvement in traffic conditions due to a reduced number of total vehicles on the route, leading to less congestion and improved fuel economy.

Modeling the impact of a migration to large bus operations was driven by the following information:

- Lagos vehicle fleet estimated to be 75,000 vehicles, of which about 1,000 are *molue* (larger buses). The Lagos public transit vehicle population therefore represents 16 percent of total base year minibus vehicles numbers.
- Danfo and molue vehicles are modeled to travel 30,000 kilometers per year.
- Eighty-three percent of modeled "light goods" classified vehicles are minibus vehicles (based on vehicle registration data).
- Average occupancy of paratransit assumed to be 12 passengers
- Average large vehicle occupancy assumed to be 60 passengers (capacity 100).

In the scenario, the impact of the policy was focused on the city of Lagos initially, before extrapolating the observed benefits to other major cities in Nigeria that would benefit from organized transport.

Lagos has over 600 bus routes currently operating between a multitude of terminals and motor parks. Not all of these routes are appropriate for large bus operations. Routes exhibiting sizeable demand levels are most suited to support large bus operations. However, these routes are the routes that most vehicles ply for trade presently.

The study's estimate is that at least 60 percent of the existing paratransit vehicles currently ply the major routes (expressways and highways) that exhibit the greatest numbers of travelers. These major routes may be considered suitable for large bus operations.

Taking a conservative assumption of 50 percent abstraction from existing danfo operations, the introduction of large vehicle operations could potentially lead to the replacement of 30 percent of Lagos's paratransit activity (representing almost 5 percent of modeled light goods vehicle activity globally, with just one-fifth the number of large bus vehicles.

Large bus operations can be effectively rolled out in other cities that exhibit sufficient levels of demand on main corridors (typically 2,000+ passengers per hour per direction) and where the regulatory capacity to effectively control operations exists. For the purposes of this scenario, Nigeria's principal cities were considered: those having more than 800,000 inhabitants—equivalent to a half million in the 1991 census (City Population 2013). Table 24.6 shows how the 10 largest cities after Lagos compare to the Lagos in terms of population size.

On the assumption that large bus operations can provide a similar level of amenity along the major corridors in other cities (60 percent replacement of paratransit), global light goods vehicle activity would see a reduction of 8.2 percent.

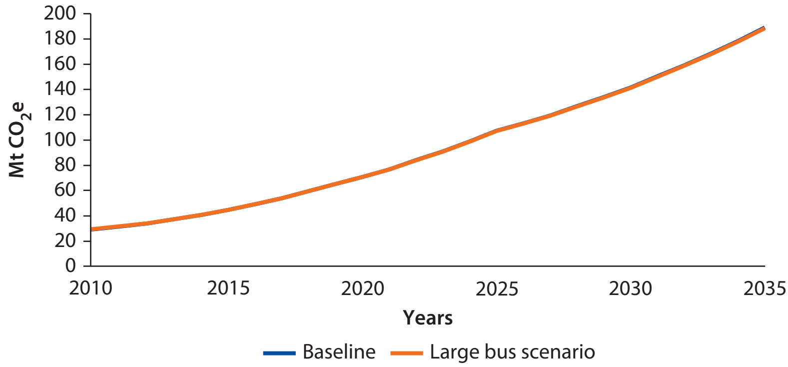
In terms of impact on emissions, the carbon savings that could be expected from the placement of paratransit vehicle activity with large buses, assuming implementation in 2015, are presented in figure 24.5. It is important to note however that the implementation of a regulated public transport system would require complementary regulation to ensure that scrappage of older vehicles ensures that paratransit vehicle numbers are reduced accordingly, rather than continuing operation.

**Table 24.6 Population of Nigeria's Principal Cities**

| | *City (State)* | *Population* | *% of Lagos population* |
|---|---|---|---|
| 1 | Lagos(Lagos) | 9,000,000 | |
| 2 | Kano(Kano) | 3,626,068 | 40 |
| 3 | Ibadan(Oyo) | 3,565,108 | 40 |
| 4 | Kaduna(Kaduna) | 1,582,102 | 18 |
| 5 | Port Harcourt(Rivers) | 1,148,665 | 13 |
| 6 | Benin City(Edo) | 1,125,058 | 13 |
| 7 | Maiduguri(Borno) | 1,112,449 | 12 |
| 8 | Zaria(Kaduna) | 975,153 | 11 |
| 9 | Aba(Abia) | 897,560 | 10 |
| 10 | Jos(Plateau) | 816,824 | 9 |
| 11 | Ilorin(Kwara) | 814,192 | 9 |

*Source:* Geonames.org: http://www.geonames.org/NG/largest-cities-in-nigeria.html.

**Figure 24.5 Large Bus Operation Scenario**




*Source:* Modeled based on data sources listed in chapter 20 and previous model assumptions.

**Table 24.7 Large Bus Scenario: Impact on $CO_2$ Emissions**

| *Annual emissions (Mt $CO_2e$)* | *2010* | *2020* | *2030* | *2035* |
|---|---|---|---|---|
| Annual $CO_2$ emissions: baseline | 27.64 | 69.33 | 140.02 | 187.39 |
| Annual $CO_2$ emissions: large bus scenario | 27.64 | 68.99 | 139.40 | 186.56 |
| Emissions savings | 0 | –0.33 | –0.62 | –0.82 |
| Cumulative savings | 0 | –2.14 | –6.96 | –10.65 |

*Source:* Modeled based on data sources listed in chapter 20 and previous model assumptions.

Table 24.7 summarizes the impact of the large bus operation scenario on global vehicle emissions.

The reduction in global carbon emissions attributable to the introduction of large bus operations in the major cities of Nigeria leads to a reduction in global emissions levels of 0.4 percent to 0.5 percent per year. Over the projected period, these carbon savings amount to 10.6 *Mt of* $CO_2$.

### *Bus Rapid Transit*

Bus rapid transit (BRT) brings the ability to transport large numbers of people more quickly and reliably, through the delivery of a bus based system which operates in its own segregated infrastructure.

In addition to the benefits of large bus operations highlighted above, BRT operations typically offers the following benefits.

Large bus vehicles are able to carry a greater number of people more efficiently. The BRT corridors are typically regulated to avoid duplication of services and direct competition. Therefore, BRT can replace existing public transport routes, removing a much greater number of public transport vehicle km from the corridor due to the larger bus vehicles.

Priority infrastructure, which typically supports the BRT operations, would reduce public transport (BRT) run times, allowing a greater number of round trips to be made in a given period, hence further enhancing the efficiency of the system (less bus vehicles required to carry a given number of people). Improved reliability also brings smoother driving patterns, thus reducing emissions.

The replacement of the existing paratransit vehicles leads to a reduced number of vehicles on the corridor which is likely to bring benefits to other road users. These benefits can be experienced despite the new BRT infrastructure, which reallocates road space to BRT from other road users. This is because the loss of road space is offset by the reduction in public transport vehicles, and the improvements to junctions and to running conditions on the remaining road space lead to a better managed environment. Correcting driving behavior, which is the cause of much of the existing congestion, improves traffic flow and can have a positive impact on congestion.

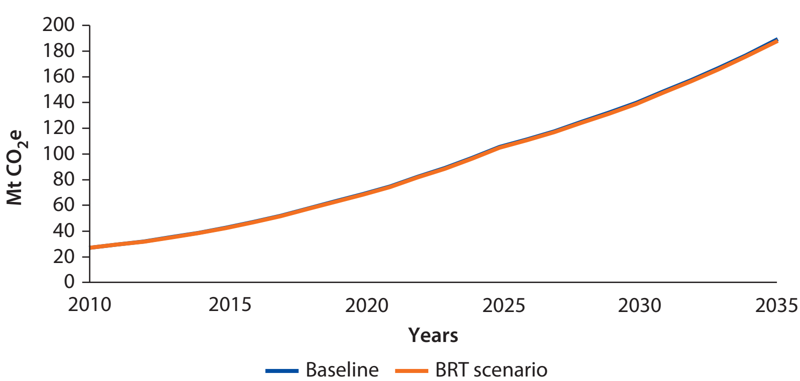
BRT is typically successfully implemented on corridors exhibiting at passenger movements of over 6,000 per hour per direction. Lagos has successfully implemented a BRT route on a key corridor from the mainland onto the island. The 22-kilometer route currently carries approaching 200,000 passengers a day. Further routes were planned on two major routes within the city, in addition to two light rail lines.

The extent of implementation of mass transit is constrained by the number of corridors that exhibit the conditions conducive to the scale of investment required. The scale of travel demand in Lagos necessitates a mass transit network in order to meet the demand for travel. The smaller cities may have a limited number of corridors that could be considered appropriate for mass transit. A conservative estimate of 20 percent of trips carried by mass transit in the principal cities was adopted for the purposes of this evaluation.

BRT brings efficiency enhancements due to priority infrastructure which allows a greater number of round trips to be made with by each vehicle.

Based on a target assumption of 30 percent of public transport trips to be made by mass transit, and an abstraction rate of 75 percent of danfo trips, at a global scale, a reduction of 10.3 percent of light goods vehicle activity is forecast, with an associated increase in large bus vehicle activity of 1.3 percent. The reductions in emissions levels are shown in figure 24.6 and table 24.8.

**Figure 24.6 Bus Rapid Transit Scenario**



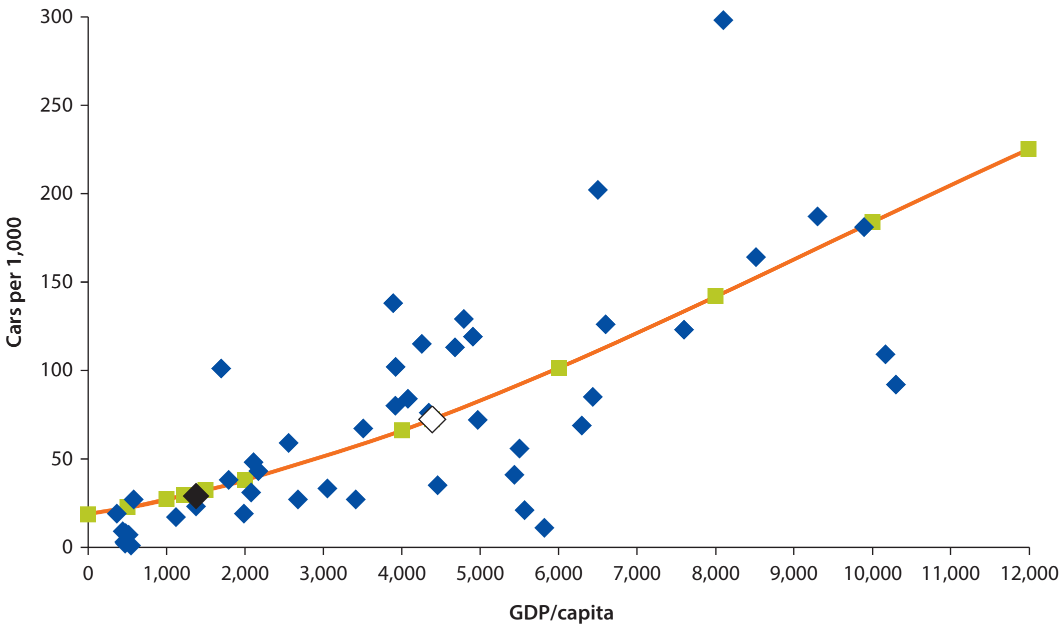

*Source:* Modeled based on data sources listed in chapter 20 and previous model assumptions.

**Table 24.8 Bus Rapid Transit Scenario: Impact on $CO_2$ Emissions**

| *Annual emissions (Mt $CO_2e$)* | *2010* | *2020* | *2030* | *2035* |
|---|---|---|---|---|
| Annual $CO_2$ emissions: baseline | 27.64 | 69.33 | 140.02 | 187.39 |
| Annual $CO_2$ emissions: BRT scenario | 27.64 | 68.89 | 139.20 | 186.29 |
| Emissions savings | 0 | −0.43 | −0.82 | −1.10 |
| Cumulative savings | 0 | −2.83 | −9.22 | −14.12 |

*Source:* Modeled based on data sources listed in chapter 20 and previous model assumptions.

**Figure 24.7 Car Ownership vs. Income in Various Countries: Nigeria in 2010 (black) and 2035 (white)**




*Source:* World Bank Development Indicators (GDP/Capita, Passenger Cars per 1,000 population).

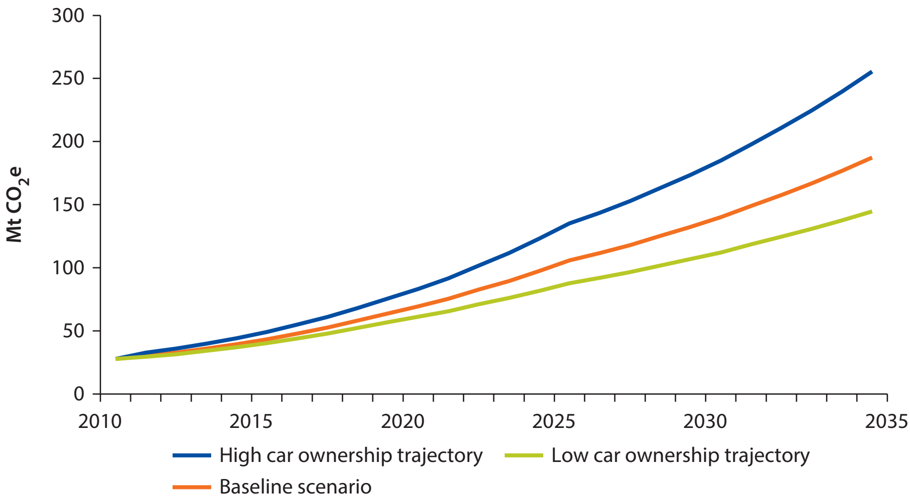
Global emissions levels decrease between 0.7 and 1.1 percent over the projected period, resulting in an overall reduction in carbon emissions *of* 14.1 *Mt* $CO_2e$ over the forecast period.

### *Automobile Ownership Levels*

Figure 4.4 in chapter 4 develops the relationship between per capita income levels and automobile ownership. Income has a major bearing on bringing car ownership within reach of greater numbers of the population. However, there are also other factors at play, as evidenced by the range of different car ownership levels observed at similar levels of income in countries around the world.

A closer look at the variation in car ownership levels around the projected level of real income in Nigeria by 2035 shows that at the $4–5,000 GDP/capita level, car ownership varies from 35 to 130 vehicles per 1,000 people, as shown in figure 24.7. At 72 cars/1,000, Nigeria's projected car ownership level by 2035 lies broadly in the middle of this range.

**Figure 24.8 Effect of Low and High Car Ownership Trajectories on GHG Emissions**




*Source:* Modeled emissions based on different car ownership trajectories taken from World Development Indicators (World Bank 2011).

However the implications of taking a different path in terms of car ownership on overall vehicle emissions would be significant. Figure 24.8 shows the scale of impact that following alternative car ownership growth paths may have on emissions. Government policy decisions can significantly increase or decrease car ownership levels over a range of approximately 35–130 vehicles/1,000 population at Nigeria's expected level of per capita GDP.

The impact of emissions levels by 2035 between the low and the high projected trajectories amounts to more than a 75 percent increase from low to high car ownership growth, from 144.6 million metric tonnes to 255.4 million metric tonnes of $CO_2$ emitted annually.

Policies that do not promote the growth in car ownership can therefore have a major impact on the evolution in emissions levels going forwards. For example, subsidized gasoline and allowing the import of secondhand—lower cost—vehicles, together with a shortage of adequate public transport, can drastically increase the ownership rates; while high vehicle tariffs, coupled with a quality public transport service in urban settings, and compact, urban land use planning allow private vehicle ownership and use to be considerably lower.

A combination of the following measures should be considered by policy makers:

- High vehicle duties to keep vehicle ownership costs high
- High-quality public transport in urban settings to ensure that alternatives to private car ownership are available and convenient

- Effective vehicle inspection and licensing to ensure that un-roadworthy vehicles are not able to remain in use, reducing fleet size
- Sustainable development and land use planning to ensure that new development is accessible without the need for private transport.

### *Move to More Fuel Efficient Vehicles*

Although Euro II standards have recently been introduced for vehicles purchased in and imported to Nigeria, the majority of the vehicle fleet does not conform to these standards currently. In addition to low levels of technology in terms of the emitting of local air pollutants, vehicle efficiency in terms of fuel consumption is well behind the levels observed in Europe which are driven by carbon emissions targets. These targets are as follows:

- By 2015 average 130 g $CO_2$/km across fleet of new vehicle sales by manufacturer
- From 2012 emissions standards tightening, with 65 percent of fleet to meet above target, increasing to 75 percent in 2013 and 80 percent in 2014
- Target of 95 g $CO_2$/km average across all vehicles sold by 2020.

Beyond the planned implementation of the Euro Emissions Standards, Nigeria has no stated $CO_2$ emissions standards for cars. The current average emissions level across the Nigerian private car fleet is estimated to be 214 g $CO_2$/km. This is clearly far behind the standards being adopted in Europe.

However, implementing such regulation on Nigerian vehicle $CO_2$ emissions levels policy would have the potential to significantly alter the composition of the future vehicle fleet in terms of fuel consumption and emissions levels. Applying regulation in line with European emissions target levels with a lag of 15 years (as with the first two Euro emissions standards) would mean that new and imported vehicles should on average emit only 130 g/km by 2030.

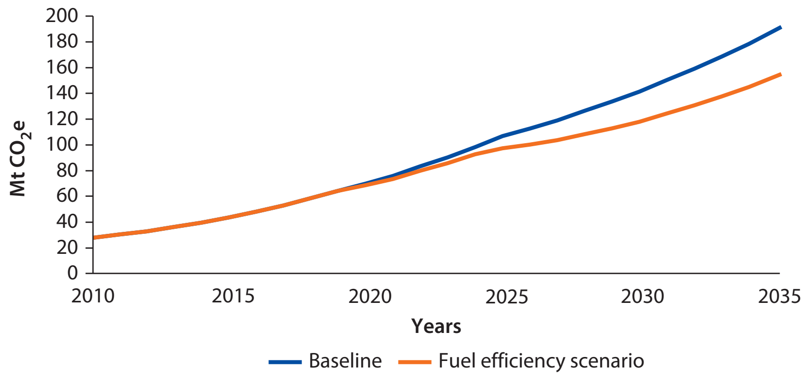
Based on the scale of expansion and new additions to the vehicle fleet, this could lead to average emissions levels for private cars being reduced to approximately 137 g/km by 2035 (figure 24.9 and table 24.9).

The abatement of total emissions from road transport increases over time as vehicles meeting the new emissions regulations are imported, with more efficient vehicles feeding into the fleet from 2020. The savings grow to 36 Mt annually by 2035 with a total reduction in carbon emissions over the forecast period of 269 *Mt* $CO_2e$.

### *Use of Natural Gas as an Automotive Fuel*

As a country, Nigeria is rich in natural gas, a by-product of the oil extraction process. Use of this gas to power transportation in the form of compressed natural gas (CNG) is in its infancy in Nigeria, although widespread worldwide in many other countries.

**Figure 24.9 Fuel Efficient Vehicle Regulations**




*Source:* Modeled based on data sources listed in chapter 20 and previous model assumptions.

**Table 24.9 Fuel Efficient Scenario: Impact on $CO_2$ Emissions**

| *Annual emissions (Mt $CO_2$e)* | *2010* | *2020* | *2030* | *2035* |
|---|---|---|---|---|
| Annual $CO_2$ emissions: baseline | 27.64 | 69.33 | 140.02 | 187.39 |
| Annual $CO_2$ emissions: fuel efficient scenario | 27.64 | 68.08 | 116.88 | 151.48 |
| Emissions savings | 0 | –1.24 | –23.14 | –35.91 |
| Cumulative savings | 0 | –1.24 | –115.73 | –269.37 |

*Source:* Modeled based on data sources listed in chapter 20 and previous model assumptions.

A trial commenced in 2010 in Edo State, promoted by the Nigerian Independent Petroleum Company (NIPCO) in partnership with Nigeria Gas Company (NGC), and now has 6 fueling stations and a further 2 under construction (2012) serving the state's large buses. These buses have successfully been converted to CNG, in addition to a fleet of 250 taxis and around 500 of the oil companies' own vehicles.

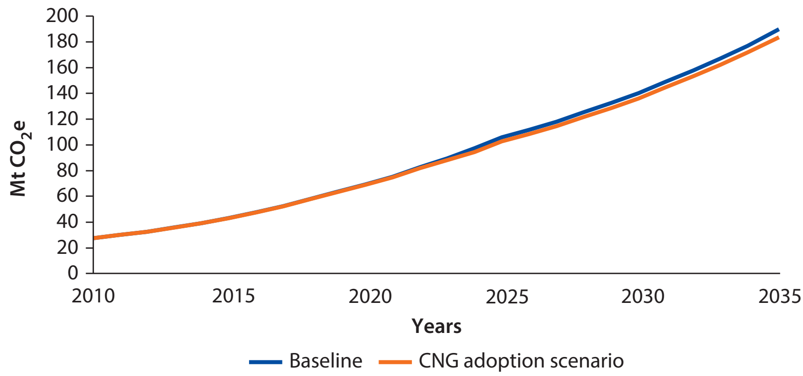
Nigeria's gas reserves and the rapid progression in technology allowing vehicles to operate efficiently and cost-effectively on CNG presents a significant opportunity in lowering the emissions from Nigeria's vehicle fleet. NIPCO aims to roll out the concept and ultimately make CNG available at 5,000 stations across the country.

Countries leading the way in this use of CNG include Pakistan, which currently has around 3,300 CNG fuelling stations countrywide and a natural gas powered vehicle fleet of over 2.8 million.

To illustrate the potential that a move to natural gas powered vehicles may have on road sector emissions, the study developed the following scenario:

- Successful roll out of CNG to all of the new large bus vehicles introduced in the mass transit scenarios set out previously (existing bus vehicles remaining on standard technology) and adoption by 50 percent of the national taxi fleet and 15 percent of other private vehicles

**Figure 24.10 Move to an Alternative Fuel Scenario**




*Source:* Modeled based on data sources listed in chapter 20 and previous model assumptions.

**Table 24.10 Alternative Fuel (CNG) Scenario: Impact on $CO_2$ Emissions**

| *Annual emissions (Mt $CO_2e$)* | *2010* | *2020* | *2030* | *2035* |
|---|---|---|---|---|
| Annual $CO_2$ emissions: baseline | 27.64 | 58.62 | 113.48 | 150.93 |
| Annual $CO_2$ emissions: CNG scenario | 27.64 | 68.94 | 135.93 | 181.96 |
| Emissions savings | 0 | –0.38 | –4.09 | –5.43 |
| Cumulative savings | 0 | –1.54 | –28.80 | –53.09 |

*Source:* Modeled based on data sources listed in chapter 20 and previous model assumptions.

- Phased introduction, which started in 2012, with an exponential increase in take-up until the target is reached in 2025.

The impact of the scheme on emission is represented in figure 24.10 and table 24.10.

Of the various scenarios the study team identified, the alternative fuel scenario is demonstrated to be able to achieve a sizeable reduction in emission levels as shown in table 24.10 (shown net of the impact of the move to mass transit).

The reduction in global road transport emissions increases from 0.2 percent to 3.0 percent by 2035 with a total reduction in carbon emissions over the forecast period of *53 Mt* $CO_2$*e*.

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CHAPTER 25

# Summary and Conclusions

The different chapters of this book presented an estimate of the current level of on-road vehicle emissions in Nigeria, and how emissions are likely to grow over time, driven by an increasing population and economic development.

The relative importance of individual drivers to the forecast emissions growth was investigated to identify areas in which targeted intervention measures may be effective in constraining emissions growth, followed by the testing of a number of scenarios to quantify the potential scale of impact that these measures may have.

This chapter provides a summary of the main findings of the analysis undertaken by the study team, with implications of the study findings examined within the conclusions.

## Current Vehicle Emissions Levels

The scale of current vehicle emissions emitted by the road sector in Nigeria is estimated to be *27.6 Mt* $CO_2$*e at 2010 activity levels*. Private vehicles account for the majority of these emissions.

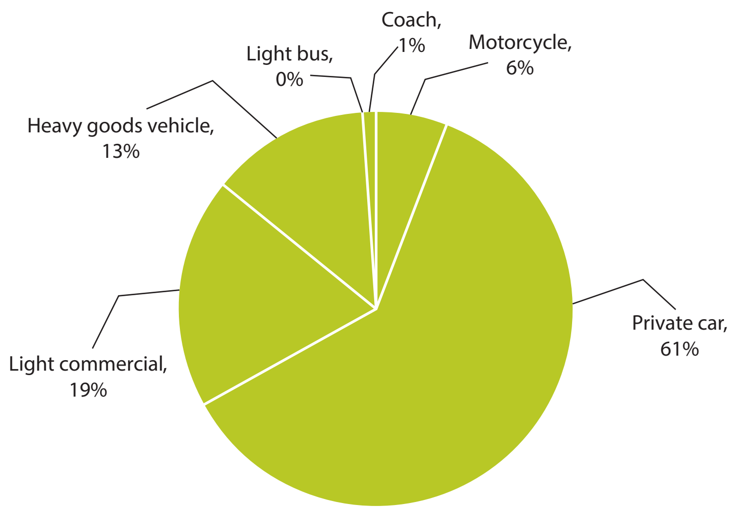
## Emissions Growth under Business as Usual Scenario

The study projected emissions levels were projected over a 25 year time horizon by considering the key factors that will impact on motorization levels and ultimately on $CO_2$ emitted by vehicles in Nigeria, as shown in figure 25.1.

Two main drivers were identified: growth in population and increasing national wealth. The combination of these factors points to an explosion in private vehicle numbers and activity, as well as an ever increasing demand for the transport of freight. As a result, emissions levels are projected to increase exponentially over the forecast period, rising by 680 percent over the 25 year period, to reach *187 Mt* $CO_2$ *emitted annually by 2035*, as shown in figure 25.2.

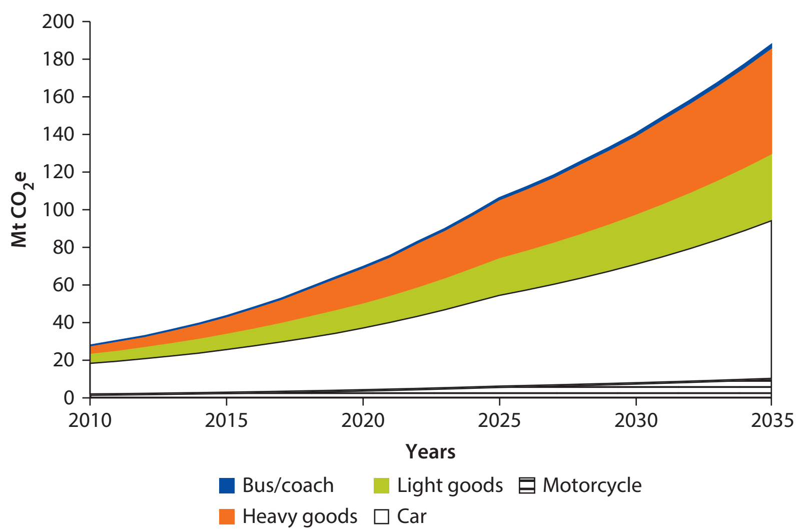
As figure 25.2 shows, the reference scenario sets out a bleak prediction on the pressure that demographic and economic growth will place on GHG emissions for Nigeria.

**Figure 25.1 Relative Proportion of Emissions by Vehicle Type, 2010**




*Source:* World Bank commissioned survey, 2012, based on State Licensing Authority vehicle registration data (SLA 2005).

**Figure 25.2 $CO_2$ Emissions over Forecast Period in the Reference Scenario**




*Source:* Modeled emissions based on vehicle fleet estimates and emissions factors from EFFECT model.

## Mitigation Measures

The following measures were identified and tested as a means of mitigating against the growth in $CO_2$ levels to support a low-carbon future for Nigeria.

- Transfer of freight movements from road to rail
- Freight efficiency gains through better management including rationalizing the freight network, moving to larger vehicles, and reducing unladen movements.

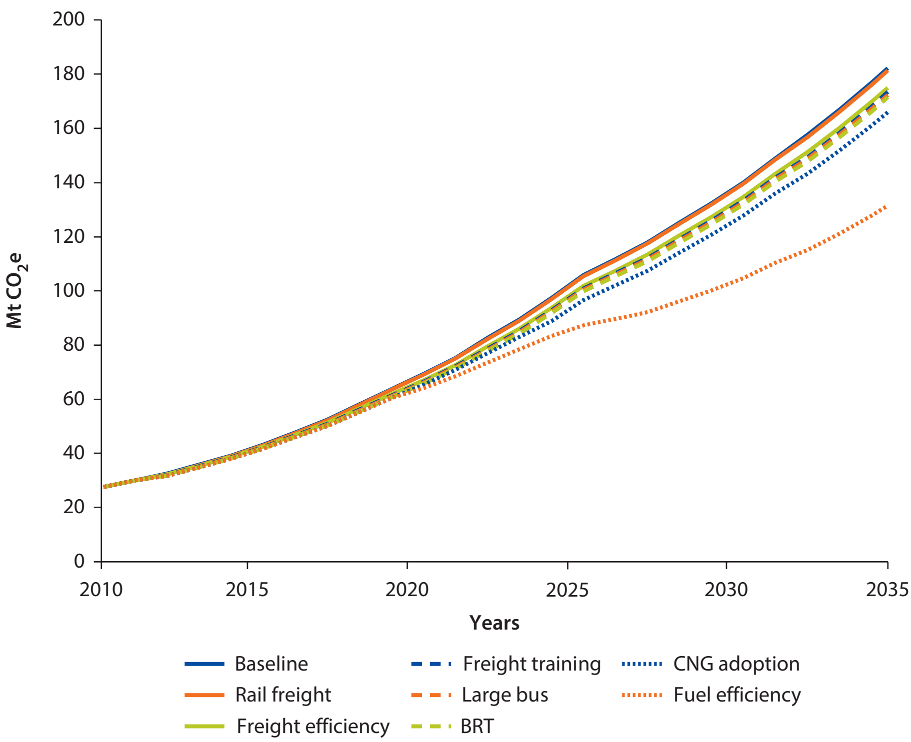
- Fuel efficiency gains to freight movements through driver training.
- Migration from paratransit to organized public transport delivered by large bus operations
- A move to mass-transit within the major urban areas
- Adoption of alternative fuel technologies, with a move to use of compressed natural gas (CNG) taking advantage of Nigeria's natural gas resources
- Introducing vehicle emissions regulations to new and imported vehicles, following the targets adopted in the Euro area.

Figure 25.3 and table 25.1 present the results of the various transport scenario tests.

In total, the combination of mitigation measures recommended by the study can achieve a reduction in emissions increasing from 0.88 Mt per year in 2012 to over 50 Mt in 2035. In total, this amounts to a reduction of 452 Mt of carbon over the 25-year projected period.

The major emissions savings would be achieved through vehicular emissions regulations, followed by freight efficiency improvements and CNG adoption.

**Figure 25.3 Impact of Mitigation Measures on $CO_2$ Emissions Levels**




*Source:* Modeled emissions based on vehicle fleet estimates and emissions factors from EFFECT model.

**Table 25.1 Summary of Emissions Savings Achievable under Mitigation Scenarios Mt $CO_2e$**

| *Annual emissions (Mt $CO_2e$)* | *2010* | *2012* | *2020* | *2030* | *2035* |
|---|---|---|---|---|---|
| Baseline | 27.636 | 32.629 | 69.319 | 140.024 | 187.388 |
| Rail freight | 27.636 | 32.391 | 69.080 | 139.600 | 186.581 |
| Freight efficiency | 27.636 | 32.337 | 66.940 | 134.732 | 179.961 |
| Driver training | 27.636 | 32.146 | 66.482 | 133.392 | 178.116 |
| Large bus | 27.636 | 32.004 | 66.154 | 132.772 | 177.291 |
| BRT | 27.636 | 31.814 | 65.721 | 131.949 | 176.196 |
| CNG | 27.636 | 31.750 | 65.345 | 127.856 | 170.764 |
| Efficiency regulations | 27.636 | 31.750 | 64.109 | 104.713 | 134.859 |
| Total reduction | 0 | –0.880 | –5.210 | –35.312 | –52.529 |
| Cumulative reduction | 0 | –0.880 | –19.975 | –223.739 | –452.195 |

*Source:* Modeled emissions based on vehicle fleet estimates and emissions factors from EFFECT model.

While the modeled savings represent a significant reduction in absolute terms, they are not as sizeable in relative terms, which points to the need for further work on opportunities for a lower-carbon development of Nigeria's road transport sector.

It remains clear that the growth in carbon emissions from the road transport sector will feature increasingly as a major contributor to Nigeria's overall greenhouse gas emissions, and it will remain an area of significant challenge if Nigeria is to move toward a low-carbon future.

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green press INITIATIVE

*Assessing Low-Carbon Development in Nigeria: An Analysis of Four Sectors* is part of the World Bank Studies series. These papers are published to communicate the results of the Bank's ongoing research and to stimulate public discussion.

The Federal Government of Nigeria has adopted Vision 20: 2020—an ambitious strategy to make Nigeria the world's 20th largest economy by 2020. In the absence of policies to accompany economic growth in key carbon-emitting sectors with a reduced carbon footprint, emission of greenhouse gases could more than double in the next two decades.

To evaluate how to achieve the objectives of Vision 20: 2020 with reduced carbon emissions, the Federal Government of Nigeria and the World Bank undertook a multiyear program of analytical work. The summary results of this program are contained in a separate book (published in the World Bank's "Directions in Development" series) entitled *Low-Carbon Development: Opportunities for Nigeria*, which concludes that Nigeria can achieve its development objectives, while stabilizing emissions at 2010 levels and providing domestic benefits on the order of 2 percent of GDP.

This volume is a collection of the background technical reports on the four sectors of inquiry: agriculture and land use, oil and gas, power, and transport. It contains details on the data, methodology, and assumptions used throughout the analysis.

For agriculture and land use, the study team developed an agriculture production growth model, which permits the evaluation of sector emissions in both a reference and a low-carbon scenario. The study finds that low-carbon practices have significant potential to make the sector more productive and more climate-resilient. For the oil and gas sector, the analysis assesses the potential of accelerated phase-put of gas flaring, reduction of leakages, and increased energy efficiency in the operation of facilities, to both reduce the sector's emission and contribute to the industry's net revenues and growth. The analysis of the power sector shows how the country can expand power generation and broaden access to electricity while reducing associated emissions, through renewable energy, energy efficiency, and lower-carbon technologies in thermal power generation. Finally, this analysis assesses the expected growth in $CO_2$ emissions from on-road transport under a normal business development scenario up to the year 2035, and it identifies actions at national and local levels that would reduce this growth, resulting in fuel economies, better air quality, and reduced congestion.

*Assessing Low-Carbon Development in Nigeria: An Analysis of Four Sectors* outlines several actions that the Nigerian government could undertake to facilitate the transition to a low-carbon economy.

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