Interlocking sustainable development and decarbonisation pathways: charting Nigeria's equitable transition towards the global goal of net zero emissions by 2050, by taking a sectoral perspective

Cumulative dissertation
submitted for the degree of Dr. rer. Oec. (Doctor of Economics)

at the Schumpeter School of Business and Economics
Bergische Universität Wuppertal

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Wuppertal, 2026

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Preface

The present doctoral thesis is cumulative and builds upon the three articles included in the Appendix. Chapters 1 to 6 situate these articles within a unified research framework, in accordance with the doctoral degree regulations (2013, §11(5)). These chapters outline the overarching research questions of the thesis, present its theoretical foundation and methodological approach, and summarise the key findings of each article in relation to the broader research framework and objectives.

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Article 1: Yetano Roche, M., Verolme, H., Agbaegbu, C. Binnington,T., Fischedick, M., Oladipo, E. O. (2020): *Achieving Sustainable Development Goals in Nigeria's power sector: assessment of transition pathways*. Climate Policy, 20:7, 846-865, DOI: https://doi.org/10.1080/14693062.2019.1661818.
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Article 2: Yetano Roche, M. (2023). *Built for net-zero: analysis of long-term greenhouse gas emission pathways for the Nigerian cement sector.* Journal of Cleaner Production, 383, 135446, DOI: https://doi.org/10.1016/j.jclepro.2022.135446.
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Article 3: Yetano Roche, M., Slater, J., Malley, C., Sesan, T., Eleri, E. (2024). *Towards clean cooking energy for all in Nigeria: pathways and impacts*. Energy Strategy Reviews, 53, 101366, DOI: https://doi.org/10.1016/j.esr.2024.101366.
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Persistent Identifiers

This thesis is available through the following persistent identifiers:
DOI: https://doi.org/10.25926/BUW/0-990
URN: https://nbn-resolving.org/urn:nbn:de:hbz:468-2-6769

Abstract

This thesis examines the interplay between sustainable development and decarbonisation in Nigeria, focusing on transition pathways in three critical economic sectors: electricity, cement production, and cooking energy. Positioned at the nexus of climate policy, development economics and socio-technical transition theory, the research addresses the dual challenge of achieving equitable development and meeting global climate commitments. Using a mix of qualitative and quantitative scenario methods, this cumulative thesis provides a sectoral perspective on how Nigeria – set to become the world's third most populous country by 2050 – can ensure inclusive and equitable development amidst the need for urgent climate action.

The findings of this thesis reveal that Nigeria can meet its electricity access goals and decarbonisation pledges for the power sector by 2030 by scaling up off-grid renewable solutions and despite the continued dominance of fossil-based self-generation. The emission goals that the Nigerian government committed to in its Nationally Determined Contribution can be comfortably met, and a higher level of ambition may be warranted in future goals.

In the cement sector, meeting decarbonisation targets will require innovation in energy efficiency, reduced clinker-to-cement ratios, and demand management. Decarbonisation pathways in the cement sector are unlikely to be consistent with Nigeria's stated goal of achieving net zero emissions in the sector by mid-century. However, an optimal transition pathway would set the sector on course to meet net zero goals later in the century.

For clean cooking energy, the transition depends on enabling the widespread adoption of cleaner fuels such as liquefied petroleum gas and electricity. A plausible but very rapid transition can deliver the government's access and decarbonisation objectives for the cooking energy sector by 2050, while also achieving an absolute reduction in annual premature deaths from exposure to household air pollution.

Across all sectors, the research underscores the critical role of enabling policy and investment in driving transformative change, as well as the importance of managing and protecting niche innovations.

A key contribution of this thesis lies in its methodological approach, which combines quantitative scenario analyses with stakeholder engagement to better explore feasible transition trajectories under data-scarce conditions. The findings shed light on critical uncertainties—ranging from macro-economic shocks to the dynamics of demand for electricity or cement —and emphasise the need for adaptive planning to address these challenges.

By synthesising empirical findings with the socio-technical transitions framework, this thesis contributes to advancing the theory and empirical study of sustainability transitions in the global south.

It highlights the unique dynamics of transitions in developing economies, including informal institutions, sectoral disparities, and socio-economic trade-offs.

In addition to theoretical contributions, the thesis provides actionable insights for policymakers, private sector actors, and development practitioners. It emphasizes the need for sector-specific strategies that address governance gaps, reduce investment risks, and balance decarbonisation with inclusive sustainable development. The findings demonstrate how Nigeria, one of Africa's largest economies and a key player in global climate governance, can achieve its development objectives while being consistent with its own decarbonisation targets and the world’s need to reach net zero emissions by 2050. Ultimately, the thesis deepens the understanding of pathways to sustainable development in developing and emerging economies that are aligned with global climate goals.

Zusammenfassung

Diese Dissertation untersucht das Zusammenspiel zwischen nachhaltiger Entwicklung und Dekarbonisierung in Nigeria und konzentriert sich auf Übergangspfade in drei kritischen Wirtschaftssektoren: Elektrizität, Zementproduktion und Kochenergie. An der Schnittstelle von Klimapolitik, Entwicklungsökonomie und sozio-technischer Transitionstheorie angesiedelt, befasst sich die Forschung mit der doppelten Herausforderung, eine gerechte Entwicklung zu erreichen und die globalen Klimaverpflichtungen zu erfüllen. Unter Verwendung einer Mischung aus qualitativen und quantitativen Szenariomethoden bietet diese kumulative Dissertation eine sektorale Perspektive darauf, wie Nigeria - das bis 2050 das drittbevölkerungsreichste Land der Welt werden soll - eine inklusive und gerechte Entwicklung sicherstellen kann, während gleichzeitig dringende Klimaschutzmaßnahmen erforderlich sind.

Die Ergebnisse dieser Dissertation zeigen, dass Nigeria seine Ziele für den Stromzugang und die Dekarbonisierung des Stromsektors bis 2030 erreichen kann, indem es netzunabhängige Lösungen für erneuerbare Energien ausbaut, trotz der anhaltenden Dominanz der fossilen Eigenerzeugung. Die Emissionsziele, zu denen sich die nigerianische Regierung in ihrem Nationally Determined Contribution verpflichtet hat, können problemlos erreicht werden, und für künftige Ziele könnte ein höheres Maß an Ehrgeiz gerechtfertigt sein.

Im Zementsektor sind zur Erreichung der Dekarbonisierungsziele Innovationen in den Bereichen Energieeffizienz, Verringerung des Klinker-Zement-Verhältnisses und Nachfragesteuerung erforderlich. Es ist unwahrscheinlich, dass die Dekarbonisierungspfade im Zementsektor mit dem erklärten Ziel Nigerias vereinbar sind, bis Mitte des Jahrhunderts Netto-Null-Emissionen in diesem Sektor zu erreichen. Ein optimaler Übergangspfad würde den Sektor jedoch auf Kurs bringen, um die Netto-Null-Emissionsziele später in diesem Jahrhundert zu erreichen.

Bei sauberer Kochenergie hängt der Übergang davon ab, dass sauberere Brennstoffe wie Flüssiggas und Elektrizität auf breiter Basis eingeführt werden. Ein plausibler, aber sehr schneller Übergang kann die Ziele der Regierung in Bezug auf den Zugang und die Dekarbonisierung des Kochenergiesektors bis 2050 erreichen und gleichzeitig eine absolute Reduzierung der jährlichen vorzeitigen Todesfälle aufgrund von Luftverschmutzung in Haushalten bewirken.

In allen Sektoren unterstreicht die Studie die entscheidende Rolle von politischen Maßnahmen und Investitionen, um transformative Veränderungen voranzutreiben, sowie die Bedeutung des Managements und des Schutzes von Nischeninnovationen.

Ein wichtiger Beitrag dieser Arbeit liegt in ihrem methodischen Ansatz, der quantitative Szenarioanalysen mit der Einbindung von Stakeholdern kombiniert, um machbare

Transformationspfade unter datenarmen Bedingungen besser untersuchen zu können. Die Ergebnisse beleuchten kritische Unsicherheiten - von makroökonomischen Schocks bis hin zur Dynamik der Nachfrage nach Strom oder Zement - und unterstreichen die Notwendigkeit einer adaptiven Planung, um diese Herausforderungen zu bewältigen.

Durch die Synthese der empirischen Ergebnisse mit dem Rahmenwerk für soziotechnische Übergänge trägt diese Arbeit dazu bei, die Theorie und empirische Untersuchung von Nachhaltigkeitsübergängen im globalen Süden voranzutreiben. Sie hebt die einzigartige Dynamik von Übergängen in Entwicklungsländern hervor, einschließlich informeller Institutionen, sektoraler Disparitäten und sozioökonomischer Kompromisse.

Zusätzlich zu den theoretischen Beiträgen liefert die Arbeit umsetzbare Erkenntnisse für politische Entscheidungsträger, Akteure des Privatsektors und Entwicklungsfachleute. Sie unterstreicht die Notwendigkeit sektorspezifischer Strategien, die Lücken in der Regierungsführung schließen, Investitionsrisiken verringern und die Dekarbonisierung mit einer integrativen nachhaltigen Entwicklung in Einklang bringen. Die Ergebnisse zeigen, wie Nigeria, eine der größten Volkswirtschaften Afrikas und ein wichtiger Akteur in der globalen Klimapolitik, seine Entwicklungsziele erreichen und gleichzeitig mit seinen eigenen Dekarbonisierungszielen und der weltweiten Notwendigkeit, bis 2050 Netto-Null-Emissionen zu erreichen, vereinbar sein kann. Letztlich vertieft die Arbeit das Verständnis für Wege zu einer nachhaltigen Entwicklung in Entwicklungs- und Schwellenländern, die mit den globalen Klimazielen im Einklang stehen.

Acknowledgements

First and foremost, I would like to thank my supervisor, Prof. Manfred Fischedick. He has been a tremendous source of inspiration throughout my career, and I thank him for his sharp insights, and for being consistently constructive and encouraging. I feel extremely fortunate to have had his guidance throughout this thesis.

I am grateful to everyone I had the privilege of interviewing during my research. While I cannot name each person, I am thankful for the knowledge shared by sustainability and development practitioners along the way. A special thanks goes to the many Nigerian sustainable energy entrepreneurs I was lucky to engage with over the years, and whose openness and enthusiasm left a lasting impression on me.

I owe my wholehearted thanks to my co-authors. First and foremost, Hans Verolme—more than a co-author, he has been a true mentor under whose guidance I have grown both professionally and personally. Collaborating with Chibuikem Agbaegbu, Jessica Slater and Temilade Sesan has been a gift. I am grateful for their wisdom, the countless hours of work we shared, and our friendship.

A very special thanks to the Nigerian office of the Heinrich Böll Stiftung. Christine K, possibly the coolest person I have ever met, planted the seed for this thesis the very first time we met in 2015, and I learnt much from her in the years that followed. I am also very thankful to Jochen Luckscheiter and Ikenna Donald Ofoegbu, and the entire kind and committed team at HBS.

I am indebted to three true forces of nature in Nigeria's energy and climate space who contributed immensely to my research during my years in Abuja: Emeka Okpukpara, Carlos Miro Baz, and Ewah Otu Eleri. My heartfelt thanks also go to Joshua Garba, Ene Macharm, and the team at GIZ's Nigeria Energy Support Programme, as well as to Precious Onuvae and the team at ICEED.

My research is inextricably linked to the Wuppertal Institute and to the brilliant colleagues who supported me with their brains, passion, and good laughs. A huge *herzlichen Dank* to Willington Ortiz, Carmen Dienst, Sophia Schneider, Julia Terrapon-Pfaff, Timon Wehnert, Aileen Reichmann, Georg Holtz, Peter Viebahn and Jochen Luhman. I am especially grateful to Stefan Lechtenböhmer, who helped me in key moments of the journey. Warm thanks also to Tatjana Kausemann and—at the very beginning—Sanja Vidovic, for helping me navigate the many hoops along the way.

Of all the extraordinary friends who fill my life, I want to thank my dearest *chicas lila* María Villellas and Belén Rosado. Our conversations about each other's research grounded me and helped me more than they can ever imagine.

Finally, thank you, *gracias* and *grazie* to my spectacular family: my mum, the entire Yetano family, and the Grego family.

And to Simone, Giorgio, and Lorenzo—you are my heart and my reason. Thank you.

“When we reject the single story, when we realize there is never a single story about any place, we regain a kind of paradise.”

Chimamanda Ngozi Adichie

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List of abbreviations

ABM	Agent-based Modelling
BAU	Business-as-Usual
BMR	Baseline Mortality Rate
CCS	Carbon Capture and Storage
CO2	Carbon Dioxide
COP	Conference of Parties
CRD	Climate-Resilient Development
ERGP	Economic Recovery and Growth Plan
ETP	Energy Transition Plan
EU	European Union
FCAS	Fragile and Conflict Affected Settings
GDP	Gross Domestic Product
GHG	Greenhouse gas
HDI	Human Development Index
ICS	Improved Cookstove
IPCC	Intergovernmental Panel on Climate Change
IRP	Integrated Resources Plan
LPG	Liquefied Petroleum Gas
LTS	Long-term Strategy
MLP	Multi-level Perspective
MSME	Micro, Small and Medium Enterprise
MW	Megawatt
NCCC	National Council on Climate Change
NDC	Nationally Determined Contribution
NDP	National Development Plan
NGN	Nigerian Naira
NNPC	Nigerian National Petroleum Company
PPA	Power Purchase Agreement
PV	Photovoltaic
QCA	Quantitative Comparative Analysis
RES	Renewable Energy Sources
RQ	Research Question
SDG	Sustainable Development Goals
SHS	Solar Home Systems
SME	Small and Medium Enterprise
SNM	Strategic Niche Management
STS	Socio-Technical System
UNFCCC	United Nations Framework Convention on Climate Change
USD	United States Dollar

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1. Introduction

1.1. Statement of the problem

Sustainable development has emerged as a global imperative, addressing the urgent need to deliver ecosystem stewardship and social equity simultaneously. At the heart of the sustainable development challenge is the pressing need to halt global warming by reducing greenhouse gas (GHG) emissions, with deep and rapid action that is equitable and just. Climate change also adds to the sustainable development challenge by exacerbating long-standing social inequities.

Nigeria, as the most populous country in Africa and a significant player in the global energy landscape, stands at a critical juncture in its pursuit of climate and sustainable development goals. This thesis seeks to shed light on the critical challenges and opportunities Nigeria faces in achieving this transition in three key sectors of its economy.

The problem can be divided into three areas:

1. Challenge in finding an equitable emissions trajectory

Despite having one of the lowest per capita GHG emissions in the world, Nigeria was the world's 25th biggest emitter of greenhouse gases in 2022 (European Commission *et al.*, 2023), and the second highest in Africa after South Africa. As Nigeria prospers and its population grows, its emissions will increase. Nigeria illustrates the key role that emerging and developing economies have in achieving the world's climate goals.

The international climate governance system acknowledges that there are differentiated responsibilities in mitigating climate change, given that global emissions are distributed unevenly, both in the present day and cumulatively since 1850 (IPCC, 2023; Pauw *et al.*, 2014). Since the adoption of the Paris Agreement, and as the carbon emissions from emerging and developing economies have become more significant, there has been a shift towards tailored emission reduction targets that take into account different national circumstances. Like many countries in Africa, Nigeria faces the challenge of addressing equity and justice within its emission reduction targets and policy, in line with its national conditions and capabilities.

2. Insufficient integration of climate and sustainable development policies

The interplay between climate and development goals was established in both the Paris Agreement and the 2030 Agenda for Sustainable Development. In actual policy there is however still little progress and the connections are addressed on an *ad hoc* basis and mostly in the energy sector (Hermwille *et al.*, 2023). Developing economies face additional constraints in aligning their climate and development governance (IPCC, 2023). It is challenging for emerging and developing economies like Nigeria to strengthen the interaction between climate and development policy and goals. Moreover, while attitudes have evolved in the last decade, key actors remain concerned that the two goals are incompatible, or that climate goals should override near-term economic development goals. Evidence is needed to inform such debates.

Nigeria's policy landscape lacks comprehensive strategies for systematically addressing development in conjunction with decarbonisation. A number of political barriers as well as inconsistent regulatory frameworks, weak enforcement, and macro-economic uncertainties hinder the effective implementation of sustainable development and decarbonisation strategies. This problem is part of a broader context in the management of processes of socio-technical change in rapidly developing economies (Ramos-Mejía *et al.*, 2018).

3. *Lacking sectoral perspective:*

Opportunities and challenges for decarbonisation and development vary significantly across sectors and sector-specific strategies and interventions are required (Rayner *et al.*, 2021). A detailed sectoral perspective on how to achieve sustainable development and climate goals is crucial to providing effective guidance to relevant sectoral actors. Nigeria's current development and decarbonisation transition strategies lack a detailed examination of individual sectors, including energy, agriculture, transportation, and industry.

Sectoral perspectives guide effective action at the sectoral level, but this does not preclude the need for effective integration of action across sectors. The cumulation of actions across sectors, actors and timeframes enables the broader societal development pathway (Eriksen *et al.*, 2024).

1.2. Research objectives and research questions

In light of these challenges, this thesis aims to provide a thorough analysis of Nigeria's path towards sustainable development and decarbonisation. The research conducted contributes to the global discourse on sustainable development and decarbonisation while addressing the unique challenges faced by Nigeria, a nation that is central to Africa's dynamic development landscape.

The specific goal of the research is to understand what transition pathways Nigeria can plausibly follow to meet its development and decarbonisation goals in three key sectors:

- Electricity
- Cement production
- Cooking energy

The three sectors are selected for their relevance to the country's emissions profile and because of their significance in terms of development goals. They are moreover relevant to different types of businesses (from micro and small enterprise to large companies; from informal to formal).

The four specific research questions are:

1. **Which transition pathways are likely to bring about optimal outcomes for the achievement of Nigeria's development and decarbonisation goal in the three sectors studied?**

This question seeks to identify plausible pathways for achieving specific development goals set by Nigerian policymakers in the electricity, cement production and cooking energy sectors, focusing on their environmental and socio-economic impacts. For electricity, the research examines the integration of renewable energy sources and the achievement of universal access to electricity. For cement production, it examines how the sector can meet growing demand and continue to be a major contributor to the Nigerian economy as the sector transitions to a net zero future. For cooking energy, it considers the adoption of cleaner fuels and cooking stoves, which would significantly reduce mortality from indoor air pollution and reduce emissions from land use. By analysing these positive transition pathways, the research presents and analyses plausible futures that meet development needs while achieving emissions reductions.

2. **What are the impacts of non-optimal transition pathways on Nigeria's development and decarbonisation goals in these three sectors?**

This question considers the potential consequences of failing to deliver the development and decarbonisation goals, such as persistent lack of access to services, poor economic performance or increased emissions. In the electricity sector, this might involve continued reliance of economic activity on expensive fossil-fuel based back-up generators. In cement production, it includes the lock-in of carbon-intensive production technologies, while in cooking energy, it involves the persistence of high mortality rates due to continued use of traditional biomass. Understanding these impacts highlights the significant costs and risks associated with lack of consistent integration of equity and decarbonisation goals.

3. **What niche developments will be key in inducing the transition in these three sectors and what factors affect them?**

This question focuses on identifying technological innovations and niches that can catalyse the transition and lead to larger systemic changes. For electricity, this includes off-grid and on-grid renewables (which can be considered emerging technologies in the context of Nigeria, especially at the time of the study). In cement production, a range of niches are explored, from alternative feedstocks to carbon capture. In cooking energy, the research explores technologies of high potential in the mid-term (such as LPG) and others with longer term potential (e.g. biogas and electric cooking). Factors such as market structure, policy and finance are also analysed to understand what enables or hinders these niches.

4. **What are the critical uncertainties in the planning and management of Nigeria's transition?**

This question examines the unpredictable factors that could influence the transition, such as prices, policy stability, and global economic conditions. It moreover highlights the areas where we do not have enough data or understanding of the future dynamics, for example the role of cement exports in the estimation of the development of Nigerian cement manufacturing capacity in the future. This research question seeks to aggregate the areas of uncertainty that warrant special attention and emphasises the importance of flexibility in transition planning across all three sectors, ensuring that strategies remain resilient to unexpected developments and shocks.

1.1. Contributions to research and policy

By addressing these research questions, this thesis aims both to use the Nigerian case to provide broader lessons for the scientific community on the dynamics of transitions in data-constrained and rapidly developing contexts. Furthermore, it aims to generate actionable insights for Nigeria's sustainable development and decarbonisation efforts. The contributions of the findings to research and policy can be summed up as follows:

RQ1: Which transition pathways are likely to bring about optimal outcomes for the achievement of Nigeria's development and decarbonisation goals in the three sectors studied?

- **Contributions to science:** the findings advance the academic understanding of sector-specific transition pathways and shed light on how sustainable development and decarbonisation can be balanced in a developing economy, contributing to the broader literature on sustainability transitions in low- and middle-income countries.

- **Contributions to policy:** the findings provide actionable strategies that align with Nigeria's specific development priorities and decarbonisation targets and can guide decision-makers in formulating evidence-based policies and directing investments that support an equitable and effective transition, and in removing barriers that hinder it.

RQ2: What are the impacts of non-optimal transition pathways on Nigeria's development and decarbonisation goals in these three sectors?

- **Contributions to science:** the findings shed light on the cost of inaction, and on potential trade-offs between development and climate goals, contributing to the body of knowledge on transition dynamics.
- **Contributions to policy:** the analysis can help policymakers understand the potential risks and costs associated with suboptimal transitions, enabling them to proactively address planning and implementation and mitigate the risk of negative outcomes.

RQ3: What niche developments will be key in inducing the transition in these three sectors and what factors affect them?

- **Contributions to science:** the findings contribute to the theoretical understanding on the role of innovation, emerging technologies, and socio-technical systems in enabling transitions in developing and emerging economies.
- **Contributions to policy**: the findings point actors in government, private sector and civil society, to high-impact areas for policy and investment, such as renewable energy technologies, innovative cement production technologies, and capacity-building initiatives. It also highlights critical barriers, such as financing gaps or data constraints, that need to be addressed to unlock the potential of these niches.

RQ4: What are the critical uncertainties in the planning and management of Nigeria's transition?

- **Contributions to science:** the study of Nigeria's transition points to specific uncertainties of two types – those to do with unpredictable dynamics (which can be best managed by adaptive planning) and those to do with the strong lack of data in the field of transition studies in the global south.
- **Contributions to policy:** the findings point to critical uncertainties, helping policymakers in understanding them and addressing them where possible (e.g. enhanced data), or to create flexible and adaptive transition strategies.

1.2. Structure of the thesis

The present doctoral thesis is cumulative. Chapter 1 introduces the research goals and questions as well as the country context. Chapter 2 presents the theoretical framework applied in the research as well as the research methods. Chapter 3 presents the empirical work, namely the three articles presented in the context of this thesis as well as complementary publications of the author. Chapter 4 discusses the empirical results as a whole and answers the overarching research questions in the context of the theoretical framework. Chapter 5 presents the conclusions and further research needs. Finally, the three articles follow in the Appendix.

Figure 1 illustrates the structure of the thesis and the most important elements of each chapter.

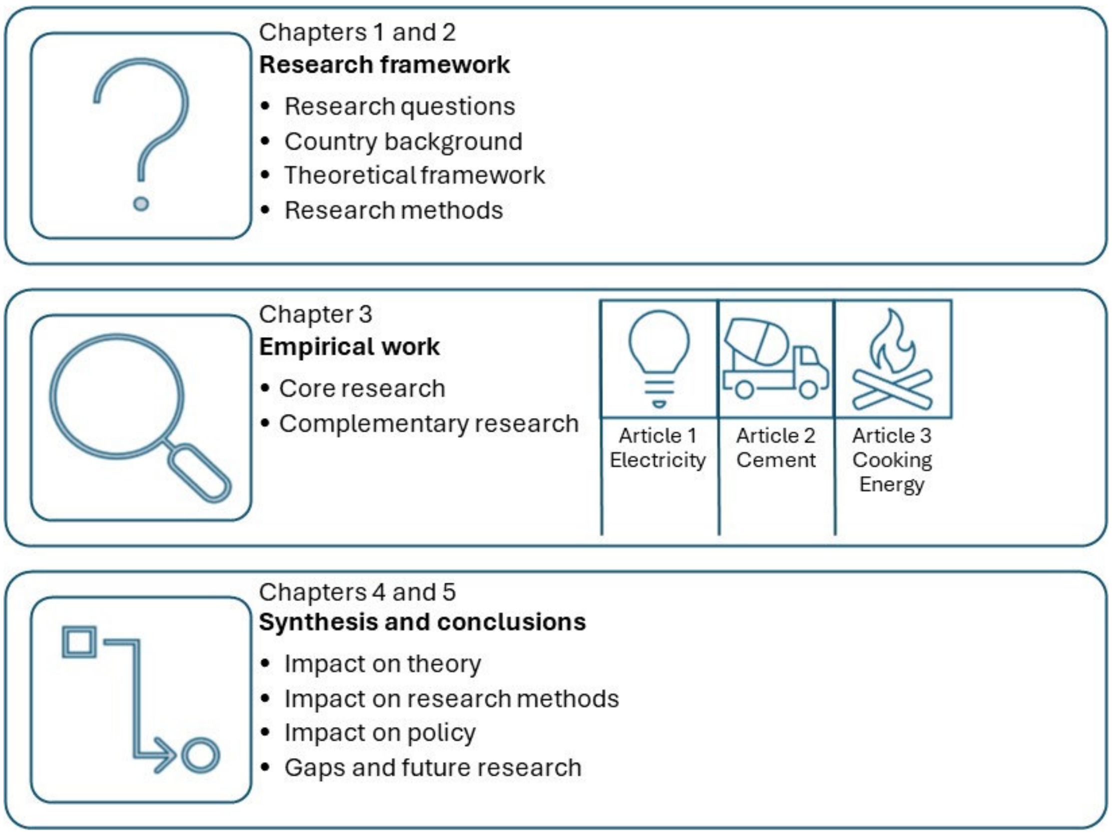

Figure 1. Structure of the doctoral thesis

1.3. Definitions

The nature of the thesis is interdisciplinary and refers to concepts that are not common across all disciplines. For ease of understanding, the following is a list of definitions for key concepts in this thesis.

Clean cooking: the use of efficient, low-emission stoves and fuels, such as electricity, biogas, or liquefied petroleum gas (LPG), to reduce health risks, environmental degradation, and greenhouse gas emissions associated with traditional biomass use.

Climate resilience: the capacity of systems, communities, and economies to anticipate, prepare for, and adapt to climate-related risks. These include physical risks, such as extreme weather events and sea-level rise, and transition risks, which arise from shifts in policies, technologies, or market conditions during the shift to a low-carbon economy.

Decarbonisation: the process of reducing or eliminating carbon dioxide emissions from energy production, industry, and other sectors to mitigate climate change.

Energy access: encompasses the provision of reliable, affordable, and sustainable energy services, including electricity and clean cooking options, to meet basic needs. Globally, nearly 760 million people worldwide lack access to electricity around 2.3 billion people still lack access to clean cooking solutions.

Energy Transition Plan: Nigeria's strategy to achieve its long-term net zero emissions goals, shift from fossil fuels to renewable energy sources, improve energy access and foster sustainable development.

Hard-to-abate sector: sectors in which it is particularly challenging to reduce greenhouse gas emissions.

Just Transition: an approach that ensures the shift to a low-carbon economy is fair and inclusive, addressing social, economic, and employment impacts on affected communities.

Land-use change emissions: greenhouse gas emissions resulting from alterations in the use of land, such as deforestation, agricultural expansion, or urban development, which release stored carbon from soil and vegetation into the atmosphere.

Long-Term Strategy (LTS): a national plan submitted under the Paris Agreement outlining long-term, low greenhouse gas emission development goals, often targeting net zero emissions by mid-century.

Low Emissions Development Strategy (LEDS): a national plan outlining pathways for sustainable economic growth while minimizing greenhouse gas emissions over the long term.

Nationally Determined Contribution: climate action plans that individual countries submit under the Paris Agreement, outlining their voluntary targets and strategies to mitigate greenhouse gas emissions and adapt to climate change.

Net zero: refers to achieving a balance between the amount of GHG emitted into the atmosphere and the amount removed or offset, resulting in no net increase in emissions.

Process emissions: greenhouse gas emissions released during industrial processes, not from fuel combustion, but as a direct result of chemical or physical reactions, such as in cement production, steelmaking, or chemical manufacturing.

SDG 7: part of the United Nations Sustainable Development Goals, focuses on ensuring universal access to affordable, reliable, sustainable, and modern energy by 2030.

1.4. Country background

Given the highly focused geographical scope of this thesis, it is necessary to provide a general background to Nigeria's demographics, economy, development, and climate policy context.

Figure 2. Location and map of Nigeria. Sources: Ukabia (CC BY-SA 3.0) and CIA World Factbook (public domain); both obtained via Wikimedia Commons.

Demographic significance

Nigeria plays a pivotal role in Africa due to its large population, economic strength, and political influence. With a population of 218 million people in 2022, Nigeria stands as the most populous country in Africa and the seventh most populous in the world (World Bank, 2023). Between 2020 and 2060, Nigeria's population is expected to double in size, reaching 375 million in 2050 and making it the third most populous country in the world, after India and China (UNDESA, 2022). Half of Nigeria's population currently is under the age of 17. In demographic terms it is a country of immense significance globally, with implications in a range of political and economic fields.

Economic development, governance and environmental challenges

Economically, Nigeria is one of Africa's largest economies in terms of size of its Gross Domestic Product (GDP) and, despite its ongoing economic challenges, it is widely considered to be a member of the group of emerging economies. Its GDP is estimated at USD 477 billion in 2022 (World Bank, 2023), largely driven by its oil resources, which have historically been the cornerstone of its economy.

Nigeria's development trajectory has been marked by both progress and persistent challenges. Its Human Development Index (HDI) ranking remains very low, positioned at 163 out of 191countries (UNDP, 2022). While the economy as a whole is considered to be in the low to middle-income range, the country grapples with widespread poverty, inadequate infrastructure, and issues related to healthcare and education.

Nigeria is the country with the second highest number of people living below the poverty line, after India, with 32% of its population living in extreme poverty (World Data Lab, 2023). The country's health indicators are marked by an average life expectancy of 62 years (among the lowest in the world), and high maternal and child mortality rates (UNICEF, 2023; WHO, 2023). In education, there are substantial out-of-school rates (25.2 % of children in primary and lower secondary education are out of school) and low literacy rates (only 62% of population over 15 years of age is literate) (UNESCO, 2023; UNICEF, 2022). These challenges are especially acute in rural areas.

Nigeria's economy has traditionally been heavily reliant on oil revenue, which has made it vulnerable to global oil price fluctuations. To reduce this dependence and promote economic stability and growth, the government has made many attempts to diversify its economy. The National Development Plan (NDP, 2021 – 2025) and other national initiatives - Economic Recovery and Growth Plan (ERGP, 2017-2020), and the Nigerian Industrial Revolution Plan (NIRP, 2014-2019)- aim at achieving this diversification (FGN, 2021a; FMBNP, 2017; FMITI, 2014). These policies prioritise sectors such as agriculture, manufacturing, and technology, with the goal of creating jobs, increasing non-oil revenue, and achieving sustainable economic growth. Two examples of policy programmes in strategic non-oil sectors are the Anchor Borrowers' Programme to boost agricultural productivity and reduce food imports, by providing financial support to smallholder farmers, or the suite of policies that seeks to foster digital access as well as encourage startups and innovation (Nigeria has one of Africa's more established startup ecosystems (The Economist, 2021)).

Between 2000 and 2014, the Nigerian economy experienced robust growth, with an average annual GDP growth rate of around 6%, driven largely by high oil prices and expanding sectors such as telecommunications and services. However, since 2016, the country has experienced economic decline and grappled with a succession of recession periods. Central to this tumultuous period was the sharp decline in global oil prices, but government policies have played a key role as well. To finance budgetary shortfalls, the Nigerian government had to resort to increased borrowing, resulting in a significant rise in public debt resulting in a significant rise in public debt, which reached approximately 120 trillion (around USD 91 billion) by mid-2024 (NBS, 2024).

The economic crisis reached a peak in 2023, when annual inflation reached 22%, the highest for 18 years, and 96% of government revenues were spent in debt servicing (The Economist, 2023). Addressing these challenges has demanded comprehensive economic reforms, which included the removal of subsidies for petroleum products in May 2023, a measure that has profound implications in Nigeria's energy transition.

Corruption, weak governance and lack of security further hinder Nigeria's socio-economic development. The country struggles with pervasive corruption and low public trust in institutions, as reflected in its consistently low rankings on international indices (Transparency International, 2023). Moreover, a mix of security challenges, including insurgency, terrorism, communal conflicts, and kidnappings, have surged in the last decade, impacting all regions and economic sectors (Human Rights Watch, 2023).

Environmental challenges constitute another critical dimension of Nigeria's multifaceted landscape. The nation is confronted with environmental issues such as deforestation, land degradation, and desertification, particularly in the northern regions, as well as coastal erosion and oil pollution in the Niger Delta region (UN, 2022) . These challenges have far-reaching implications for livelihoods, food security, and the overall sustainability of Nigeria's environment. Specifically, most of the highest-ranked causes of Death and Disability-adjusted Life Years (DALYs) in Nigeria are related to environmental risk factors, with air pollution (both household and ambient) as the highest ranked cause of death, followed by other environmental risk factors related to water, sanitation, and hygiene (WaSH), ambient ozone pollution, and lead exposure (Murray *et al.*, 2020).

Climate policy, vulnerability to climate change, and the role of fossil gas

Nigeria, as a signatory to the Paris Agreement, has committed to reducing its GHG emissions and mitigating the effects of climate change. The country has set ambitious climate goals that aim to address the climate emergency while fostering sustainable economic growth. One of the primary targets is stated in the 2021 enhancement of its Nationally Determined Contribution (NDC), where the government committed to reduce GHG emissions by 20% below business-as-usual (BAU) by 2030 unconditionally and by up to 47% below BAU by 2030, conditional on international support (FMEnv, 2021). Furthermore, Nigeria announced its net zero goals in November 2021 at the United Nations Climate Change Conference (COP26) in Glasgow, Scotland (FGN, 2021b). The country committed to reaching net zero emissions by 2060, making it the first major developing economy to do so.

In 2021, the Nigerian government also submitted a preliminary long-term strategy (LTS) to the UNFCCC, with a time horizon of 2050. As per Article 4.19 of the Paris Agreement, the LTS is intended to complement and give coherence to the shorter-term national climate commitments enshrined in the NDC. At the time of its publication, the LTS was not fully aligned with the country's net zero goal. The LTS has since been updated and fully elaborated into Nigeria's Long-term Low Emissions Development Strategy (LEDS) (NCC, 2024), which is more aligned with the stated net zero ambition stated in 2021.

To achieve both its short-term and long-term objectives, Nigeria is focusing on various strategies, including transitioning from fossil fuels to renewable energy sources, enhancing energy efficiency, and implementing reforestation and afforestation programs to absorb carbon emissions. The country's Climate Change Act, which was passed in November 2021, provides a legal framework for achieving Nigeria's climate goals (FGN, 2021c).

Climate change is a major threat to Nigeria, and the country consistently ranks among the world's most vulnerable to climate change (IRC, 2023; ND-GAIN, 2023; WBG, 2021). Nigeria is already experiencing the effects of climate change, such as more extreme weather events, rising sea levels, and desertification. These impacts are disproportionately affecting the poor and vulnerable. Flooding is one of the most damaging impacts, and it is estimated that the 2023 floods alone amounted to around 2% of the annual GDP.

Despite the country's high vulnerability to climate change and its very significant policy advances, climate change does not play a significant role in the wider context of Nigeria's politics. The political debate is instead typically centred around addressing security, corruption and economic reform (Climate Action Tracker, 2023). Nevertheless, Nigeria plays a significant role in international climate governance. The country's influence in African and developing country negotiations helps shape global climate policies. For example, it has been a strong voice regarding rules that restrict investments in natural gas to meet Africa's development and climate targets (Osinbajo, 2022).

There is, however, yet no consistent government message on the role of fossil gas in reaching development and climate targets. On the one hand, Nigeria has declared 2020 to 2030 the "Decade of Gas" as part of its broader economic diversification goals, both for the export and domestic markets. On the other hand, there are also concerns regarding long-term fossil gas demand, and the risk of locking

Nigeria into emissions-intensive infrastructure and major stranding of assets (Climate Action Tracker, 2023).

In conclusion, Nigeria's economic diversification goals and climate goals are inextricably linked. Taking steps towards both goals simultaneously, seeking synergies, and understanding trade-offs, is not only crucial for Nigeria but also can provide valuable lessons to other comparable nations seeking to balance economic development with their climate commitments.

2. Theoretical framework: sustainability transitions and development

In order to gain insights into Nigeria's path towards sustainable development and decarbonisation for the coming decades, this thesis departs from a socio-technical transitions theoretical framework. It also makes use of scenarios as a methodological tool, an approach that is common in socio-technical transitions studies. This chapter starts by introducing the theoretical framework applied and the key concepts of relevance for the research. It then describes the research methods and other key considerations derived from related research fields. Finally, the chapter outlines alternative methodologies that could be used to address the research questions.

2.1. Socio-technical transitions: theory and key concepts

There are multiple schools of thought with which to approach the understanding of the fundamental change processes required in sustainability transformations (Geels, 2019). Schneidewind and Augenstein (2016) distinguish three different conceptual approaches: idealist/culturalist, institutionalist/political and technological innovation. The latter school of thought has its roots in the 20th century, when technological progress became central to understanding what drives societies as whole. From the field of innovation studies, socio-technical transitions research arose in the early 2000s and, after testing through several case studies of historical transitions, it emerged as a relevant conceptual framework for the design of innovation policies that address grand challenges such as climate change and the Sustainable Development Goals (SDGs).

There are also different ways to understand the systems that need transforming: socio-technical systems (e.g. energy, mobility), socio-economic systems (e.g., education, finance), and socio-ecological systems (e.g. fisheries, agriculture) (Loorbach *et al.*, 2017). Socio-technical systems (STS) refer to integrated frameworks that encompass both social and technical components within an organization or a broader societal context (Trist, 1981). This concept recognizes the interdependence and interaction between human and technological elements to achieve specific goals or functions.

The theoretical approach of socio-technical transition analysis aims not only to understand but also to guide transitions toward more sustainable and equitable societies that foster sustainable development. Sustainability is a normative goal and it implies a subjective understanding of "what the world should be" (Savaget *et al.*, 2019) and about the relative importance of various social equity and planetary health problems, which entail deep-seated values and beliefs (Geels, 2010). This has implications in the empirical approach to this thesis, as it requires the interpretation of the complex links between economic and social development and emission pathways. It involves examining whether they present trade-offs or "win-win" solutions and considering whether they are inherently interconnected and therefore cannot be "balanced" or meaningfully analysed in isolation.

Socio-technical transitions theory provides a framework to understand the intricate transformations within STS, and emphasize the need to consider both *social* factors, such as organizational structures, culture, and human behaviour, and *technical* factors, including tools, processes, and technology. At the heart of this theoretical framework is the multi-level perspective (MLP) introduced by Geels in 2002 and underpinned by a broad empirical evidence base (Figure 3). The MLP posits that transitions occur across three interconnected levels: the niche, where innovations originate; the regime, representing existing socio-technical structures; and the landscape, encompassing broader socio-economic and cultural contexts (Markard and Truffer, 2008). These three levels from the backdrop for the analysis of the empirical results of this thesis, in particular where they relate to niche innovations.

Socio-technical transition analysis considers radical innovations a key driver of societal transformations. This draws on, among other things, Schumpeterian evolutionary economics and the concept of 'waves of creative destruction'. It thus incorporates insights from innovation studies, which examine how innovations emerge, diffuse, and shape societal structures at national, sectoral or corporate level (Carlsson *et al.*, 2002; Lundvall *et al.*, 2011). In the context of transition theory, innovations can be defined as technological advancements that are embedded within broader social and economic contexts. Innovation system studies highlight the interconnectedness of actors, institutions, and networks in shaping the trajectory of technological change. Furthermore, a specific strand of innovation studies literature examines innovation in the context of developing countries, and the link between innovation, poverty and inequality (e.g., (Cozzens and Kaplinsky, 2009)).

The field of Strategic Niche Management (SNM) studies how innovation can be facilitated by creating niches that allow the co-evolution of technology, user practices, and regulatory structures (Schot and Geels, 2008). The assumption is that if such niches are protected and appropriately built, they can trigger broader socio-technical transitions.

In summary, the theoretical concepts outlined here support in the understanding and guiding of sustainability transformations. These interconnected concepts are critical to analysing the empirical results of this thesis through a socio-technical lens, particularly in evaluating how niche innovations can catalyse changes at the regime level, and the role of the broader socio-economic landscapes.

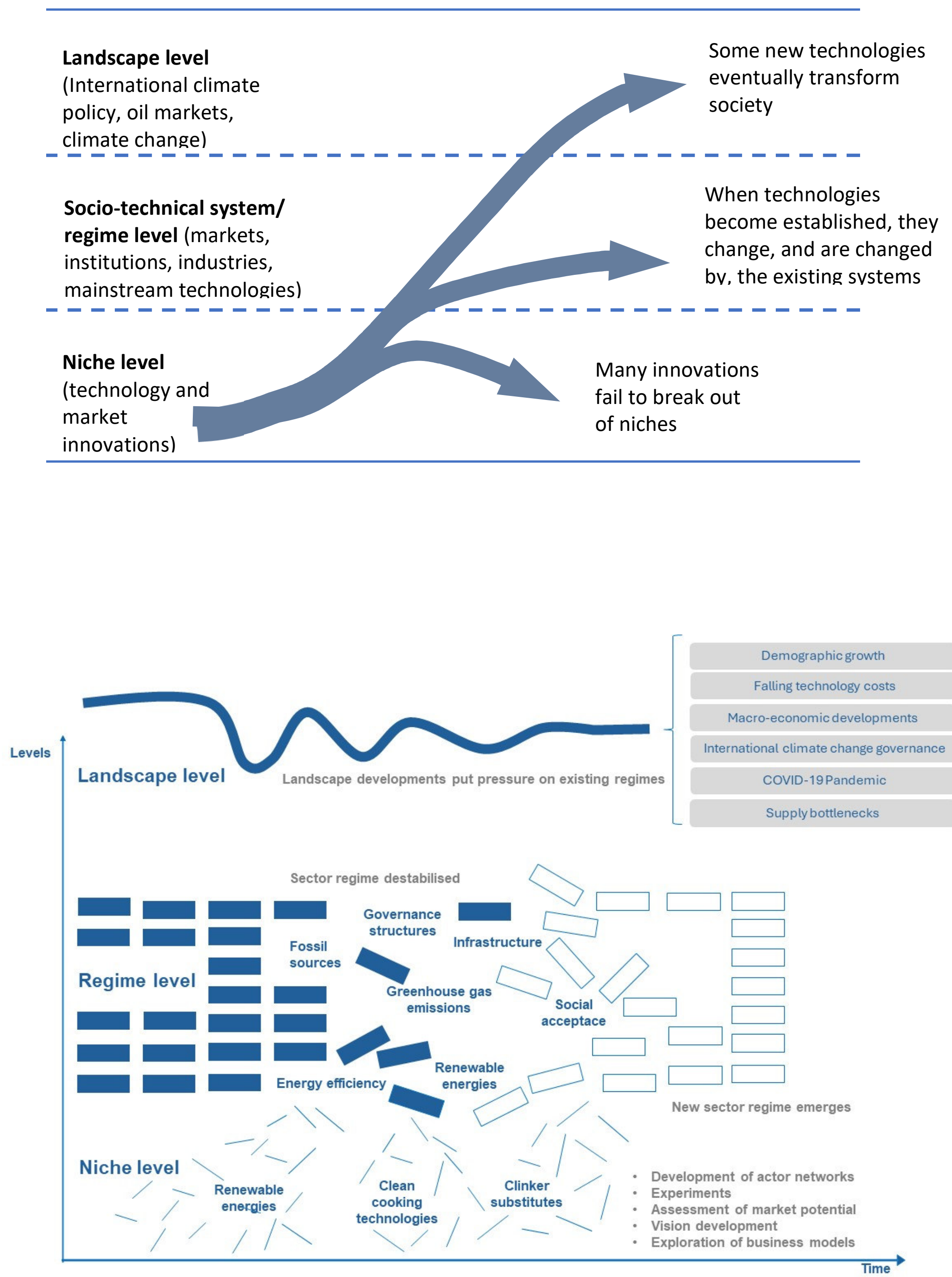

Figure 3. Two views of the multi-level perspective for socio-technical transitions. Adapted from Geels, (2019, 2002) and (Terrapon-Pfaff and Ersoy, 2022).

2.2. Critique

Having described the key concepts that form the theoretical framework of this thesis it is useful to consider its key shortcomings, especially where they relate to the context of study. Some of the following criticisms are accepted by socio-technical transition scholars and are being tackled in recent literature, whereas others are only recently emerging.

One key criticism is that the field says less about social sustainability — for example, inequality and poverty – than about environmental sustainability (Geels, 2019; International Science Council, 2019). Recent studies put more emphasis on mapping social and justice aspects of transitions (Jenkins *et al.*, 2018; Sareen and Haarstad, 2018), and have also shifted towards acknowledging the issue of trade-offs and "winners and losers" produced by transition processes (Newell *et al.*, 2022). This is seen as necessary to better manage rapid transitions.

Early socio-technical transitions research focused heavily on supporting niches and fostering bottom-up disruptive innovations, but research has recently given more attention to the processes of "unmaking" innovations (e.g., return of walking as a form of transport) (Shove, 2012) or of actively overturning incumbent regimes (Turnheim and Geels, 2012). It is increasingly understood that mixes for transitions should ideally aim for "creating the new and destabilising the old" (Kivimaa and Kern, 2016). This is also linked to concepts of justice, whereby compensatory measures can sometimes be necessary in order to counter the impacts of the decline in the regime and ensure a "just transition".

Socio-technical transition theory has also seen elaborations concerning the issues of politics and agency. For example, Markard *et al.* (2016) provide an alternative framework that complements the Multi-Level Perspective and explain how policy drives socio-technical change and how in turn the dynamics between different coalitions of actors drives policy.

Finally, and of great relevance to this thesis, are the limitations of using socio-technical transition frameworks in a developing world context (Ramos-Mejía *et al.*, 2018; Wieczorek, 2018). One key area identified by authors in the field include the diverging understanding of what sustainability is. Also, regimes in developing countries are found to be less uniform than in the Western world and are often not tied to a specific technology. There is a high level of uncertainty about rules, and there is a dominance of informal institutions. In a context of weak governance, the inefficiency of state interventions to protect niche innovations has been found to give rise to alternative approaches, as in the case of customer financing models for Bottom-of-Pyramid markets. Transitions in developing countries often have the opportunity of filling 'unserved' spaces, either due to absent or undeveloped infrastructure, or to a weak policy and regulatory regime.

To further articulate the dynamics of transitions in developing countries it is important to delve into two key related research fields: development economics and global climate governance.

2.3. Development economics, and features of economic development in Nigeria

Development economists are interested in promoting economic development[1] through policy: reforming agricultural policy or investing in infrastructure to support high productivity sectors are just examples of the range of policies that are considered to drive structural change and economic growth and standard measures of it, such as growth in per capita income (Todaro and Smith, 2020). Structural change does not refer only to the reallocation of labour to sectors with higher productivity levels, but also to changes elsewhere in the economy, such as in savings and investment rates, demographic transitions (including urbanisation), changes in income inequality, and changes in institutions.

Patterns of structural change and of adoption of policy approaches can be identified. For example, Nigeria underwent a transformation from an agricultural economy to an oil-dominated one during the 1960s and early 1970s, and pursued structural adjustment policies from the early 1980s to 1990 (IMF, 1997). The theoretical backdrop of this thesis puts Nigeria's socio-technical transition towards sustainability within the context of patterns of structural economic changes and policy approaches often observed in developing economies.

Development economists pay special attention to the relationships between economic growth, poverty and inequality, which are also an important consideration in this thesis. Currently, around 1 in 5 poor people in Sub-Saharan Africa live in Nigeria (World Bank, 2022), and therefore Nigeria is an important country of focus for many development economists. Economic growth represents an important means for reducing poverty in the developing world, when income distribution is held constant.

The experiences of countries that have succeeded in translating growth into poverty reduction (such as Indonesia or Vietnam), and those that have mostly failed (such as Nigeria itself), guide policies at many levels: macro-economic policies, investments in human capital and infrastructure, taxation, social programmes that alleviate poverty directly, etc. (Carter *et al.*, 2024). Economic growth in Nigeria has by and large not been inclusive. Growth has been concentrated in the oil sector, poverty alleviation programmes have not been effective, and subsidies have tended to favour richer Nigerians (Carter *et al.*, 2024).

[1] While a full definition of the concept of development is beyond the scope of this review, it is important to underline that "economic development" is part of the broader notion of "human development", which includes social, political and ethical dimensions.

Understanding the multidimensional facets of poverty is crucial for guiding economic policies, and this requires more than a headcount of the people living in poverty. For example, in Nigeria, poverty is strongly tied to being rural, young, and engaged in agriculture as an economic activity. Measures of non-monetary poverty such as education and access to basic infrastructure are highly correlated with monetary poverty. Finally, Nigeria is characterised by having a significant share of the population who is very close to the poverty line, and only "one shock away" from falling into poverty (World Bank, 2022).

Development economists also study why economic inequality exists and persists, both among countries and within countries. Countries with strong welfare systems tend to be more successful in using policies such as taxes and benefits to curb the processes that drive income inequality. Developing countries with weak institutions face clear disadvantages in this respect (Stewart and Samman, 2014).

Inequality in Nigeria, as captured by the Gini coefficient, is moderate, compared to other regional peers (and significantly lower than that of Brazil or South Africa). This however masks crucial dimensions of Nigeria's inequality: one is spatial, with higher rates of poverty in the northern states of the country. For example, in Sokoto state, 80% of the population is living below the national poverty line (USD 2.15 a day), while in the southern states poverty incidence is consistently lower and no higher than 26% (World Bank, 2024). Dramatic disparities are found between rural and urban population segments. Moreover, there is a pattern of inequality between the poor and the non-poor, with richer households shown to disproportionately benefit from the country's economic growth in the early 2010s (World Bank, 2022).

In summary, core concepts from development economics provide critical insights into Nigeria's into the factors that shape the country's development pathway. These factors are essential for understanding the socio-economic context in which Nigeria's sustainability transitions are unfolding, and as such the concepts form one part of the broader theoretical backdrop of this thesis, complementing the socio-technical transition framework. The next section will complete the theoretical framework by situating Nigeria's sustainability and development transition within the global climate governance architecture and exploring key concepts in that field of research.

2.4. International climate governance and links with development policy and goals

The purpose of international climate governance is to prompt effective accelerated and equitable action to address climate change mitigation and adaptation (Oberthür *et al.*, 2017). International climate governance research is a highly multidisciplinary field which draws from a range of political and social science traditions. This thesis taps into this scholarship as it relates to decarbonisation (i.e. climate change mitigation) and brings two central concepts of international climate governance practice and research into play: justice in climate action, and synergies between climate action and other development goals.

Climate justice means ensuring that rights, benefits, burdens and responsibilities related to climate change are fairly distributed and that all stakeholders are meaningfully involved (Okereke, 2018). Considerations of equity and justice have always been central to understanding past and present forms of international climate governance, as well as the goals and motivations of different actors.

With regards to fairness in the distribution of responsibilities, the Paris Agreement ushered in a new era in global climate governance that influenced the conceptual backdrop of this thesis. While the Kyoto Protocol required only developed countries to reduce their greenhouse gas emissions, the Paris Agreement called on all countries to set emissions targets. This represented a shift in the understanding of the concept of "common but differentiated responsibilities" (Pauw *et al.*, 2019). Article 4 of the Agreement recognises that "developed countries should continue taking the lead" and recognises that "peaking [of emissions] will take longer for developing country Parties" (UNFCCC, 2016). Nevertheless, within the framework of the Paris Agreement, every nation presents its unique nationally determined contribution (NDC) "in the light of different national circumstances".

A second key points of departure for the research design and analysis of this thesis is the recognition of, as stated in the Paris Agreement, "the intrinsic relationship that climate change actions, responses and impacts have with equitable access to sustainable development and eradication of poverty". As such, a number of developing countries' NDCs have begun to refer to synergies with SDGs and quantify opportunities to meet their development goals while also meeting their emissions targets (UNDESA, 2023).

The IPCC AR6 sums up evidence on this two-way relationship, and on the most prevalent synergies and trade-offs between decarbonisation and development. It confirms that "Literature highlights that climate change mitigation action designed and conducted in the context of sustainable development, equity, and poverty eradication, and rooted in the development aspirations of the societies within which they take place, will be more acceptable, durable and effective" (IPCC, 2023).

The concept of "climate-resilient development" (CRD) and its many possible pathways, as proposed by the IPCC AR6, is an attractive idea for developing countries. In order to transform CRD from a rather abstract concept into an operational approach in these countries, recent literature has tried to extract lessons from past failings of climate governance and development aid and shed light on the key changes that are needed: explicit attention to the political economy and development framings or paradigms that are prevalent in the countries, sufficient levels of finance, and coordination of adaptation and mitigation action (traditionally considered very separate), among many others (Eriksen *et al.*, 2024; Sánchez Rodríguez and Fernández Carril, 2024).

As a final note, it is important to highlight that the interfaces between climate governance research and socio-technical transition theory are recently emerging in literature. International climate governance is increasingly recognised as a driving force for transitions in developing countries, by shifting the landscape or regime levels (Newell and Bulkeley, 2017).

Having established this theoretical foundation, the following section will now turn to the methodological approach, detailing how these concepts are operationalised in the research design, data collection, and analysis to address the research questions of this thesis.

2.5. Research methods: transition scenarios as a methodological tool in socio-technical transitions studies

The research questions in this thesis are framed in a socio-technical transitions conceptual approach and draw from multi-level perspective and niche innovation theories. A range of research methods can be used to address the questions and explore future transition trajectories and policy options in the context of Nigeria's development and decarbonisation goals. This thesis takes a sector-specific approach and uses a mix of qualitative and quantitative scenario methods. This section introduces the methodological framework and how it was used in the empirical work.

A scenario is a coherent and plausible description of a possible future state of a socio-technical system. It incorporates internally-consistent assumptions about the drivers, relationships, and constraints in the system (Thompson *et al.*, 2012). Scenarios are a tool used within transition studies to improve the understanding of the complex interactions within socio-technical systems and the dynamics of the transition from one system state to a future one (Amer *et al.*, 2013; Varum and Melo, 2010; Zolfagharian *et al.*, 2019). The long-term, system-level foresight provided by scenarios can anticipate key features of transitions, as well as key risks and uncertainties.

Scenario analysis in climate change mitigation research helps to evaluate the implications of and trade-offs between different approaches to mitigation as well as critical areas of uncertainty (Moss *et al.*, 2010; van de Ven *et al.*, 2025). Transition scenarios provide a structured framework to envision and analyse potential future trajectories. Moreover, they provide a tangible and accessible way to engage stakeholders in discussions about the future. By involving diverse perspectives, researchers can enhance the robustness of scenarios and ensure that the resulting transition strategies are socially acceptable and politically feasible.

There are several drawbacks in the use of scenarios as a methodological tool. First, there is a challenge in defining and constructing realistic transition scenarios. While it is well understood that scenarios are not predictive tools and are inherently biased, the complexity of socio-technical systems—characterized by intricate interconnections between social, technological, and environmental factors— the complexity of socio-technical systems, involving intricate interconnections between social, technological, and environmental factors, makes it challenging to develop comprehensive and accurate representations. Scholars such as Geels (2011) and Markard *et al.* (2012) highlight the difficulty in capturing the multifaceted nature of transitions in a structured scenario.

Second, scenarios inherently involve uncertainties, and their reliability depends on the assumptions made during their development. Uncertainties are inherent in predicting technological advancements, policy changes, and societal shifts (Bale *et al.*, 2015; Otto *et al.*, 2015). Communicating these uncertainties transparently is central to ensuring the robustness of the findings. Third, developing comprehensive transition scenarios requires the integration of insights from diverse disciplines. Achieving a balance between depth and breadth in scenario development can be challenging but is crucial for the success of the methodology (Zolfagharian *et al.*, 2019). Finally, even if increasingly common in policy processes, transition scenario approaches often struggle to incorporate diverse viewpoints of stakeholders (Scolobig and Lilliestam, 2016).

The scenarios analysed in this thesis are designed to test the feasibility and impacts of Nigeria's policy targets in the areas of climate and development. The scenarios present a combination of forecasting and back-casting elements (Figure 3). Back casting can be defined as "*generating a desirable future, and then looking backwards from that future to the present in order to strategize and to plan how it could be achieved*" (Vergragt and Quist, 2011).

The process of applying scenario methods in the three sectoral deep dives of this thesis share some commonalities. In general, the process included 3 main stages: (i) identifying the key goals and driving forces for that sector; (ii) developing a few selected scenario narratives that synthesise those forces and (iii) assessing the impact and uncertainty of each of the narratives. Stakeholder and expert insights (collected via interviews or workshops) drove mainly the development of narratives, but also the identification of quantitative assumptions. It is important to note that given the specific data scarce environment in which the research takes place, key historical data trends and baseline projections were lacking and needed to be developed on the basis of stakeholder interviews only. This is a common limitation of transition studies in global south contexts.

The scenarios used also had some differences: for examples, the impacts that are analysed vary across the three sectors studied. Moreover, while the scenarios were all long-term, they spanned different time frames depending on the key policy goal under discussion.

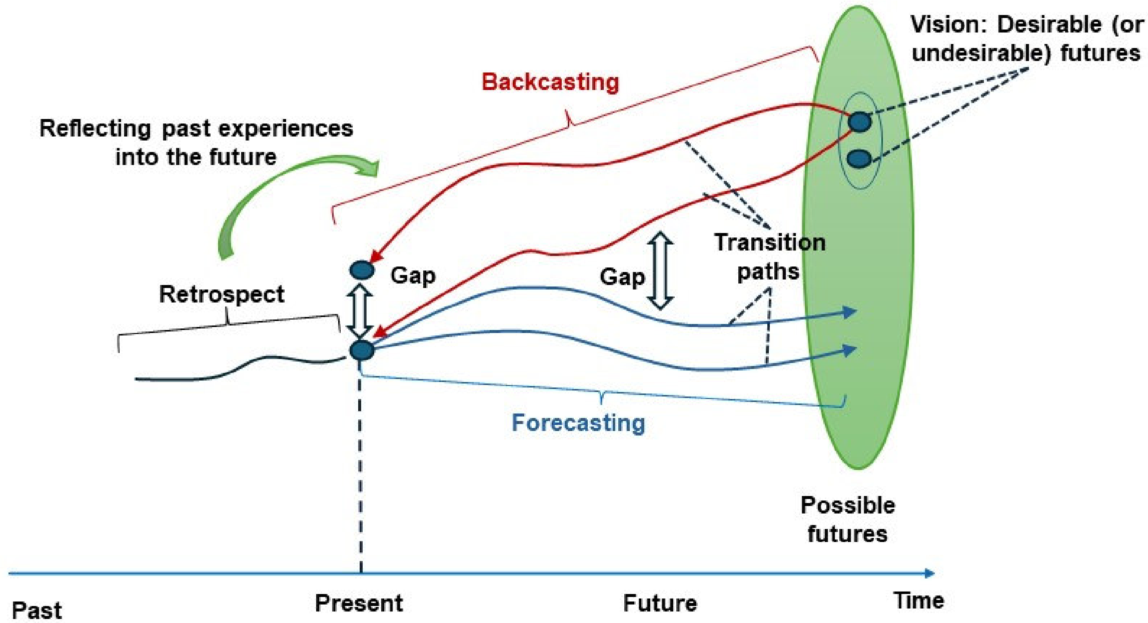

Figure 4. Core elements of the scenario approach (historical/observed trend, starting point, possible futures and transition paths). Adapted from Kishita *et al.* (2016).

2.6. Alternative methods for exploring the research questions

The study of transition pathways that meet Nigeria's development and decarbonisation goals could be approached through various alternative methods, providing a different perspective to those provided by the scenario development and analysis (combined with stakeholder validation and engagement) employed in this thesis. Some of these alternative methods that could have been employed or combined with scenarios are:

Econometric analysis of time series and geospatial data could help to identify relationships between key variables such as development indicators (e.g. health, energy access), economic growth and emissions, and map these geographically This would involve in-depth analysis of existing cross-sectional or panel data and geospatial databases. Hypotheses about the relationships between variables would be tested using statistical methods, and various optimisations could be applied to identify relationships across space and variables (e.g. locations where cooking energy demand is particularly well matched to infrastructure availability). Such analysis of historical trends would improve understanding of the dynamics of transition under future policy and economic scenarios. However, this approach was not applied in this thesis due to the limited availability and reliability of consistent, high-quality time-series and geospatial data for Nigeria, particularly in relation to disaggregated socio-economic indicators and emissions data. Moreover, econometric methods are often better suited to analysing historical trends and may not effectively capture the complexities of future transition pathways that involve significant structural changes beyond existing data patterns.

Agent-based modelling (ABM) (An *et al.*, 2021) has been widely used in energy transition studies to explore behavioural and market dynamics, and its application in Nigeria could enhance understanding of grassroots-level interactions has been widely used in sustainability transition studies (independently or in combination with other methods such as scenario modelling) to explore behavioural and market dynamics (K. H. van. Dam *et al.*, 2013; Geels, 2020). Its application in Nigeria could capture the behaviours and dynamics of adoption of innovations among individual agents—such as households or cement manufacturing businesses. Despite its strengths, ABM was not employed in this thesis due to its limited applicability in analysing long-term, large-scale structural changes in socio-technical systems. ABM tends to rely on detailed behavioural data and assumptions about agent interactions, which are scarce in the Nigerian context.

The **Delphi process** is a forecasting method that relies on a panel of experts to collect their judgments on a particular topic through a series of feedback rounds. There is an opportunity for the experts to revise their initial estimates on the basis of this feedback. Delphi-derived estimates can be of the probability of a future event occurring, or the time when a particular future event might occur. These findings can be combined with scenario approaches to give further insights into plausible futures (Wright *et al.*, 2013). Delphi methods were not applied in this thesis due to a limitation in the resources needed to consistently engage a representative panel of experts familiar with Nigeria's specific socio-economic and climate context for each specific sector. Moreover, Delphi may introduce subjective biases that could limit the robustness of the analysis when not complemented by quantitative modelling.

Another alternative method is **qualitative comparative analysis (QCA)** (Ragin, 1987), which identifies patterns across multiple case studies. The research could draw on data from other emerging economies with comparable socio-economic and policy contexts, such as similar energy access challenges or macroeconomic characteristics. By systematically comparing transition experiences in countries like India, Kenya, or South Africa, QCA could uncover transferable strategies or highlight Nigeria-specific barriers. However, QCA was not adopted as the unique socio-political, economic, and environmental factors influencing Nigeria's development and decarbonisation pathways could limit the applicability of lessons from other countries. Additionally, QCA focuses on identifying patterns and causal pathways across cases, which may not provide the granular, context-specific insights required to inform Nigeria's complex transition dynamics.

This chapter has established a comprehensive theoretical and methodological foundation for investigating Nigeria's sustainability transitions. The socio-technical transitions framework, underpinned by the Multi-Level Perspective (MLP), provides a robust theoretical lens for analysing Nigeria's sectoral transitions in electricity, cement, and cooking energy. The chapter also critiques the framework's limitations, particularly its challenges in applying it in developing economies like Nigeria. The chapter then integrates insights from development economics and climate governance, emphasising the interconnections between transition studies and other disciplines. Finally, the chapter describes the scenario-based methodology used in this thesis, justifying its selection and addressing potential limitations. This sets the stage for the empirical findings presented in the next chapter.

3. Empirical work

3.1. Introduction and framing

Drawing from the above-mentioned theoretical concepts, the present thesis treats Nigeria's economy as a socio-technical system that consists of different elements: infrastructure, knowledge, markets, regulation, etc. This section describes how the empirical work has used this conceptual framework and methodological approach to tackle the research problem and questions, and how the results contribute to the theory and practice of socio-technical transition studies, specifically in developing economies.

The empirical work approached three different sectors that are crucial to attaining Nigeria's sustainable development and climate goals and uses scenarios as a tool to make a detailed examination of the transition pathways Nigeria can plausibly follow to meet them, and what are the impacts of alternative pathways that do not meet them.

This section summarises the three published research articles presented in the context of this thesis as well as additional publications of the author. Each publication focuses on one sector (electricity, industry and cooking energy). For each publication, there is a consideration of how the empirical work helps to answer the research questions, what is its contribution to theory, and what are the implications for businesses (from micro and small enterprise to large companies; from informal to formal).

It is important to keep in mind that the empirical work was carried out during a highly dynamic period in Nigeria's economic and climate policy, and an equally fast-changing international climate governance context (Figure 5). For example, over the course of the research, the Nigerian government revised its Nationally Determined Contribution (July 2021) and announced its net zero goals (November 2021). For this reason, a summary of relevant updates (chiefly research and policy developments) is provided for each publication.

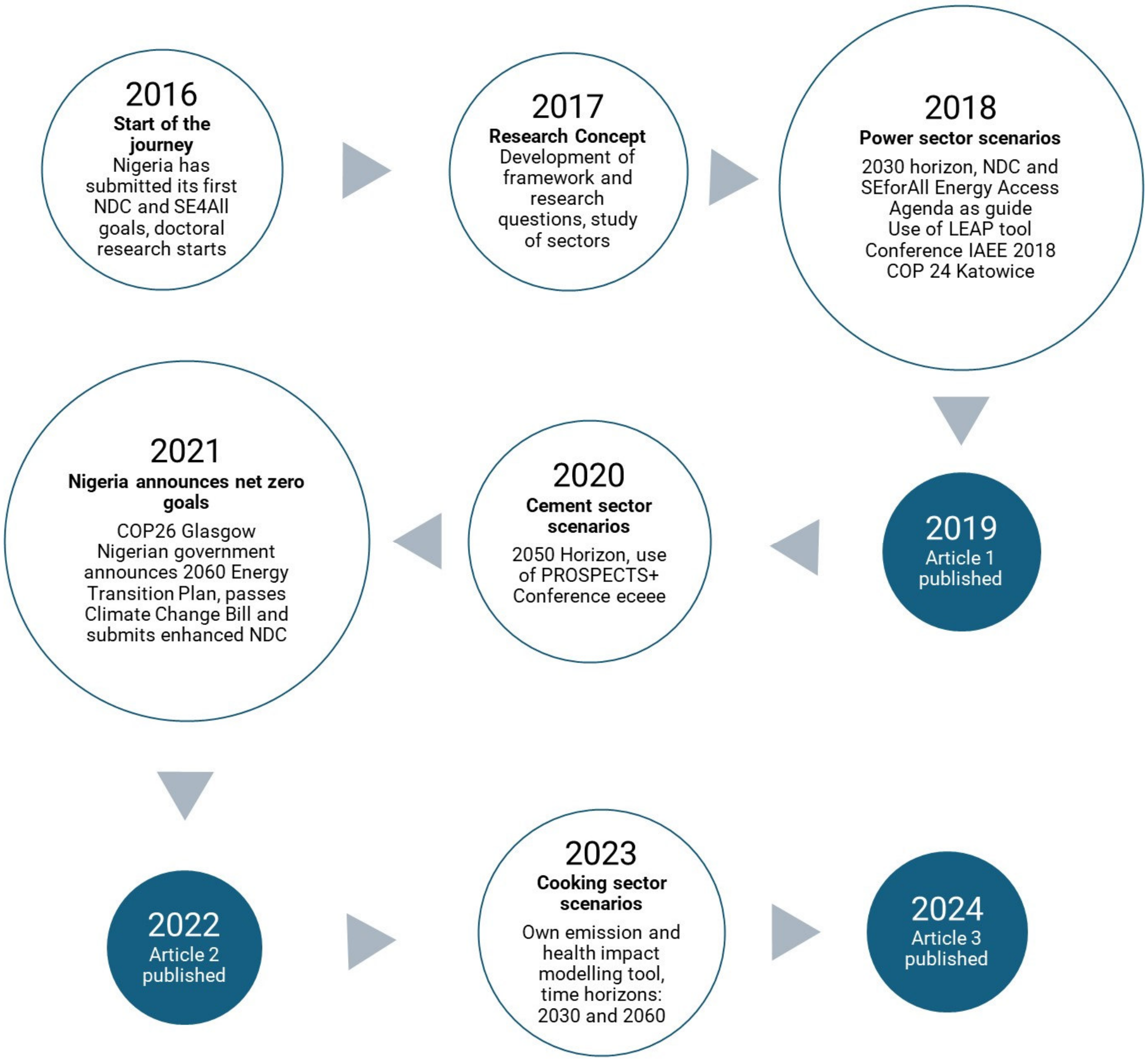

Figure 5. Timeline depicting milestones in the research concept and empirical research in relation to the evolution of Nigeria's milestones in the international and national climate governance space.

3.2. Article 1: Achieving Sustainable Development Goals in Nigeria's power sector: assessment of transition pathways

Originally published as: Yetano Roche, M., Verolme, H., Agbaegbu, C. Binnington,T., Fischedick, M., Oladipo, E. O. (2020): *Achieving Sustainable Development Goals in Nigeria's power sector: assessment of transition pathways*. Climate Policy, 20:7, 846-865, DOI: https://doi.org/10.1080/14693062.2019.1661818.

Note on reproduced material:

Abstract of the published article (reproduced verbatim):

Nigeria is Africa's largest economy and home to approximately 10% of the unelectrified population of Sub-Saharan Africa. In 2017, 77 million Nigerians or 40% of the population had no access to affordable, reliable and sustainable electricity. In practice, diesel- and petrol-fuelled back-up generators supply the vast majority of electricity in the country.

In Nigeria's Nationally Determined Contribution (NDC) under the Paris Agreement, over 60% of the greenhouse gas emissions (GHG) reductions are foreseen in the power sector. The goal of this study is to identify and critically examine the pathways available to Nigeria to meet its 2030 electricity access, renewables and decarbonisation goals in the power sector.

Using published data and stakeholder interviews, we build three potential scenarios for electrification and growth in demand, generation and transmission capacity. The demand assumptions incorporate existing knowledge on pathways for electrification via grid extension, mini-grids and solar home systems (SHS). The supply assumptions are built upon an evaluation of the investment pipeline for generation and transmission capacity, and possible scale-up rates up to 2030.

The results reveal that, in the most ambitious Green Transition scenario, Nigeria meets its electricity access goals, whereby those connected to the grid achieve a Tier 3 level of access, and those served by sustainable off-grid solutions (mini-grids and SHS) achieve Tier 2. Decarbonisation pledges would be surpassed in all three scenarios, but renewable energy goals would only be partly met. Fossil fuel-based back-up generation continues to play a substantial role in all scenarios. The implications and critical uncertainties of these findings are extensively discussed.

Graphical abstract

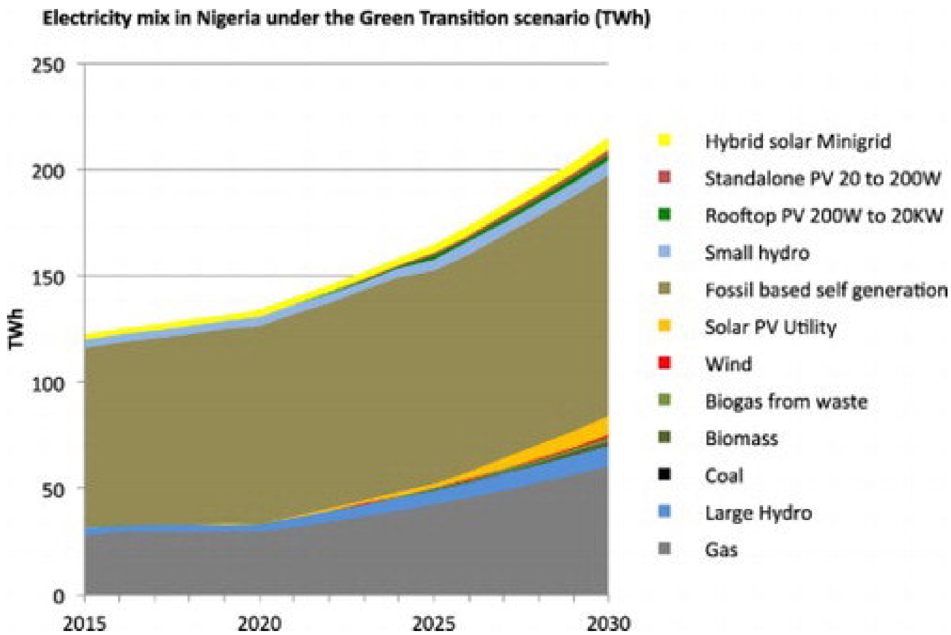

Figure 6. Graphical abstract Article 1

Links to theoretical framework

The following is a discussion of how this research article uses existing theory and concepts, and in turn contributes to advancing the fields of socio-technical transition studies and international climate governance:

Socio-technical transition studies in a global south context

The article considers the Nigerian power sector to be a *socio-technical system (STS)* that encompasses both social and technical components within a broader societal context (Trist, 1981). The underlying narratives of the three scenarios relate to the MLP theory, distinguishing three levels in transition processes:

(a) the *niche level*, especially in the area of off-grid electrification, and including technologies which are not new in developed economies, but were relatively innovative in the Nigerian context, in particular at the time of the study (and to this day in the case of grid-connected renewables);

(b) the *regime level*, which represents the incumbent energy systems, and very importantly the dominance of fossil-fuel based self-generation; and

(c) the *landscape level*, including various external pressures that affect Nigeria's transition processes, such as its policy goals (but not others such as fuel subsidies or oil and gas prices, which were beyond the scope of the study).

In this sense the research article contributes to a growing body of knowledge on socio-technical transitions in a context of developing countries. STS concepts and approaches have to date been predominately developed and applied in industrialised countries and, according to many authors, overlook the realities of transitions in countries with different characteristics. These differences may include less uniform regimes, higher dominance of informal institutions, or higher prevalence of 'unserved' technological spaces (Ramos-Mejía *et al.*, 2018; Wieczorek, 2018).

The issue of unserved spaces is very much the case of Nigeria, where 77 million Nigerians lacked access to electricity at the time that the study was developed (this figure has since increased to 86 million (World Bank, 2023)). In the research study, the Green Transition scenario sees 88.2 million people receiving electricity from sustainable off-grid solutions by 2030, including over 40 million from standalone systems. While this was considered feasible by some of the experts consulted, it would entail an unprecedented speed and scale of transition in the off-grid sector and, more importantly, a strong coordination of grid expansion plans with roll-out of off-grid solutions. It is important to understand that, while off-grid electrification is regulated to an extent, Nigerian power sector institutions are strongly dominated by on-grid centralised technological approaches. This greatly constrains the shift to a decentralised energy supply system.

The research also touches on the prevalence of fossil-fuel based self-generation, which represents a key element of the *regime* level in Nigeria's energy transition. In their study of Nigeria's renewable energy sector, Osunmuyiwa *et al.* (2018) argue for a more nuanced understanding of the regime level in rentier states[2] with weak political institutions and well-established coalitions and elites that may resist transitions. This is the case of Nigeria's diesel and petrol generator importer monopoly. A more recent study takes a further look at the regime level of Nigeria's power sector and specifically at how general inefficiencies act as a barrier to investments in utility-scale renewables sector in Nigeria (Adeniyi and Isah, 2023).

Creating and protecting niches for technological innovations in the power sector

In the context of the Nigerian power sector and its electricity access and climate goals, relevant technological innovations include renewable electricity sources, energy efficiency, and off-grid electrification approaches. Solar PV technologies (both on-grid and off-grid) play a key role in the innovation landscape. Since around 2010, falling prices and large technical resource potential have

[2] Rentier states rely disproportionate upon sources of rents, notably oil and gas, for income (Neal, 2019).

fuelled the emergence of solar PV in Nigeria's power mix, but to date it remains a niche in terms of its market coverage. The scenarios shed light into which would be the impacts of protecting this and other niches to trigger the broader socio-technical transition.

The article integrates elements of innovation studies and Strategic Niche Management (SNM) in two ways: within the qualitative scenario assumptions (as a key driver of the transformation scenarios), and in the discussion of the study's findings.

The underlying narratives that drive the scenario parameters draw from elements of SNM framework in terms of factors that would foster niches for solar PV and other technologies to develop: technology feasibility, various forms of capabilities and competencies, institutional structures, national policies, and flows of international resources via donor interventions, among others (Wieczorek, 2018).

The scenario drivers also encompass strategies to shield the niches from incumbent systems, i.e. back up diesel ad petrol generators. In other words, the focus goes beyond the creation of new energy technologies, to look also at policies that destabilise or destroy the existing regime (Kivimaa and Kern, 2016).

The discussion returns to the issue of niches in the context of the findings from the scenarios, and where appropriate, critiques the simplifications that were made about these niches while building the scenarios. For example, the modelling approach was not able to capture the interaction between the growth of grid-connected renewables and that of sustainable off-grid solutions, nor how their combined growth would affect the rate of replacement of diesel and petrol back-up generators.

Long-term scenarios to guide decarbonisation and development transition pathways

Sectorally-detailed scenarios are a key component of developing long-term emission reduction strategies that become progressively more ambitious as per the Paris Agreement requirements (Waisman *et al.*, 2019). This research article provides detail and transparency to address Nigeria's double pledge of decarbonisation and energy access while incorporating its country-specific context. In this way, the article contributes to the actual follow-up on these pledges and supports sectoral planning under deep uncertainty, while aiming at systemic change.

Moreover, from a methodological perspective, the article contributes to the advancement of the use of *back casting* scenarios in international climate governance. The identification of pathways to reach energy sector objectives and emissions reductions starts from the definition of realistic future indicators (e.g. share of population reached by sustainable off-grid solutions by 2030). The back casting approach is then applied to identify the changes required to arrive to those indicators from the present, and the rate of change at which change is needed.

While not a fully participatory scenario study, the article also contributed to a growing trend for the use of stakeholder engagement for futures-thinking in studies regarding transitions in developing countries (Cork *et al.*, 2023). The study used extensive stakeholder engagement as a basis for the development of scenario narratives and assumptions. A total of 28 expert interviews and small-group discussions were held. Key stakeholders from government, regulation, finance, technical assistance, private firms, and advocacy informed the scenario assumptions on a range of topics, including underlying conditions and scenario storylines, demand forecasts, on-grid value chain, and off-grid market developments. Furthermore, the preliminary outputs from the simulation were fed into some of the stakeholder interviews.

A key methodological challenge in applying scenarios as a methodology for Nigeria's economic sectors is data scarcity. This particularly affected the electricity demand projections which were an exogenously defined driver of the model. Nigerian on-grid power generators have not met natural customer demand since the 1990s, hence historic statistics are insufficient to understand the level of suppressed demand among the population. Contrary to other studies and to the government's own NDC, in this study we explicitly chose to avoid deriving demand assumptions from macroeconomic assumptions. Instead, the article takes a view that demand would grow differently depending on the type of electricity access that is achieved.

The main drivers for demand in the scenario are therefore driven by assumptions on feasible electrification rates, as revealed by least-cost electrification studies quoted in the article. This was a methodological innovation for Nigeria, and drew from an emerging body of literature at the time that linked links spatial electrification models with long-term energy planning (Moksnes *et al.*, 2017). The scenarios also integrate a quantitative interpretation of Nigeria's 2030 access goal that allows the quantification of electricity demand. Using the World Bank's Multi-Tier Framework, the study assumes that those connected to the grid achieve a Tier 3 level of access, and those served by sustainable off-grid solutions (mini-grids and SHS) achieve a Tier 2 level of access.

Links to research questions

The following are some of the key conclusions from the research, in relation to the research questions of this thesis:

RQ1. Which transition pathways are likely to bring about optimal outcomes for the achievement of Nigeria's development and decarbonisation goal in the three sectors studied?

The study demonstrates a pathway in which Nigeria could meet its electricity access goals and decarbonisation pledges for the power sector as defined in the study (i.e. '90% electricity access by 2030'). In the very ambitious Green Transition scenario, 148.5 million people would be connected to the grid by 2030 and would have a Tier 3 level of energy access (500 kWh per capita per year) and that those with sustainable off-grid access would shift from zero to Tier 2 (100 kWh per capita per year).

Key underlying conditions for achieving this optimal outcome would include: strong mitigation of investment risks in the on-grid and sustainable off-grid electricity sectors through finance, policy and enabling environment measures, a strong drive from the government for renewables-based generation, rapidly shifting financial flows from grid-connected investments to off-grid systems, coordinating grid expansion plans with roll-out of off-grid solutions, and improving capacity and standards.

Interestingly, the results indicate that in all three scenarios:

- The NDC's pledges for the power sector would be comfortably met.
- Nigeria's electricity mix continues to be dominated by fossil fuel-based self-generation (between 53 and 62% of the mix, depending on the scenario) and natural gas generation (26–29%).

Nigeria however falls short of its renewable energy goals even in this very ambitious scenario: a 14.7% share of renewables in the energy mix would be achieved by 2030, when excluding large hydropower. This is in line with the government's goal of 15%. However, when large hydropower is included, the share of renewables in the mix is only 19.3%, far from the 30% government goal. In other words, the renewable energy targets are only partly met.

RQ2. What are the impacts of non-optimal transition pathways on Nigeria's development and decarbonisation goals in these three sectors?

In contrast to the Green Transition scenario, the BAU and Moderate scenarios point towards a delay in the transition of the power sector, where population growth overshadows the impact of policies and investments, and access to electricity stagnates or decreases by 2030 (achieved electrification rates are 53.3% and 65.9%, respectively). The BAU and Moderate scenarios result in a share of approximately 9% for renewables in the mix excluding large hydro, and 12% when including large hydro.

These non-optimal pathways imply that national plans are weakly implemented and that the change in elements of the socio-technical system continues along historical trends. There are incremental improvements in some elements, mainly on gas-based and centralised electricity supply solutions, but the scale-up of decentralized and renewable energy markets proceeds at a slow pace. The underlying driver is the lack of significant mitigation of investment risks (via finance, policy and enabling environment) for both on-grid (generation, transmission, distribution) and sustainable off-grid investments (mini-grids and standalone systems). In the intermediate (Moderate) scenario, there is no strong drive for renewables-based on-grid projects, but continued reductions in the cost of renewable energy technologies eventually bring about their presence in the mix.

RQ3. What niche developments will be key in inducing the transition in these three sectors and what factors affect them?

According to this study, the transition of the power sector strongly relies on niche innovations in renewable electricity sources, energy efficiency, and off-grid electrification approaches. The ambitious (Green Transition) scenario sees 88.2 million people receiving electricity from sustainable off-grid solutions over a 15-year period, including over 40 million from standalone solar PV systems. While this rate of scale up was considered feasible by some of the experts consulted, it would entail an unprecedented speed and scale of transition in the off-grid sector.

The transformation of the renewables sector various and interconnected challenges, some of which are common to both grid-based and decentralised systems. The key challenges that they have in common are lack of finance, high investment risks and a poor enabling environment.

Stakeholders highlighted the role that emerging financing tools and funds can play in stimulating the growth of these key niches. They address key barriers for investments in the off-grid electricity market, such as the lack of access to capital by consumers, the high investment risk that prevails in Nigeria, the weak enabling environment, and the lack of data to make investment decisions. Sources of finance to underwrite or de-risk off-grid investments or provide guarantees to mini-grid and standalone PV system developers are fundamental to trigger the systemic transition.

One of the vital factors slowing the growth of the niches lies in the existing regime and specifically the very large share of fossil fuel-based back-up generation in the mix. In the absence of clear policy signals (e.g. fuel price reform, import duties) many millions of households and businesses will still opt for diesel and petrol back-up generators rather than sustainable off-grid solutions.

RQ4. What are the critical uncertainties in the planning and management of Nigeria's transition?

The underlying conditions (financial, policy and enabling environment-related) that underpin the transition (and that drive the scenarios as described in the Supplementary Material of the article) are very dynamic and uncertain. Moreover, their effect is strongly influenced by larger political economy realities (some of these are discussed further under the section "updates since publication" below).

Planning and managing the transition in the power sector, and indeed researching it, suffers from strong data inadequacies and limitations in gaining access to expert knowledge that is available but fragmented. In particular, the development of demand is very difficult to project (the limitations in this respect are described in the article). Some other key areas of uncertainty include the baseline for fossil fuel-based back-up generators, as well as their pace of scale-up and the relationship between scale-up of sustainable off-grid access solutions and the shift away from back-up generators. In some areas, there are no reliable figures on techno-economic potential (e.g. small hydropower in Nigeria).

Implications for businesses

The many links between the study's findings and business innovation in the power sector can be grouped into two main categories: on the one hand, the impact of lack of reliable power on businesses (from micro and small enterprise to large companies; from informal to formal); on the other, the role of new businesses displacing the incumbents and delivering the transformation of Nigeria's power sector.

Businesses impacted by lack of affordable reliable power

Across Africa, over three-quarters of firms experience regular power outages, and for two-fifths of these businesses, electricity is the biggest constraint on operations (Cole *et al.*, 2018; The Economist, 2024b). Around half of all African companies depend on petrol and diesel back-up generators, with Nigeria's generator capacity being, by some estimates, up to four times what the national grid can reliably supply (Heinemann *et al.*, 2022).

Access to electricity ranks as one of the major constraints for the Nigerian private sector according to the World Bank's Ease of Doing Business report (World Bank, 2020). The lack of access to power and reliance on disrupts productivity, increases operational costs, and limits business growth, particularly for small and medium enterprises. The investment into backup power solutions diverts funds that could otherwise be used for innovation or expansion. The impact is particularly strong in the MSME sector. According to the Nigerian Bureau of Statistics, there are currently over 39,6 million MSMEs in the country, with micro enterprises constituting 96.9% and SMEs making up 3.1% (SMEDAN, 2022).

Role of businesses in delivering the transformation of the power sector

The scenarios in the study aim to capture the challenges faced by both on-grid and off-grid renewable energy businesses, such as investment risk, limited access to finance, and bureaucratic red tape. In the current high risk investment environment, renewable energy businesses need support from patient and flexible capital (Financial Times, 2023; Isah *et al.*, 2023) as well as supportive policies.

As well as the different policy and financing initiatives in place aiming to lower risks, there are also different regime-level forces influencing the development of these emerging niches. Notable developments include Nigeria's phasing out of petrol subsidies last year, which has had dramatic social impacts, but has increased competitiveness of businesses in the renewables sector. Another change at the regime level has been a shift towards decentralised governance of the power sector by way of new legislation: the Electricity Act of 2023 has paved the way for more flexible electrification planning that will likely remove barriers for renewables investments (see next section on updates since publication for further details).

The article also captures the role of innovation for creating and sustaining niches in the transition. Evidence is now clear that business models for renewable energy in Africa are rapidly evolving to access new markets, implement niche technologies, and comply with emerging policy frameworks (Mukoro *et al.*, 2022; The Economist, 2024b). A range of policy initiatives are correlated with technical and business innovation in the renewable energy sector in African countries (Nyiwul and Koirala, 2024). The interactions between the policy strategies are as well a key factor in creating conducive conditions for business model innovation (Trotter and Brophy, 2022).

Finally, the article provides valuable insights for businesses active or willing to enter Nigeria's power sector, regarding where the country's long-term planning could be heading and how this would affect business strategies. The different climate and development goals that Nigeria has in place for the power sector allow businesses to adopt a strategic outlook in the face of policy and market trends, anticipating future challenges and opportunities and adjusting their strategies in response to evolving circumstances.

Update since publication

At the time of its publication in 2020, the article demonstrated potential pathways towards meeting Nigeria's transition goals in the power sector, as well as the potential outcomes in case of lack of policy action. The results pointed to important inconsistencies in the country's first NDC regarding, on the one hand, the full extent of emissions arising from Nigeria's vast fleet of back-up fossil-based generators and, on the other, the overlooked potential for development pathways that meet demand for electricity while staying within Nigeria's emission reduction goals.

Since the study was published, a number of important developments have taken place in Nigeria's power sector as well as in scenario studies for the sector. However, overall, the rate of access to electricity has seen very little change. While some gains have been made, these have been offset by the growth in population, and the lack of electricity continues to be a key barrier to socio-economic development in Nigeria.

At the time of the study was conducted, data regarding the rate of electricity access in Nigeria indicated that 77 million Nigerians had no access to grid power, based on data from 2017 (IEA, 2018b). This figure has currently increased to 86.25 million. In the last years, Nigeria surpassed India as the top country in the world in terms of number of people without access to electricity. The country continues to represent about 10% of the world's electricity access deficit, and consequently and is the priority for many policy and financing initiatives globally (IRENA *et al.*, 2024) .

Despite this stagnation, the trend towards an increasingly distributed energy system, where small-scale solutions play a significant role in meeting demand, has gained pace since the time of publication. Nigeria's off-grid renewables sector has seen considerable growth, and in particular the sales of solar home systems (SHS) sales, increasing by 89% in 2022 and by 14% in 2023 (GOGLA, 2024). The slower growth in 2023 can still be considered an achievement in the sector, given the severe inflation and economic crisis in that year. A shift in the market is also seen in terms of the business landscape, with several large multinational companies now firmly established in the country and selling off-grid solar products in the scale of 100,000 units yearly.

On the other hand, grid-connected renewables have not taken off: Nigeria is yet to have any significant grid-connected renewable generation capacity. Fourteen solar PV companies which had signed power purchase agreements (PPAs) in 2016, with a combined capacity of 1 GW, were considered as a basis for the optimistic scenario in the article. As of 2024 these have yet to be commissioned due to a deadlock in the negotiation between the developers and the government (Energy for Growth, 2019) . Electricity output from solar PV remains a negligible share of the country's mix, in contrast to the growth seen in other African economies in the last half a decade (IRENA, 2024).

As to natural gas-based generation, the output remains approximately at the same level as when the article was written. Despite some relevant increases in capacity in hydro (Zungeru plant of 700 MW, was financed with support from China and inaugurated in 2024), these supply technologies have continued to face strong bottlenecks in transmission as well as financing and liquidity barriers (Anyaogu, 2024).

When it was published in 2020, the article became the first to explicitly model the extent of self-generation. However, there continues to be a strong uncertainty around the size and trends in the market. In recent reports, the IEA has begun to acknowledge the vast amount of power that is consumed from back up generation (a figure of 40% was cited in a recent report (IEA, 2023), but no national statistics are available to confirm this). The removal of subsidies for petroleum products in May 2023 is expected to have profound implications in Nigeria's electricity sector (Adeoye, 2024) , but the full effects on the electricity access rates and uptake of alternative supply technologies are yet to be observed.

There have been since other academic studies that look at different elements of the transition of the power sector in Nigeria, often with the use of scenarios and occasionally with Socio-Technical Transition studies as a theoretical backdrop (Adedokun *et al.*, 2023; Adeoye, 2024; Adeshina *et al.*, 2024; S. Isihak *et al.*, 2024; S. R. Isihak, 2023; Shari *et al.*, 2024). There however continues to be a lack of research that looks at the intersection between electricity access and decarbonisation.

The greatest contribution to knowledge has come from the Nigerian government and other sources of grey literature: in 2021, the Nigerian government published two new scenario plans for the sector. One was a short-term plan and was included within the updated Nationally Determined Contribution (NDC) (FMEnv, 2021b). The other is the Energy Transition Plan (ETP), Nigeria's long-term ”net zero” commitment as announced in COP26 in Glasgow (FGN, 2021), and specifically its goals for the power sector, These two policy documents provide a broad brush but ambitious visions for the sector and are aligned with many of the scenario assumptions that are used in the first article of this thesis (the ETP also guides many of the scenario assumptions in the second and third articles of this thesis). One further important development has been the creation of an Integrated Resource Plan (IRP) for the power sector in 2024. See section 4.5 Additional results for further details and discussion on the alignment between the NDC and IRP, and how the author was involved in the development of both plans.

3.3. Article 2: Built for net-zero: analysis of long-term greenhouse gas emission pathways for the Nigerian cement sector

Originally published as: Yetano Roche, M. (2023). *Built for net-zero: analysis of long-term greenhouse gas emission pathways for the Nigerian cement sector*. Journal of Cleaner Production, 383, 135446, https://doi.org/10.1016/j.jclepro.2022.135446.

Note on reproduced material:

Abstract of the published article (reproduced verbatim):

Nigeria is Africa's top cement producer and could be on course to be one of the top producers globally. The goal of this study is to identify and critically examine the pathways available to Nigeria to meet its decarbonisation goals in the cement sector. Based on a literature review, the study assesses demand drivers and decarbonisation potentials for the sector. It then presents two different quantitative pathways for growth in production of cement by 2050, and three different pathways for decarbonisation of the sector. Using published data and a scenario analysis tool, the study calculates how the sector's emissions might evolve under each of these pathways.

The results indicate that, in the most ambitious scenario, emissions from the sector can plateau by the late 2030s, resulting in an overall increase of 21% by 2050 (compared to 2015 levels). Achieving this scenario is necessary in order to put the sector on a path to net zero emissions beyond 2050. The scenario is driven by reductions in both energy-related and process emissions, as well as a small share of carbon capture and storage and demand management. A moderately ambitious scenario that relies mostly on savings on energy-related emissions results in an 84% increase in emissions by 2050. Finally, the Business-as-Usual scenario results in an almost tripling of emissions by 2050. The results indicate a strong potential for policies to drive improvements in energy efficiency and clinker-to-cement ratio. Critical areas of uncertainty within the assumptions include the production rates (including the evolution of the export market) and the fuel mix.

Graphical abstract

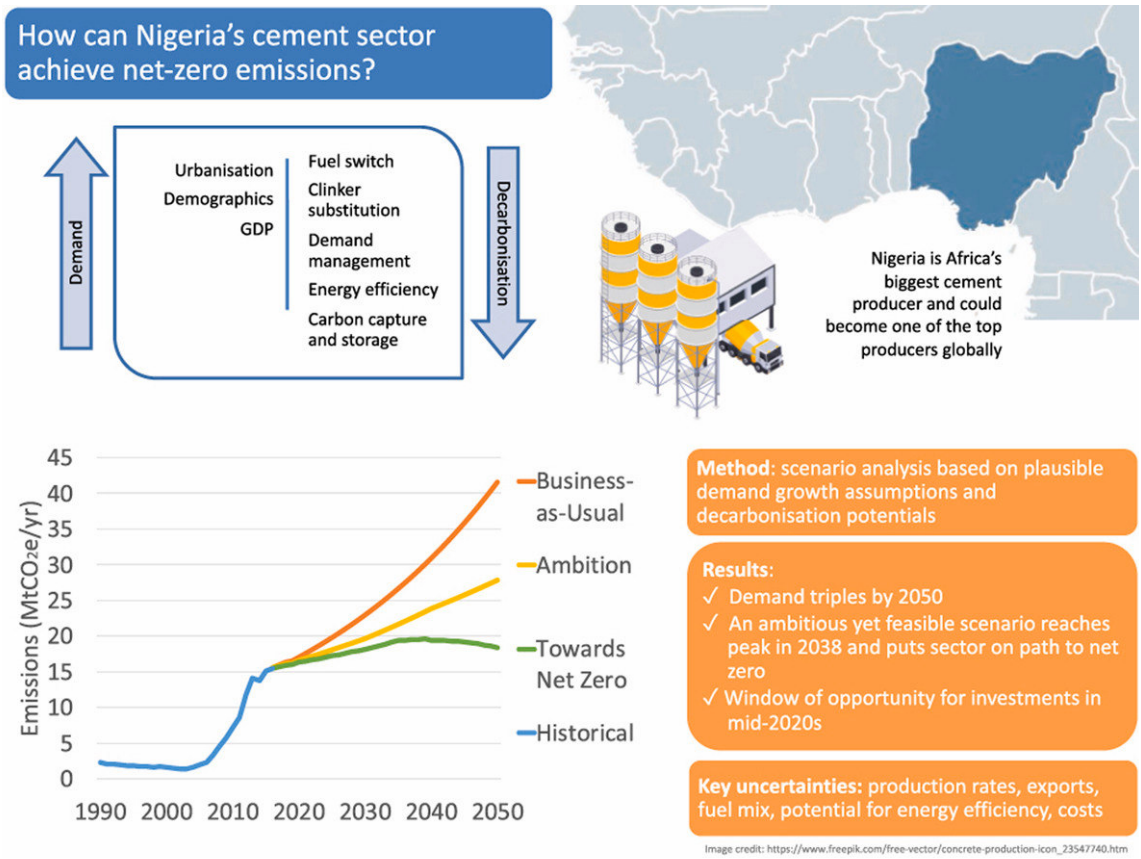

Figure 7. Graphical abstract Article 2

Links to theoretical framework

This section discusses how the research article applies existing theories and concepts, while also contributing to the advancement of socio-technical transition studies and the use of long-term scenarios in international climate governance.

<u>*Socio-technical transition studies in a global south context*</u>

Drawing on socio-technical transition studies, and using the method of scenario analysis, the article identified plausible future changes in underlying drivers of cement production (e.g. demographics, economic growth) and cement decarbonisation (e.g. technological improvements, policies, investments) and tested how they would interact and lead to outcomes in terms of the GHG emissions of the sector in the long-term.

In line with the theoretical framework of this thesis, this article considers the Nigerian cement sector to be a *socio-technical system (STS)* that encompasses different elements: infrastructure, knowledge, markets, regulation, etc. (Trist, 1981) . It is also important to note that the cement sector STS is strongly coupled with other STS such as energy and construction sectors, which are upstream and downstream of its technology value chain (Griffiths *et al.*, 2023).

The narratives underlying the two demand pathways and three decarbonisation scenarios presented in the article are based on the MLP theory. They distinguish three levels of transition processes:

(a) the *regime* level, representing established cement production technologies and markets, a set of very long-lived infrastructure investments with high potential for lock-in (Wesseling and Van der Vooren, 2017);

(b) the *landscape* level, including various external pressures affecting Nigeria's transition processes, such as its policy objectives in the areas of economic diversification (away from oil and gas), industrialisation, exports, housing and transport infrastructure, and decarbonisation.

(c) the *niche* level, particularly in the area of new technologies for cement decarbonisation, some of which are innovative in both developed and developing countries (e.g. carbon capture and storage (CCS), new value chains such as bioenergy). However, it also considers mature technologies, such as clinker substitutes, which are not yet widespread in developing and emerging countries.

The research article is highly unique in the field of STS studies in that there are virtually no studies that focus on hard-to-abate sectors such as cement in the context of developing countries. A review of over 800 studies on the cement sector by Griffiths *et al.* (2023) shows that while major global economies such as China and India are the subject of many publications, other relevant global cement producers remain understudied.

Studying the socio-technical transition of the cement sector in developing countries is challenging due to the lack of production data at the factory and unit level for clinker and cement (Uratani and Griffiths, 2023). For example, the coverage of energy intensity and clinker-to-cement ratio in the world's leading cement industry database is very low for Africa: 29% coverage in 2017, compared to 86% for the European Union (GCCA, 2022). This paucity of data is compounded by a limited understanding of the drivers and dynamics of future demand in these markets, where most of the world's population growth is expected to occur.

The assumptions underlying the study aim to capture some of the key characteristics of STS in a developing country. These include an immature innovation system and a limited role for centrally planned infrastructure and locally developed technology solutions, as well as weak and poorly enforced regulatory frameworks (Ramos-Mejía *et al.*, 2018a). An example of this is the choice of data sources for the study's assumptions on the electricity mix in the cement sector. The sector study found that Nigerian cement plants rely heavily on self-generation of electricity. Therefore, the use of centrally reported information on grid electricity (such as grid mix averages provided to the International Energy Agency (IEA)) was not an appropriate proxy. Instead, the assumptions were based on an in-depth study of cement manufacturers' reports, complemented by stakeholder interviews.

Long-term scenarios to guide decarbonisation and development transition pathways

Developing long-term, progressively ambitious emission reduction strategies, as aligned with the Paris Agreement, relies heavily on sector-specific scenario planning (Waisman *et al.*, 2019). This article offers detailed insights to support Nigeria's dual commitment to decarbonisation and industrialisation, focusing on one of Nigeria's key economic sectors and capturing its unique national characteristics and deep uncertainties. In doing so, it not only helps to inform the country's plans and commitments for cement decarbonisation, but also helps to identify key investments and policy interventions, and to monitor performance over time.

One of the aspects that emerges from this article regarding the use of long-term scenarios to guide socio-technical transitions is the definition of *long-term* and the implicit tension between the need to accelerate transitions and the complexities of transition dynamics, such as the diffusion of innovations and the destabilisation of established regimes (Skjølsvold and Coenen, 2021). Transitions are typically understood to be long processes, often taking decades (although some evidence suggests that under certain conditions, they can occur quite rapidly (Sovacool, 2016)). The speed at which a transition can occur is a critical element to consider in transition studies. It is important to understand how time and timing affect socio-technical transition processes, and to capture this accordingly in the scenario framework.

In this sense, the scenarios in this article differ from those in the previous article in the thesis in that they are built over a 40-year time horizon, compared to the relatively shorter horizon of the power sector scenarios (15 years). There are three reasons for this longer time horizon:

- The cement sector has long investment cycles, with typical production facilities having a lifespan of 40 years. This long asset life presents both a challenge and an opportunity for decarbonisation (IEA, 2018a), as retrofitting existing facilities to reduce emissions can be costly and complex. The longevity of these investments makes it crucial to take a long-term view when considering the transition of this sector.
- While some decarbonisation measures are immediately available to the sector (e.g. improving energy efficiency, reducing clinker-to-cement ratios, or using low-emission fuels), achieving significant reductions in cement production will require the adoption of innovative technologies

that are still in development and will only be viable in the future, such as cements with alternative materials and carbon capture, utilisation and storage (CCUS) (ETC, 2018).

- At the time the study framework was developed (2021), the Nigerian government had taken its first steps towards developing a long-term strategy (LTS) with a time horizon of 2050 [3], which was intended to complement and give coherence to the shorter-term national climate commitments enshrined in the NDC (FMEnv, 2021a)[4]. In addition, later that year, the Nigerian government unveiled its national vision to achieve net-zero emissions by 2060. These two events contributed to the choice of time horizon for the analysis of decarbonisation pathways for the Nigerian cement sector carried out in this study.

Long-term scenario planning provides a structured approach to navigating the complexities of transitioning hard-to-abate sectors. The decarbonisation scenarios used in this article follow existing scenario studies (CAT, 2017; ETC, 2018; GCCA, 2021; IEA, 2018a; McKinsey, 2021) in that they are structured around a set of key levers that can drive emissions reductions. Each lever represents a different set of interventions that can be tailored based on technological readiness, costs and the policy landscape. By building scenarios around these levers and combining them, a broader picture emerges of how they could collectively contribute to meeting climate goals.

While the use of decarbonisation levers in this article is not new, the use of decarbonisation levers in the analysis includes a number of innovations. First, the choice of levers, which in some cases follows mainstream approaches (e.g. energy efficiency and clinker-to-cement ratio levers), but gives an atypical role to CCUS and demand management:

- CCUS is given a much smaller role in the decarbonisation scenarios than in many other studies (as described in the literature review section and summarised in Table 1 of the article). While CCS is seen as a transformative lever that will enable full decarbonisation of the sector, concerns have been raised about over-reliance on this technology in long-term pathways (Edelenbosch *et al.*, 2024). For the purposes of this study, it was assumed that in the best-case scenario, only a small proportion of CCUS would be deployed in the Nigerian cement sector within the time horizon of the scenarios.
- Demand management remains underexplored as a decarbonisation lever in the cement sector, despite its high mitigation potential and synergies with other objectives (Creutzig *et al.*, 2022; Watari *et al.*, 2023). Literature on the potential of demand-side measures such as material efficiency and circularity in the cement sector in Nigeria and comparable economies is

[3] As per Article 4.19 of the Paris Agreement, which stipulates that it is necessary for countries to prepare and submit long-term climate strategies that carry through to mid-century or 2050 to the Secretariat of the UN Framework Convention on Climate Change (UNFCCC).
[4] Note that this strategy has since been updated and fully elaborated into Nigeria's Long-term Low Emissions Development Strategy (LEDS) (NCC, 2024).

extremely scarce. However, it plays a minor role in the scenarios and the article discusses potential policy and economic drivers for it.

Links to research questions

The following are some of the key conclusions from the research, in relation to the research questions of this thesis:

RQ1. Which transition pathways are likely to bring about optimal outcomes for the achievement of Nigeria's development and decarbonisation goal in the three sectors studied?

The study shows that there are no transition pathways available for the cement sector which are in line with Nigeria's stated goal of achieving net zero emissions in the sector by mid-century. However, the results shed light on what would be an optimal transition pathway that would put the sector on a *path towards* net zero later in the century. This pathway balances emissions reductions with the ability to meet growing demand for housing and infrastructure. In this ambitious but feasible scenario (called "Towards Net Zero" in the study) emissions peak in the late 2030s and then gradually decline, reaching a 21% overall increase by 2050 (compared to 2015 emissions). This is a significantly slower increase in emissions compared to the tripling of cement demand assumed in the study. The results therefore demonstrate the strong potential for decoupling emissions growth from demand growth.

Key assumptions underpinning the Towards Net-Zero (TNZ) scenario are that all three decarbonisation levers (energy efficiency, decarbonisation technologies and demand management) are used to a high degree. This in turns relies on the presence of significant investments, improvement in finance, policy, and enabling environment measures.

A key finding of the study is that the optimal transition path involves the use of both incremental and discrete changes. On the one hand, incremental improvements, such as energy efficiency and the use of alternative fuels, can lead to significant emission reductions and economic savings. On the other hand, there is a window of opportunity for investment in the mid-2020s, when new cement production capacity will be built. The study shows that Nigeria's cement plant fleet is very young today, but at the same time much of the 2050 stock is yet to be built. Major investment during this window is a key step in achieving this optimal long-term transition scenario.

RQ2. What are the impacts of non-optimal transition pathways on Nigeria's development and decarbonisation goals in these three sectors?

The findings point to a substantial increase in greenhouse gas emissions from a non-optimal transition pathway (175% increase by 2050, compared to 2015 levels, in a Business-as-Usual scenario). This would of course affect Nigeria's ability to meet its climate targets under the Paris Agreement. Furthermore, non-optimal pathways where innovations are not embraced may lead to missed economic opportunities and loss of competitiveness, either through increases in production costs or to penalties and barriers to trade for high-emission cement in future low-carbon global markets. In other words, non-optimal transition pathways in Nigeria's cement sector would compromise decarbonisation objectives and could hinder long-term economic diversification efforts.

Demand for cement and economic development are closely intertwined. It is important to remember that the study does not explore a scenario where demand does not grow. In this sense, the study does not shed light on potential non-optimal transition pathways where there is no increased economic development in Nigeria. Instead, the study explores a future in which decarbonisation efforts are not pursued and high emissions technologies are locked in. While not studied in the article, other potential negative impacts include loss of competitiveness and impacts on air quality and public health.

RQ3. What niche developments will be key in inducing the transition in these three sectors and what factors affect them?

Niche developments with high potential in the transition of the Nigerian cement sector include improvements in the clinker-to-cement ratio through the inclusion of blended cement in national cement standards and the development of value chains for alternative materials to clinker. CCUS also plays a role in the late phase of the transition. Finally, material efficiency and circularity are another area where innovation (both technological and policy) has high potential to transform the sector.

The success of these niche developments will depend on factors such as policy support, technological readiness and investment availability. The TNZ scenario assumes that the cost of decarbonisation measures, which are currently not cost-competitive in Nigeria, will continue to fall. Given the structure of the Nigerian cement market (few large players operating across the region), local financing can play a key role in implementation. Government incentives and regulatory frameworks can also play a critical role in creating an enabling environment for scaling up innovative technologies and practices. However, given Nigeria's governance challenges, price incentives are more likely to catalyse innovation than policies - for example, increased energy expenditure leading to higher cement prices, or national and international market demands for low emission cement leading to loss of competitiveness for traditional cement. Together, these factors influence how effectively these niche developments can drive a sustainable transition in Nigeria's cement industry.

RQ4. What are the critical uncertainties in the planning and management of Nigeria's transition?

In Nigeria's cement sector transition, critical uncertainties include technological readiness, financial resources, policy stability, and unpredictable demand growth. Emerging technologies like alternative cement binders may face deployment challenges due to high costs and technical limitations, while economic constraints make securing investment unpredictable. Additionally, rapid or fluctuating growth in cement demand, driven by infrastructure development, could strain production capacity and delay emissions reduction efforts, particularly if sustainable practices lag behind demand growth. Policy consistency is essential, as shifts in regulatory focus could disrupt long-term decarbonisation pathways. These combined uncertainties require flexible, adaptive planning approaches to balance environmental and economic goals.

Uncertainties in the transition are also related to data availability. For example, there exists no public survey of energy consumption and saving potentials in cement plants in Nigeria, and there exists no dataset for planned production capacity in the next decades, which could reflect expected stock turnover and investments.

Implications for businesses

The implications of the study's findings on business innovation in Nigeria's cement sector need to be placed in the context of the industry's oligopolistic structure. With a few large firms dominating the sector[5], the market dynamics present challenges but also opportunities for a transition that meets the growing demand for cement and puts the sector on a path towards decarbonisation.

Oligopolies can have mixed environmental impacts, depending on how firms respond to competitive and regulatory pressures. On the one hand, oligopolistic firms may be well placed to reduce emissions through innovation, especially if supported by targeted policies and competitive pressures. There is some evidence that larger, resource-rich firms can leverage their resources to invest in environmental innovation, and that firms in concentrated industries often have better financial and technological capabilities to make sustainable investments (Ovodenko, 2016; Rexhäuser and Rammer, 2014).

On the other hand, the dominance of a few large firms can limit market competition and slow innovation, in this case inhibiting the decarbonisation of the sector. Oligopolistic market structures can lead dominant firms to prioritise maintaining the status quo over pursuing costly or disruptive innovations, or to innovate at a slower pace than they would in a more competitive market (Phillips and Scherer,

[5] This is in line with a global trend, where large companies dominate the market. It is estimated that over half of African production capacity is owned by nine pan-regional firms (Byiers *et al.*, 2017).

1971). The literature on sustainability transitions suggests that incumbents in concentrated markets prioritise existing practices over disruptive green innovations, while new entrants drive sustainability transitions (Hockerts and Wüstenhagen, 2010).

Existing policy frameworks that have supported the growth of large cement firms in Nigeria (Akinyoade and Uche, 2016; Reuters, 2021) may need to be reassessed to enable new entrants and foster a more competitive market. Meanwhile, the large established market share of firms means that they have the potential to implement decarbonisation solutions across their extensive operations, taking advantage of economies of scale. The concentration of market power can enable coordinated industry-wide efforts to adopt sustainable practices. This could ultimately benefit the whole sector, including smaller or emerging players, as technologies become more cost-effective and widespread,

However, for these opportunities to be fully realised, policy interventions will be crucial. By introducing regulations that promote sustainability without stifling competition, Nigeria could balance the dominance of large firms with market incentives for innovation and affordability. This dual approach could position Nigeria's cement sector as a leader in both development and decarbonisation, helping it to overcome the challenges of an oligopolistic market while encouraging the uptake of low-carbon technologies.

Update since publication

At the time of its publication in 2023, the article was the first to provide a detailed analysis of transition pathways for decarbonising the cement sector for Nigeria, which is already one of the leading cement producers in Africa and is poised to become a major player in the sector globally.

There are very few studies on transition pathways for the cement sector in sub-Saharan Africa. To the author's knowledge, only one similar study has been carried out for Nigeria, taking a medium-term perspective (2035) and focusing on assessing the decarbonisation potential of fuel switching, in particular the increased use of municipal solid waste (MSW) (UKAid Manufacturing Africa Programme, 2024). In addition, an initiative has explored the possibility of piloting an innovative climate finance instrument for the cement sector in Nigeria (Instiglio, 2024) (See section 3.5 Additional findings for more details).

With regards to updates in the situation of the Nigerian cement sector as a whole, it is worth mentioning the recent dynamics in the market since the publication of the article: amid the general macroeconomic crisis in Nigeria, demand for cement dropped significantly in 2023 (Adebanjo and Anegbe, 2024). In 2024, the industry showed signs of recovery and is expected to benefit from a renewed government focus on infrastructure projects, which could stimulate demand. For example, around 5% of the total federal budget for 2024 has been allocated to infrastructure investment.

In response to these signals, cement producers have announced capacity expansions to meet the anticipated increase in demand (Adebanjo and Anegbe, 2024). Specific policy changes affecting demand include a plan to double the minimum capital requirement for the Federal Mortgage Bank of Nigeria (FMBN) to improve access to capital for housing. In addition, Nigeria's recent accession to the African Continental Free Trade Area (AfCFTA) is expected to boost cement exports in the medium term.

Another development in international climate governance is relevant to Nigeria's cement sector: the COP28 in Dubai saw the launch of the Climate Club, a forum of 35 countries and the EU to support the decarbonisation of industrial sectors (Climate Club, 2023). The concept of climate clubs dates back to 2018 and refers to alliances of states that introduce carbon pricing among club members and impose fees on imports of goods from countries outside the club (Hagen and Eisenack, 2019). The Climate Club that was launched in 2023 draws on this concept but is a looser partnership that focuses on incentives to collaboration rather than punitive measures and has a specific sectoral focus (Hermwille *et al.*, 2022; Obergassel *et al.*, 2019).

One of the main objectives of the Climate Club is to support the decarbonisation of industries in emerging and developing economies, including improving access to finance and technical assistance. The Club will create a matchmaking platform and coordinate international support efforts by developed countries to catalyse investment in countries like Nigeria, and as such it is of relevance for the long-term transition of the Nigerian cement sector.

3.4. Article 3: Towards clean cooking energy for all in Nigeria: pathways and impacts

Originally published as: Yetano Roche, M., Slater, J., Malley, C., Sesan, T., Eleri, E. (2024). *Towards clean cooking energy for all in Nigeria: pathways and impacts*. Energy Strategy Reviews, 53, 101366, DOI: https://doi.org/10.1016/j.esr.2024.101366.

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Abstract of the published article (reproduced verbatim):

Over 175 million Nigerians rely on the use of traditional biomass for cooking, and it is estimated that more than 128,000 people died in Nigeria in 2019 from household air pollution from use of traditional biomass fuels. There is currently a gap in the study of possible pathways to meet Nigeria's goals in clean cooking, and in the understanding of the health and climate impacts that different pathways can bring about. In this study we explore clean cooking access scenarios for Nigeria until 2060 under a business-as usual scenario, a moderate climate mitigation scenario, and an ambitious transformative scenario. We carry out a disaggregation at state-level for the period up to 2030, to better guide shorter-term policy development. Our analysis shows that under an ambitious scenario the access goals can be reached and annual premature deaths due to exposure to household air pollution can decrease by 7%, compared to 2018 levels. A baseline scenario, on the other hand, sees a dramatic 77% increase in premature deaths. Furthermore, we find that wood fuel removals from forestland would lead to a tripling of carbon dioxide emissions from land use change. Our findings stress the multiple impacts of a clean cooking transition in Nigeria and underline the need for immediate acceleration in national efforts regarding access to clean cooking for all.

Links to theoretical framework

This section outlines how the research article draws on established theories and concepts while contributing to the advancement of socio-technical transition studies and the use of long-term scenarios in climate governance.

Socio-technical transition studies in a global south context

This research contributes uniquely to the literature on socio-technical transitions by focusing on the clean cooking sector, an area that has been relatively less studied compared to other areas of energy and sustainability transitions (Aamaas *et al.*, 2024). Where attention has been paid to the topic, research has mainly focused on individual places and countries, with fewer analyses from a global perspective or allowing for comparisons between countries (some interesting comparative studies include (Quinn *et al.*, 2018; Troncoso and Soares da Silva, 2017; Wei and Lin, 2024)).

The cases of countries such as Brazil, India, Ecuador or Indonesia, where traditional biomass has been displaced as the main cooking fuel (Astuti *et al.*, 2019a; Coelho *et al.*, 2018; Gould *et al.*, 2018; Rehman *et al.*, 2012) illustrate the complexity of socio-technical transitions in the sector. This body of research on national transitions sheds light on some key aspects of cooking energy transitions, such as: the challenges of destabilising informal regimes, the role of subsidies in protecting niches, and the critical role of understanding user preferences. These points are explored in turn below and provide an opportunity to elaborate on some key characteristics of Nigeria's case.

Challenges of destabilising informal regimes

In treating Nigeria's cooking energy sector as a socio-technical system, the study places a strong emphasis on the central role of fuelwood as an energy source in the country. Cooking energy in Nigeria is characterised by a highly stable regime level, represented by widespread biomass (firewood and charcoal) value chains. Despite a strong lack of documentation in the sector, we know, for example, that the fuelwood and charcoal sector provides employment and income to an estimated 530,000 Nigerians (expressed in full-time equivalent jobs) (ILO, 2021), and that Nigeria is one of the largest charcoal producing and exporting countries in the world (J. Van Dam *et al.*, 2017).

The sectors are therefore large and of high economic importance. Nevertheless, they mostly operate on an informal or even illegal basis, with low levels of policy enforcement (Ali *et al.*, 2023; Orimoogunje and Asifat, 2015; Schure *et al.*, 2013). Economically and politically powerful actors, such as traders and wholesalers, hold power in the value chains (Schure *et al.*, 2013). Local wood fuel industry associations can also have strong political influence. We can draw parallels with the case of Nigeria's electricity sector, and the dominance of fossil fuel-based self-generation importers and traders at the regime level. In section 3.2, we saw that the presence of weak political institutions and well-established coalitions and elites that resist change is a key feature of regimes in rentier states (Osunmuyiwa *et al.* (2018). This is arguably the case in Nigeria's wood fuel and charcoal value chains as well, and limits the extent to which broader governance and financing frameworks at the landscape level can influence the transition.

Some transition theory scholars argue that levels of informality, loose regulations and regime gaps in developing countries are opportunities for innovation to emerge (Berkhout *et al.*, 2010), while others urge caution with these optimistic views (Ramos-Mejía *et al.*, 2018b). In any case, any intervention aimed at reducing demand for wood fuel and shifting it to cleaner fuels in Nigeria must address informality. This is complex as experience shows that formalising value chains for forest products can also have negative consequences if new regulations criminalise extraction practices, marginalise harvesters, or enable or encourage corruption (Schure *et al.*, 2013).

The role of subsidies in protecting niches in the clean cooking sector

Regimes are destabilised on condition that alternatives are available to perform the same functions in society. These alternatives are developed in niches, protected spaces where innovations are developed and scaled up. The process of managing niche formation is called Strategic Niche Management (SNM).

An analysis of the political economy of clean cooking in Nigeria shows that there is a broad consensus among state, donor and market actors that large-scale private sector investment in LPG infrastructure is the way to drive Nigeria's clean cooking transition. Policies that enable households to access clean cooking through subsidies are not considered politically or economically viable by these actors (Sesan, 2021a). This contrasts with a body of empirical evidence on cooking energy transitions, which shows that price subsidies are a fairly effective element of SNM for clean cooking fuels. Indeed, subsidies are a central component of successful transitions around the world (alongside the removal of taxes and other levies on clean fuels) (Gill-Wiehl *et al.*, 2020; Rose *et al.*, 2024; Troncoso and Soares da Silva, 2017).[6] This is because the elasticity of demand for clean cooking technologies is very high, particularly among low-income and rural households (Das *et al.*, 2022). This means that changes in fuel prices are more likely to make low-income households move up or down the 'energy ladder' (i.e., towards cleaner fuels or away from them) than in the case of middle- and high-income households.

The debate regarding subsidies in clean cooking transitions provides an opportunity to look at what theory says on the role of subsidies in SNM in general. On the one hand, subsidies are seen as central to SNM, addressing market failures and providing critical financial support to emerging sustainable technologies (Kemp *et al.*, 1998). Subsidies shield nascent innovations from the pressures of incumbent regimes, allowing them to mature without immediate competition. This protective role facilitates the establishment of supportive networks among stakeholders, fostering collaboration and the co-evolution of technologies, practices and policies. Subsidies also signal government commitment to sustainable transitions, attracting private investment and enhancing the credibility of emerging niches (Meadowcroft, 2005; Schot and Geels, 2008).

There are also arguments against the use of subsidies to protect innovation niches. One is that when subsidies are eventually withdrawn, adoption may reverse. The second is that subsidies reduce incentives for market innovation, lead to market distortions and promote dependency on niche innovations rather than fostering competitiveness and self-sufficiency in the long run (Kemp *et al.*, 1998). Subsidies can also provoke resistance from incumbent industries and stakeholders who may

[6] There is some debate about the relative merits of subsidising operating costs (the price of LPG fuel or cylinder refills) rather than initial investment costs (LPG cylinders and stoves) (Soni and Chatterjee, 2023)).

perceive such measures as unfair competition, potentially delaying broader systemic transitions (Schot and Geels, 2008).

User preferences and determinants of behaviour change

The multi-level perspective is useful to map a large-scale transition process but traditionally tends to give less attention to actors (Geels, 2020; Geels and Schot, 2007). Yet, the MLP does allow the zooming into actors and their preferences, which can help optimise innovation efforts. For example, the role of energy consumers in the energy transition can be studied in detail. An interesting recent trend in transition theory looks at the links between behaviour and system change (a recent review is found in (Kaufman *et al.*, 2021)).

In this sense, a large body of literature already exists regarding the determinants of behaviour change and adoption of clean cooking fuels and practices at the level of individuals and households (Gill-Wiehl *et al.*, 2021; Sesan, 2021b; Shankar *et al.*, 2020). These studies provide comprehensive insights into the complex dynamics of household energy decisions, shedding light on factors influencing the success of niche innovations such as clean cooking fuels. In fact, there are many insights specifically for Nigeria: income, fuel accessibility, type of dwelling, household size, level of education (especially of the head of the household), belonging to a cooperative, having access to electricity, and having access to the Internet have been found by various authors to be significant determinants of household cooking fuel choice in Nigeria (Eludoyin and Lemaire, 2021; Jewitt *et al.*, 2020; Okereke *et al.*, 2023; Oyeniran and Isola, 2023). These studies also reveal important dynamics, such as that of ‘stove stacking’ (use of multiple fuels to shield against variations in fuel prices, access, and reliability of supply (Shankar *et al.*, 2020)) and ‘backsliding’ towards lower-quality fuels as a result of price variations. They also point to the limited awareness or concern about household air pollution and health risks that users have.

As pointed out in the discussion section of the article, the price-sensitive nature of cooking fuel demand, and the different dynamics across population segments (e.g. urban vs rural) are some of the well-known nuances of household energy use and technology adoption patterns that are not fully captured in the study’s assumptions. Nevertheless, there is great potential in enriching future transition studies of Nigeria’s clean cooking transition with these insights, and indeed of linking the MLP framework more strongly with knowledge about the preferences and agency of all types of actors: end users, niche actors, regime actors.

Long-term scenarios to guide decarbonisation and development transition pathways

The study captures the dynamics of the clean cooking sector in Nigeria, using scenario analysis to explore the potential pathways for its transition. In this sense it forms part of a family of studies that provide ‘hard’ evidence regarding the benefits of the transition to modern cooking energy, and the high costs of inaction in this area. Such evidence is one important (but by far not the only) driver of policy efforts to drive the transition.

The literature regarding the use of long-term scenarios for cooking energy transitions is reviewed extensively in the article, under Section 2.3 "Literature on cooking energy transitions and impacts". The review reveals that clean cooking energy scenario studies can be found at different scales (local, national and global), that they use different key drivers in their assumptions (e.g., demographic, economic) and analyse different impacts (e.g., health, gender, deforestation, climate), sometimes in isolation, and other times in an integrated way.

The key message of the review is that it is of utmost importance for scenario studies of transitions to capture the peculiarities of each local context. Only then can they guide the policy, market, and technological interventions needed to accelerate the transition. The fact that Nigeria is lacking scenario studies in the clean cooking sector must be seen in the broader context of the mismatch in abilities for strategic foresight between developed and developing countries (Reilly-King *et al.*, 2024).

Specifically in the arena of international climate governance, the preparation of nationally determined contributions (NDCs) is a cornerstone of the Paris Agreement. The availability of context-specific transition scenario studies can therefore influence a countries ability to shape its national climate ambitions. Moreover, countries that can articulate the co-benefits of their climate targets (in the case of cooking, these would be primarily health co-benefits) can use them as advocacy tools (Mayrhofer and Gupta, 2016). This is because co-benefits help to align the temporal and scalar difference between climate policy costs and climate policy benefits/impacts (co-benefits take effect immediately and are hence more politically feasible).

Links to research questions

The following are some of the key conclusions from the research, in relation to the research questions of this thesis:

RQ1. Which transition pathways are likely to bring about optimal outcomes for the achievement of Nigeria's development and decarbonisation goal in the three sectors studied?

The study sheds light on a plausible future (illustrated by the Ambition scenario) in which Nigeria's socio-technical system for clean cooking rapidly transforms under the influence of significant investments, improvements in finance, policy and enabling environment measures. In this future, Nigeria meets the government's access and decarbonisation targets for the cooking sector as outlined in the Energy Transition Plan (ETP). The study then examines how this pathway leads to outcomes in terms of health and GHG emissions (it is important to note, however, that Nigeria has no national health targets related to household energy).

In this sense, the scenario design relied heavily on a back-casting approach, testing the feasibility and impact of existing policy targets for the sector. The Ambition scenario is based on the current national vision for the cooking sector, reflecting both its long-term goals and key turning points. However, it articulates additional assumptions about what drives the transition, such as plausible displacement rates (the rate at which one fuel displaces another) and differentiated rates of transition across states (the ETP does not make state-level assumptions). In this way, it provides transparency on what Nigeria's clean cooking energy transition would entail.

While this high-level scenario cannot capture all the complexities of the clean cooking energy transition, it provides a picture of how fast the transition would need to be to meet the targets. Like the ETP, the Ambition scenario in this study assumes very rapid rates of adoption of clean cooking technologies to achieve the vision, while keeping pace with population growth. For example, it assumes that by 2030, between 30 and 45% of households using traditional biomass in each state will have switched to either LPG, ICS or electricity. Given that LPG penetration in rural Nigeria is currently only 5%, this implies a very disruptive rate of adoption. However, the uptake in this pathway is slower than in the ETP, which assumes that 75% of traditional biomass stoves will be phased out by 2030.

The Ambition Scenario also assumes a strong shift to biogas and electricity in the long term, starting in the 2030s and continuing until 2060, at which point both technologies completely displace LPG and become the only technologies in the market (in line with the ETP targets). The study's discussion questions the feasibility of this longer-term vision (see answer to Research Question 4, below).

RQ2. What are the impacts of non-optimal transition pathways on Nigeria's development and decarbonisation goals in these three sectors?

The study adds to the existing body of knowledge on the costs of inaction on clean cooking. The findings shed light on the impact of two scenarios ("Baseline" and "Moderate") in which the transition is delayed. This would perpetuate high levels of indoor air pollution, affecting public health, particularly for children under 5. For the Baseline scenario, this means a dramatic 77% increase in annual premature deaths related to household air pollution in 2060 compared to 2018 levels. This means that in 2060 over 209,000 premature deaths would occur annually due to the use of biomass for cooking, of which 94,000 children under 5. In addition, the analysis quantifies wood fuel removals under the Baseline scenario and finds that they would lead to a tripling of net carbon dioxide emissions from forestland compared to 2018 levels. Overall, these futures would undermine Nigeria's progress in development and decarbonisation.

RQ3. What niche developments will be key in inducing the transition in these three sectors and what factors affect them?

The study analyses the pathways by which emerging niches can displace polluting biomass fuels in Nigeria under different scenarios and the pace at which this displacement can occur (see Table 2 of the article for a summary of assumptions). The study assumes that in this scenario there is an effective policy framework in place as well to protect the emerging niches. The study does not elaborate on the key policies that would be required to provide this protection, but some discussion of the potential role of subsidies is provided in the section above on "*The role of subsidies in protecting niches in the clean cooking sector*".

The study sheds light on the factors influencing the success of niche innovations by drawing on the literature review section (sections 2.2. Cooking energy in Nigeria today and 2.3 2.3. Literature on cooking energy transitions and impacts) to synthesise existing knowledge, the current policy landscape and the complex dynamics of household energy choices. The latter reveals a substantial body of knowledge on the price-sensitive nature of cooking fuel demand, the determinants of household cooking fuel choice and behaviour change, and important dynamics such as 'stove stacking' and 'backsliding'. The study identifies the limitations in capturing these factors in scenario assumptions and makes recommendations on how future transition studies could better capture them. Two key priorities would be to capture the dynamics of clean cooking transitions in urban versus rural households, and a more dynamic analysis of fuel switching rates that includes backsliding and stove stacking.

RQ4. What are the critical uncertainties in the planning and management of Nigeria's transition?

Key uncertainties in the transition are identified in this study and include the pace of technology adoption, the stability of policy frameworks such as LPG infrastructure expansion programmes, the availability of financing and an enabling environment, future LPG price volatility, and the development of the electric cooking and biogas value chains (given the current scarcity and unreliability of electricity supply). Addressing these uncertainties requires adaptive planning and the strengthening of scenario-based decision making to navigate evolving conditions.

Lack of data also limits the study of the transition. For example, while there are several sources of data on household fuel and cookstove use in Nigeria, only one survey provides state-level data. There are also significant gaps in knowledge about the structure of biomass value chains, due to their largely informal nature. There is currently no map of wood fuel demand and supply areas at the national level. Other important data gaps include the lack of national-level data on cooking energy in industry, SMEs and institutions, despite this being a very important demand sector. There is also no national survey to estimate the current size of the market for improved wood and charcoal stoves. The study also notes among its caveats that the health impact calculations would benefit from incorporating the health risks of fuels other than biomass, such as LPG, and from modelling future changes in Baseline Mortality Rates (the study assumes that they remain stable over the next decades).

Implications for businesses

The scenarios analysed in this study were built on knowledge regarding the history and trajectory of the innovation landscape for both conventional and new cooking fuels and technologies in Nigeria. This knowledge had been synthesised as part of a previous publication, which formed the basis for the scenario assumptions (Yetano Roche, 2021b). During this previous study, engagement with private-sector actors in the different value chains (LPG, improved biomass cookstoves, renewable fuels, electric solar cooking) as well as several key market-enablers and sector experts painted a picture of a business ecosystem for clean cooking that remains weak, but were many opportunities can be found for the right business models in the right consumer segments. The following is a summary of the key links between the scenarios in the study and the status of the LPG, ICS and electric solar cooking value chains.

LPG value chain

In the LPG sector, key policy initiatives, such as the Nigerian LPG Expansion Plan and Lagos state policies had, by 2020 effectively supported the development of a dynamic value chain. Following the removal of the longstanding subsidy on kerosene fuel, many importers and distributors (as well as oil companies operating the downstream segment) shifted their focus towards their LPG business (Ogundari *et al.*, 2018). It is important to note however, that consumer subsidies for LPG were not put in place and are not considered politically or economically viable (Sesan, 2021a), in contrast with evidence of their success in other markets (see section "Links to theoretical framework" for full discussion on this).

The key focus of national LPG policies has been in developing supply and distribution, in what is currently a customer-owned LPG cylinder market. In other words, customers own most LPG cylinders currently in circulation in Nigeria, and there is a significant number of small firms in the segment, including informal last-mile distributors. This is characteristic of an early-stage LPG market, showing the signs of a transition to a fully mature retailer-centred cylinder market like those in Brazil or Indonesia (Astuti *et al.*, 2019b). A credit facility proposed in 2020 as part of the National Gas Expansion Programme aims to promote this by facilitating access to finance for larger retailers (Adekoya, 2020). Waivers of VAT on the domestic production of LPG and import duty on LPG equipment and accessories have been in place for some time, as are regulation and standards for LPG distribution and dispensing that will support the market (CCA, 2017).

Specific challenges and opportunities that remain for LPG is increased availability of finance for distributors and retailers, innovations to increase affordability for consumers and the strengthening of publicly available market data that aids monitoring and decision-making. One notable innovation in LPG consumer financing models is the emergence of firms integrating pay-as-you-go approaches, which can align the earning and consumption patterns of low-income households (Alderman, 2019).

ICS value chain

In contrast to LPG, where businesses are already the target of policy support and have a platform for continuous engagement with government, no national level policy framework is available to support ICS firms. Carbon finance and donor funds remain the only sources of finance in the value chain and continue to be very scarce. Finance from the Bank of Industry (BoI) is available for importers of machinery related to clean cooking (such as pellet/briquette machines) but not for importing stoves or stove components (Yetano Roche, 2021b).

There is a stark lack of financing options to allow early-stage companies to grow. Expert interviews indicated that business incubation and support mechanisms for early-stage ICS firms are a crucial next A number of catalytic funding and investor matchmaking initiatives have emerged, but they remain negligible compared to the number of business incubation initiatives in other areas, for example the off-grid renewable electricity space.

One further barrier in the ICS value chain is the lack of standards. The range of ICS models available in the Nigerian market typically reduce fuel consumption by 20% or more and reduce emissions of indoor air pollutants such as particulate matter and carbon monoxide. However, the quality of ICS it is often unknown how well the stoves perform as there is no quality assurance programme in place. A quality standard was approved in 2017 but is yet to be enforced (CCA, 2017).

Finally, there is a complete lack of awareness about the sector among commercial banks and very limited experience within microfinance institutions. In sum, ICS businesses have a larger set of barriers to navigate than LPG, and less attention from donors and financial institutions.

Solar electric cooking value chain

Though not yet present in the national business ecosystem, solar electric cooking is a potentially transformative addition to the business landscape. Recent price drops in battery technology are opening the door for the use of solar PV panels to charge a battery which can then be used for cooking. Pilot projects have shown promising results, and the Modern Energy Cooking Services (MECS) Programme has developed research on policy barriers to the adoption of solar electric cooking in Nigeria (Carlin *et al.*, 2021). Among the challenges, grid reliability issues and the high cost of off-grid solar electricity, and lack of national data on cooking preferences. Regarding opportunities, a robust private sector, both in the form of entrepreneurs and investors, and the opportunity to take advantage of the recent success of the solar off-grid sector, including increased capacities in government agencies and coordinated donor support.

In sum, key challenges to market penetration of clean cooking technologies and business innovations in Nigeria include cost, consumer awareness and social norms, whereas there are also large opportunities in the untapped market, and synergies with innovations in other sectors such as off-grid renewables. The next section provides some important updates in the sector since the time of the publication.

Update since publication

The work carried out for this publication spans a 5-year period, between the first steps in the research in 2019 and the publication of the study in 2024. Important developments have taken place during this time.

In the early phases of the research (2019-2020), some notable characteristics of the market included the momentum in the LPG value chain (particularly in urban areas) and the recent establishment of larger multinational companies who had attracted important investments and were applying innovative business models and strategies tailored to local contexts. The expectation was that the market was about to see a strong acceleration. In 2021, Nigeria unveiled its Energy Transition Plan, including ambitious plans to achieve access and decarbonisation targets for the sector, with a strong role for LPG in the transition. The research set out in late 2021 aiming to inform future policies in this sense.

However, as the research progressed, an economic crisis of unprecedented scale started unfolding in 2022 (The Economist, 2024a). The cost of living and inflation crises was preceded by an already harsh economic shock triggered by the covid pandemic (World Bank, 2021). Amid this crisis, the price of LPG has soared, tripling its average retail price between 2022 and 2024 and effectively quadrupling 2021 prices (NBS, 2024a). This is despite the withdrawal of Value Added Tax (VAT) on the fuel and a limit set on LPG exports (Addeh, 2024; Adeoya, 2024).

The picture that emerges from the latest national household survey published in November 2024 (with data collected between July 2023 and March 2024) (NBS, 2024b) is mixed: on the one hand, LPG use has continued to increase. On the other, so has the use of solid biomass. There is a clear transition away from kerosene (with an 18.4% decrease in its use since the last wave of the survey in 2019, with only 2% of households currently using it) and a continued increase in LPG adoption (13.1% increase overall, more in urban areas). However, the sharp rise in LPG prices has slowed down the shift towards this fuel and instead forced many Nigerian households to revert to cooking with firewood and charcoal, with households now reporting an even greater use than in 2019.

Another notable development since the time of the study was the government's approval of the country's first National Clean Cooking Policy, which provides some clarity on governance structures for the transition as well as short term (2030) targets (FMEnv, 2024). However, the government's long-term plan for the sector is still to be reviewed.

In sum, recent developments demonstrate that significant shifts in the economic landscape can influence both the pace and scale of clean cooking transition pathways. To achieve the clean cooking transition envisioned by the Ambition scenario the study, policies for clean cooking should anticipate and aim to mitigate the effects of macroeconomic shocks and fuel price fluctuations, such as those still unfolding in Nigeria at the time of writing.

3.5. Additional research results

In parallel with the empirical work presented above, the author conducted additional research (Table 1) that complements the thesis' findings and provides further insights into the research questions. Below is a summary of ten of these publications and their key insights.

Table 1. List of additional research results that complement or expand on the empirical research

Relevance	Publication and year
Article 1 Electricity	Update of NDC target for the power sector – *lead author* (2020)
	Power sector planning - Integrated Resource Plan (2023)
	Renewables in fragile and conflict afflicted settings (2023)
	Alignment of Nigeria's ETP, NDC and other climate goals (2023)
	Nigeria Off-grid Solar Knowledge Hub and case study series (2023)
Article 2 Cement	Transition pathways for the Nigerian cement sector. Conference paper Eceee Industry – *lead author* (2020)
	Cement sector demand and decarbonisation scenarios report – *lead author* (2021)
Article 3 Cooking Energy	Analysis of cooking energy business ecosystem – *lead author* (2021)
	Participatory Visioning Process for Nigeria's Clean-Cooking Goals – *lead author* (2022)
	Research article on base year data and methodology that formed the basis for the scenarios (2025)

Publications relevant to Article 1

Nigeria's enhanced Nationally Determined contribution: Report to support the update of the mitigation target for the electricity sector (Yetano Roche, 2020)

This report supported Nigeria's Federal Ministry of Environment in revising its Nationally Determined Contribution (NDC) submission as stipulated under the Paris Agreement. The author was contracted by Gopa Intec Consultants to deliver a proposal for updated and transparent mitigation targets for Nigeria's electricity sector by 2030 under Business-as-Usual, Unconditional, and Conditional scenarios. The work was funded by the Nigerian Energy Support Programme (NESP)[7] and as part of a UNDP Technical Assistance programme to support developing countries in the updating of their NDCs. Key contributions by the author (who was the sole author of the report):

- Highlighted the critical role of data (e.g., fossil-fuel-based self-generation) and government strategies like the Presidential Power Initiative in achieving sustainable energy goals.
- Emphasised stakeholder engagement, with consultations held in 2020 to validate findings and recommendations.

Technical Assistance to Develop an Integrated Resource Plan (IRP) for Nigeria's Power Sector (ECA Consultants, 2023)

Integrated Resource Planning (IRP) is a supply and demand-side planning approach which identifies the mix of resources for meeting long-term electricity needs at minimum cost and risk. This project was part of a long-term process for developing an integrated plan for Nigeria's power sector aligning with its NDC commitments and Energy Transition Plan (ETP). Key contributions by the author:

- Stakeholder engagement to familiarize key institutional players with IRP principles.
- Assessment of institutional, technical, and political capacities for IRP implementation.
- Development of scenarios for the power sector, including demand forecasting, assessments of renewable energy supply resources, and analysis of relevant strategies for alignment.

Study for the NDC Partnership: Aligning Nigeria's Energy Transition Plan, NDC, and Long-Term Strategy Targets (Ricardo Energy & Environment, 2023)

This study assessed the alignment across Nigeria's key climate and energy planning policy goals and documents, including the ETP and NDC, Long-Term Low Emissions Development Strategy (LT-LEDS) and the associated Deep Decarbonisation Project (DDP), the Nigeria Energy Calculator 2050 (NECAL2050), and the Integrated Resource Plan (IRP). The study identified differences in the long-term "visions" of each document, with differing balances between transition to renewables versus utilization of local gas resources, and often differing envisioned timelines for electrification (a key development objective for Nigeria). Differences in scope between the projects was also found – the ETP focuses on the energy sector alone, while the LT-LEDS and NDC have full sectoral coverage, and the NECAL2050 tool covers all sectors but with focus on energy-related aspects of non-energy sectors. The author provided input in the scoping of the project as well as expert review of the recommendations and

[7] NESP is co-funded by the European Union and the German Government and implemented by GIZ (Deutsche Gesellschaft für Internationale Zusammenarbeit) and the Federal Ministry of Power (FMP). Under a UNDP-funded programme, NESP supported the FMEnv in the updating of the mitigation target for the electricity sector.

of the findings for the power sector, in particular goals and timelines for renewables, gas utilisation, and electrification.

Understanding Peace and Conflict Dynamics of Renewable Energy Projects in Fragile and Conflict-Affected States (Beijer et al., 2023)

Achieving targets for universal energy access and net zero emissions requires an exponential expansion of investment in renewable energy in fragile and conflict-affected settings (FCAS). These countries are home to many of the 675 million people living without access to electricity globally. Drawing on literature and interviews with project developers, investors, affected communities, energy practitioners, and researchers, this study offered key recommendations on the integration of conflict sensitivity throughout the lifecycle of the RE projects. These insights are relevant for some of Nigeria's high-risk investments in renewables which are crucial to meeting the country's energy access and climate goals.

Nigeria Off-grid Solar Knowledge Hub and Case study series of the PeopleSuN Project (Energypedia, 2023)

The author led the development of this online knowledge hub, which offers curated guidance materials and tools to support Nigerian off-grid solar practitioners in the development of successful, inclusive and sustainable off-grid solar interventions. It is geared to meet the knowledge needs of early-stage off-grid solar businesses. In addition to the guidance there is a series of in-depth case studies delving into the approaches taken by Nigerian practitioners in designing solar off-grid business models and market interventions. The author was the lead author for 4 case studies and contributing author for another 4 case studies.

Publications Relevant to Article 2

Assessment of transition pathways for the Nigerian cement sector. Conference paper Eceee Industry (Yetano Roche, 2020)

This paper contained an early version of the analysis that has been fully developed in Article 2. It was presented (online) at the conference session 'Deep decarbonisation of industry' at the annual conference of the leading ECEEE association. The main difference between this conference paper and Article 2 was the use of a 2040 timeframe and the lack of a comprehensive review of decarbonisation levers that specifically considered the Nigerian context (the conference paper was based on global assumptions, while Article 3 used more refined data and Nigeria-specific assumptions on potential pathways).

Cement sector demand and decarbonisation scenarios *(Yetano Roche, 2021a)*

This internal report laid out the early results of the analysis that is fully developed in Article 2. Importantly, it proposed an action plan for engagement with key stakeholders, in particular the three larger manufacturers, as well as key national industry associations and institutions.

Publications Relevant to Article 3

Report on Strengthening the Nigerian Clean-Cooking Business Ecosystem *(Yetano Roche, 2021)*

This publication was part of a series of research pieces commissioned by the Nigerian office of the Heinrich Boell Foundation, with the aim of guiding advocacy and policy efforts in this space. The study analyses the current business ecosystem for clean and conventional cooking fuels and technologies in Nigeria. Drawing on the knowledge of private-sector actors as well as a number of key market-enablers and experts, the study examines recent trends, drivers and barriers influencing the clean-cooking market and estimates its potential growth by 2030 in the future under three preliminary scenarios. These scenarios were taken up later in 2021 by the teams developing Nigeria's enhanced NDC and were used as a basis for the commitments included in the final NDC as submitted to the UNFCCC. The publication also formed the basis for the participatory visioning process carried out in 2022.

Report on participatory visioning process for Nigeria's national and state-level clean cooking goals *(Yetano Roche, 2022)*

This report encapsulates the results of a stakeholder engagement process that the author designed and facilitated. The goal of the process was to inform clean-cooking transition scenarios by engaging stakeholders in the definition of baseline data, feasible goals, and transition priorities, bringing together actors across the LPG, biomass cookstove, and clean cooking energy value chains. This process explored the current state of cooking energy data, clarified goals and their potential impacts on emissions and health, and priority policy recommendations. Key recommendations emerging from the process included aligning the NDC with the Energy Transition Plan, enhancing demographic surveys and land-use change assessments, strengthening evidence on job creation and just transition impacts, establishing a public registry for clean cooking initiatives, and assessing the long-term potential of biogas, bioethanol, and electricity for achieving clean cooking goals.

This stakeholder engagement process formed the basis of the detailed transition scenarios that are analysed in Article 3. This process brought together actors in the LPG, improved biomass cookstove and other clean cooking energy value chains via a series of online workshops and 1-to-1 interviews.

An estimation of the health and climatic impacts of household biomass consumption across Nigeria in 2018 (Slater et al., 2025)

Developed in collaboration with some of the co-authors of Yetano Roche et al., 2024, this peer-reviewed article delves deeper into the base year calculations and health and climate impact calculation methodology, both of which are used (and further developed) in Yetano Roche et al., 2024. Yetano Roche e al., 2024 makes frequent reference to Slater et al., 2025, and *vice versa*.

4. Synthesis of results

This thesis set out to provide a thorough analysis of Nigeria's path towards sustainable development and decarbonisation in three key sectors of its economy. Nigeria faces the challenge of addressing social equity and the diversification of its economy, and at the same time stands at a critical position in the pursuit of global climate goals, as a regional leader and a country of great significance globally.

The thesis was guided by four research questions:

RQ1: Which transition pathways are likely to bring about optimal outcomes for the achievement of Nigeria's development and decarbonisation goals in the three sectors studied?

RQ2: What are the impacts of non-optimal transition pathways on Nigeria's development and decarbonisation goals in these sectors?

RQ3: What niche developments will be key in inducing the transition in these sectors, and what factors affect them?

RQ4: What are the critical uncertainties in the planning and management of Nigeria's transition?

This section synthesises the key findings of the thesis in relation to these research questions and positions them within the broader context of ongoing academic and policy discussions, highlighting their key contributions.

4.1. Main findings in the context of the thesis' theoretical and conceptual framework

This thesis draws on the interface between development economics, international climate governance, and socio-technical transition theory, adopting a multidisciplinary approach. Development economics informs strategies for fostering economic growth and reducing poverty, while the field of international climate governance provides key concepts of equity in climate action and synergies between climate action and other development goals. Socio-technical transition theory provides a framework for understanding systemic changes across societal, technological, and institutional levels. By integrating these perspectives, the thesis sheds light on plausible development pathways for Nigeria that are consistent (or not) with the country's national climate goals and provides insights into the dynamics of the future transformation.

The following is a synthesis of five key findings of the research (Figure 8), as they relate to the key concepts of the theoretical background and to the four original research questions:

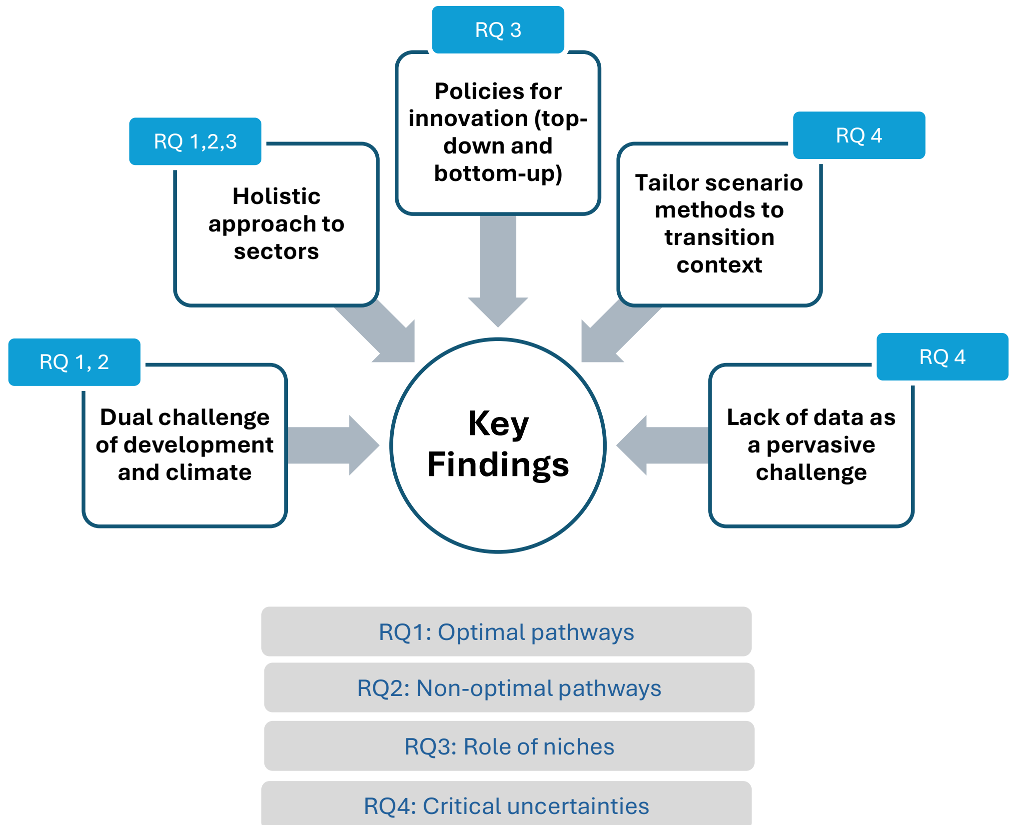

Figure 8. Key findings of research in relation to the research questions (RQs).

Key Finding: Nigeria epitomizes the complex relationship between development and climate objectives

Addressing RQs 1 and 2: This key finding responds to the first two research questions by identifying plausible transition pathways for Nigeria's development and decarbonisation goals and examining the consequences of failing to deliver these transitions. The analysis demonstrates that Nigeria can meet its electricity access goals and power sector decarbonisation pledges, though challenges remain in sectors like cement and cooking energy. The impacts of non-optimal pathways are also highlighted, such as persistent reliance on fossil fuels, economic inefficiencies, and very heavy health burden from traditional biomass use.

Climate and development practitioners face the complex challenge of balancing human development with safeguarding the planet's stability (Rockström *et al.*, 2021)[8]. While this interaction is critical in all contexts, the dual challenge holds particular urgency in developing countries, where socio-economic

[8] The research recognises that this dual objective is rooted in a normative vision of "what the world should be" (Savage *et al.*, 2019), and that development and climate goals are subjective constructs shaped by values, beliefs, and societal priorities (Geels, 2010).

vulnerabilities and environmental pressures often intersect. For example, this thesis highlights the case of Nigeria's power sector transition, where the challenge of expanding electricity access to millions of unserved people coexists with the need to decarbonise the power sector. In this sense, the findings contribute to the broader discourse on sustainable transitions in developing economies.

The findings emphasise the importance of a context-specific understanding when it comes to aligning development priorities with climate goals. The principle of differentiated responsibilities, as recognized by the Paris Agreement, acknowledges the need for a context-specific lens, emphasizing that emission reduction targets should be tailored to national circumstances and capacities (IPCC, 2023; Pauw *et al.*, 2014). In this research, the analysis is based on an understanding of some of Nigeria's most pressing development needs at sector level (electricity access, economic diversification, health, poverty reduction), in combination of the national goals and specific potential for decarbonisation.

While the interplay between climate and development goals is well-established in global frameworks such as the Paris Agreement and the 2030 Agenda for Sustainable Development (de Jong and Vijge, 2021), actual policy integration remains limited. The synergies between climate action and sustainable development are often addressed on an ad hoc basis and primarily in the energy sector (Hermwille *et al.*, 2023). In Nigeria, the absence of a comprehensive policy framework, combined with weak regulatory enforcement and macroeconomic instability, hinders the systematic integration of these objectives.

The findings in this thesis can stimulate discourse around a development-centric approach to climate change action (SPP *et al.*, 2023) and provide evidence to those who may view climate and development goals as incompatible. Some of the high-level findings include:

- Nigeria can meet its electricity access goals and decarbonisation pledges for the power sector by 2030. In fact, The NDC's pledges for the power sector can be comfortably met, and a higher level of ambition may be warranted in future goals.
- Decarbonisation in the cement sector is unlikely to be line with Nigeria's stated goal of achieving net zero emissions in the sector by mid-century. However, an optimal transition pathway would put the sector on a *path towards* net zero later in the century.
- A plausible but very rapid transition can deliver the government's access and decarbonisation objectives for the cooking energy sector by 2050, alongside an absolute reduction in annual premature deaths due to exposure to household air pollution.

Through transparent, context-specific and conceptually robust analysis, the research identifies opportunities to align Nigeria's national development goals with its international climate commitments. While recognising limitations and caveats, it illustrates what a Climate Resilient Development (CRD) pathway (Eriksen *et al.*, 2024) could look like for three key sectors in Nigeria.

Key Finding: Approaching Nigeria's sectors holistically is vital for identifying leverage points in the transition towards decarbonisation and development

Addressing RQs 1, 2 and 3: This key finding connects with the first three research questions by emphasising the need for a holistic view to understand both optimal and non-optimal future pathways and to identify critical niche developments that can catalyse transitions. The research shows how sectoral interdependencies influence transition outcomes, with particular attention to innovations in the energy sector.

The research treats the Nigerian power sector, the cement manufacturing sector, and the cooking energy sector as socio-technical systems, capturing in the transition scenarios the interplay between social and technical elements within a societal context. This thesis applies the framework and demonstrates its applicability in a developing economies context characterised by informal institutions, weak formal institutions and well-established coalitions and elites that may resist transitions (Osunmuyiwa *et al.*, 2018). This is for example the case of Nigeria's diesel and petrol generator importer monopoly, or of the wood fuel and charcoal value chain. The analysis of the findings reflects on the broader difficulties in managing socio-technical transitions in developing economies compared to industrialised economies (Ramos-Mejía *et al.*, 2018).

Central to the research is the Multi-Level Perspective (MLP), which conceptualizes transitions as interactions across three levels: niches (innovation spaces), regimes (established socio-technical structures), and landscapes (broader contextual factors) (Markard and Truffer, 2008). In Nigeria, the power sector's transition involves niche innovations like off-grid renewables, challenging the fossil-fuel-based regime, influenced by landscape pressures such as price drops in renewables and cost of capital. The cement and cooking energy sectors exhibit similar multi-level dynamics, with niche innovations aiming to disrupt entrenched regimes under various landscape pressures. These levels are articulated in the scenarios and used as guide for building the underlying assumptions and discussing the findings of the quantitative analysis.

Key Finding: Innovation policies are crucial to protecting niches and destabilising regimes across Nigeria's economic sectors

Addressing RQ3**:** Directly addressing the third research question, this key finding highlights the role of niche developments, and the enabling conditions required to protect and scale them. The study identifies key innovations, such as off-grid solar PV in the power sector, alternative materials in cement production, and clean cooking technologies, and analyses the policy, market, and financial factors that support or hinder their growth.

The research delves into dynamics of innovation that are very specific to Nigeria, and sheds light on the understanding of the matter in the context of development (Cozzens and Kaplinsky, 2009). The three articles in this thesis integrate in the scenario assumptions the need to promote niches like off-grid solar PV in the power sector, alternative materials in cement production, and clean cooking technologies. In each optimistic scenario, effective Strategic Niche Management (SNM) is present and creates conducive environments for these innovations to develop and scale through targeted policies and subsidies.

The research also pays attention to the destabilising of incumbent regimes, and considers that the protection of new entrants through policy and financing frameworks is insufficient without deliberate policies to dislodge technologies and market structures that currently dominate (Hockerts and Wüstenhagen, 2010). In Nigeria's power sector, the dominance of diesel generators exemplifies a stable regime resistant to renewable integration. The cement sector's reliance on carbon-intensive production methods and the cooking energy sector's dependence on biomass are other examples. The three research pieces consider these entrenched systems in tandem with the niche disruptions.

Key Finding: Tailored scenario methods can address the unique needs of data-scarce (but not knowledge-scarce) transition contexts

Addressing RQ4: This key finding speaks to the fourth research question by exploring the critical uncertainties in transition planning. The thesis demonstrates how scenario-based methodologies can help manage these uncertainties, accounting for uncertainties related to economic conditions, policy shifts, and technological developments. The research shows how scenarios can incorporate diverse stakeholder perspectives and how this can be of use particularly in contexts where reliable data is scarce but expert knowledge is present.

Scenario analysis serves as a powerful tool to explore plausible futures, enabling policymakers and stakeholders to navigate uncertainties and design strategic decisions. Within the socio-technical transitions framework employed in this thesis, scenario methods were used to analyse pathways for Nigeria’s power, cement, and clean cooking sectors, integrating qualitative and quantitative approaches to address the dynamics of technological adoption, policy interventions, and socio-economic factors.

Scenarios are defined as “coherent and plausible descriptions of a possible future state of a socio-technical system” (Thompson *et al.*, 2012). In this thesis, the scenarios were developed in three main stages: identifying key sectoral goals and driving forces, developing scenario storylines, and crafting coherent sets of quantitative assumptions that capture the different goals drivers and storylines. For instance, in the power sector, scenarios examined the interplay of grid expansion, off-grid solutions, and decentralized technologies, while the cement sector scenarios focused on four different decarbonisation levers and two different demand trajectories. The scenarios integrate both forecasting and back casting elements, enabling an exploration of feasible futures and the steps required to achieve them. Back casting, in particular, is valuable for designing pathways to align Nigeria's development objectives with its stated climate goals, identifying key milestones and intervention points.

Transition scenario approaches often struggle to incorporate diverse viewpoints of stakeholders (Scolobig and Lilliestam, 2016). In this thesis, scenario development and analysis drew heavily on stakeholder and expert insights to enrich narratives and compensate for data scarcity (see more on the latter under Key finding 5 below). A key learning from the research is that while data is scarce, much expert knowledge is available (albeit fragmented and difficult to access).

However, as highlighted in the literature, scenarios are not without challenges. The scope of the scenarios used in this thesis is limited by nature. For example, much knowledge on user preferences regarding clean cooking technology adoption could not be captured in the transition scenarios. Moreover, each scenario assumed that economic conditions, policies, and broad incentives to innovation such as access to financing were stable, not subject to shocks. This is a strong limitation given Nigeria's dynamic economic and policy instability, as illustrated by the volatility of LPG prices during the time of the study.

As stated by Zolfagharian *et al.* (2019), constructing comprehensive and realistic scenarios in the context of complex socio-technical systems demands balancing *depth* and *breadth*. There are inherent uncertainties in predicting technological advancements, policy shifts, and societal changes (Bale *et al.*, 2015; Otto *et al.*, 2015). Scenarios are robust when these limitations are communicated transparently. Interpreting the findings from scenarios involves acknowledging these shortcomings and understanding scenarios as a tool to explore multiple futures and strengthen resilience against evolving conditions. Such an approach ensures that transition strategies remain flexible and responsive to emerging challenges while keeping the long-term goals in sight.

Despite these challenges, the scenario analysis in this thesis contributed to bridging academic research and policymaking. By engaging stakeholders, including government, industry, and civil society, the scenarios became tools for co-creation (Moss *et al.*, 2010) and elements from them were taken up in national policy processes such as Nigeria's NDC (power sector and cooking energy scenarios).

Key Finding: The lack of reliable and comprehensive data a common thread that hampers transition planning

Addressing RQ4: Expanding on the fourth research question, this key finding highlights how data gaps create significant uncertainties that affect transition planning and decision-making. The findings and learnings from the methodological approach and data collection underline the importance of improving data to support more robust and adaptive policy frameworks in Nigeria's power, cement, and cooking energy sectors.

Data scarcity is a pervasive limitation in global south contexts, affecting academic research, government policy, and in the case of this thesis, scenario development and the analysis of transition pathways. Across Nigeria's power, clean cooking, and cement sectors, critical data shortages pose significant challenges to planning and managing the country's transition. In the power sector, uncertainties include data on baseline electricity demand and the size of the fossil fuel-based backup generator markets. Similarly, the clean cooking sector faces data gaps, particularly in mapping biomass value chains, estimating demand from non-household sectors, and current market shares for certain clean cooking technologies. In the cement sector, the absence of datasets on energy consumption in cement manufacturing plants and planned additions to installed capacity over the coming decades complicates efforts to anticipate technological and investment needs. These gaps limit the understanding of current baselines and as a result hinder scenario-based planning and adaptive management.

This section summed up the key findings through the lens of the research goals and research questions. The following section shifts the focus to the relevance of these findings for businesses operating within Nigeria's transitioning sectors.

4.2. Findings in the context of business management

The findings of this research present a nuanced picture of both opportunities and challenges for businesses (both incumbents and new entrants) seeking to engage in Nigeria's transition towards its development and climate goals.

The findings provide actionable insights for businesses in different sectors:

- Electricity sector: businesses can leverage insights on the potential market for on and off-grid renewable solutions and their precise role in achieving strategic policy goals.
- Cement sector: The research offers insights into aspects of the decarbonisation pathway that would also enhance competitiveness, such as energy efficiency, clinker reduction, and material

circularity. Moreover, early adoption of emerging technologies such as alternative cement could position Nigerian firms as regional leader.

- Cooking energy sector: the research into the potential benefits of the transition and the displacement dynamics of clean cooking technologies can be tapped into by large market actors (e.g. LPG sector) as well as smaller clean cooking firms in other fields (biogas, electricity) and used to leverage partnerships with development finance institutions to mitigate financial risks.

The findings can also guide multi-stakeholder collaborations to co-design policies that align commercial objectives with government goals in each sector.

The following are some of the cross-sectoral implications of the research for businesses:

Systemic challenges: a shared challenge across all three sectors is the inadequacy of infrastructure, compounded by data scarcity and regulatory inconsistencies. For example, the lack of stability and clarity in fuel subsidy removal policies hampers innovation across sectors.

Strategic opportunities: businesses have opportunities to lead systemic change by addressing infrastructure gaps and pioneering innovative models. For instance, the integration of decentralised renewable energy solutions in the power sector can support the potential for electric cooking in the long term. Businesses can leverage cross-sectoral synergies by investing in overlapping technologies and value chains, such as battery technologies that support both renewable energy and solar-electric cooking applications.

The role of partnerships: businesses can enhance their competitiveness by forming in-sector or cross-sector partnerships that share resources and knowledge in planning for the transition and seizing the opportunities in it. Engaging non-business actors is equally critical. By involving regulators, civil society and development finance institutions they can ensure that business strategies remain resilient in the face of evolving conditions.

5. Conclusions

This final section offers a distilled reflection on the findings of this thesis and outlines their implications for research, policy, and business. It concludes with a forward-looking perspective that builds on these insights to consider Nigeria's role in the global transition toward sustainable development.

5.1. Implications for research

This thesis reinforces the value of integrating international climate governance principles with development economics and socio-technical transition theory to analyse national and sectoral sustainability transitions. Moreover, the work reveals both the potential and limitations of scenario-based approaches as a tool for transition planning in data-scarce environments. As stated in the Synthesis of results, one significant challenge was the lack of reliable, granular data to model long-term scenarios of sectoral transitions. Another was the difficulty of reconciling sustainability transitions theoretical concepts with the realities of Nigeria's socio-technical systems. Incorporating stakeholder insights into scenario narratives proved crucial for enhancing the robustness and contextual relevance of the scenario assumptions and for guiding the analysis and interpretation of the results.

Despite these obstacles, the research successfully demonstrated the utility of combining qualitative and quantitative methodologies to explore transition pathways in national contexts that are currently underrepresented in literature. These methodological contributions provide a framework for future research in similarly settings.

It is important to remember that this research was conducted during a particularly dynamic period in both Nigeria's national policy landscape and the broader international climate governance context. Over the course of the work, major developments unfolded—such as Nigeria's updated Nationally Determined Contribution and its net-zero commitment—shaping the direction and relevance of the analysis. Rather than offering a static snapshot of Nigeria's climate and development goals, the thesis engages with an evolving planning and policy process, capturing key shifts as they occurred. This temporal context shaped not only the research design and empirical findings at the time but also the discussion of these findings in retrospect. This underlines the importance of designing research approaches that are flexible and responsive to changing political and policy environments—particularly in fast-evolving contexts like Nigeria's.

Several avenues for future research emerge from this thesis, offering opportunities to deepen the understanding of sustainable transitions in Nigeria and similar contexts. First, exploring sectoral interconnections is critical, particularly how advancements in one sector, such as electricity, influence others like transportation, agriculture, and industry. For instance, both the decarbonisation of Nigeria's cement industry and the success of clean cooking solutions are closely tied to the reliability and expansion of renewable energy infrastructure. Research on these interdependencies can provide holistic insights into cross-sectoral synergies and potential trade-offs, enabling better-integrated planning.

Second, a deeper exploration of actors' behaviour, including consumer adoption of sustainable technologies and practices, could significantly enrich the socio-technical systems (STS) framework. Understanding the preferences, barriers, and enabling factors that shape consumer behaviour—such as affordability, cultural norms, and awareness—will be crucial for scaling innovations like clean cooking technologies, renewable energy solutions, and low-carbon cement.

Comparative analysis of transitions in similar economies could also yield valuable insights into replicable strategies and context-specific challenges. Lessons from best practices as well as from negative experiences from other economies that are adaptable to Nigeria's unique conditions can inform Nigeria's approach to planning and managing its sectoral transitions.

Finally, assessing the long-term effectiveness of emerging policies, such as Nigeria's Energy Transition Plan and Long-Term Low Emission Development Strategy (LT-LEDS), is essential to building a robust evidence base for the country's future transition. This includes evaluating the impact of policy instruments like subsidies, tax incentives, and regulatory reforms in the power sector such as the 2023 Electricity Act. Longitudinal studies tracking policy outcomes over time could also identify gaps and opportunities for recalibration, ensuring that policies remain effective in achieving both development and decarbonisation goals. Additionally, integrating stakeholder perspectives into these assessments can help align policies with the needs of businesses, civil society, and financiers.

5.2. Implications for policy

The findings emphasise the importance of integrating development and decarbonisation objectives within Nigeria's policies, not just in international policy commitments, such as Nationally Determined Contributions (NDCs). Key recommendations include accelerating policy reforms to remove investment barriers in renewable energy and clean cooking technologies, and initiating incentives in the cement sector. These steps are essential for ensuring coherence across strategies like the Energy Transition Plan and Nigeria's economic and industrialisation policies.

Institutional capacity building will play a pivotal role in implementing these policies. Strengthening the ability of government agencies to monitor, evaluate, and adapt strategies is crucial for maintaining progress toward climate and development goals. Additionally, integrating stakeholder engagement into the policymaking process—by meaningful involvement of businesses, civil society, and financiers—can enhance policy relevance and ensure that transition strategies are inclusive and equitable.

Finally, the thesis highlights the link between sectoral transformations and investment. Nigeria's ability to attract international and private financing will depend on demonstrating clear, actionable transition plans with measurable outcomes for different sectors as well as for the whole of its economy. Policies that create enabling environments for private sector investment will further accelerate these transitions.

5.3. Implications for businesses

Businesses operating across Nigeria's power, cement, and cooking energy sectors face significant structural constraints, including unreliable infrastructure, regulatory uncertainties, and weak governance. Yet, they also have opportunities to drive strategic innovation and position themselves as leaders in the transition to sustainability. By aligning their business strategies with national climate and development goals, businesses can unlock new markets and enhance competitiveness.

In the power sector, businesses can capitalise on the growing cost-competitiveness of decentralised renewable energy solutions, particularly off-grid systems, to reduce their energy costs. There is significant potential for new business models such as those using tailored consumer financing solutions, targeting low-income households and small enterprises. Similarly, in the cement sector, businesses that adopt low-carbon technologies, including energy-efficiency and clinker reduction can achieve cost savings while positioning themselves as frontrunners in the African market. The cooking energy sector presents further opportunities for SMEs to scale innovations like cleaner fuels and consumer financing models, and to leverage synergies with the expanding renewable energy sector.

Businesses also have an opportunity to shape policies that align commercial objectives with sustainability goals. For instance, advocating for consistent enforcement of quality standards can de-risk investments into the off-grid renewables and clean cooking sectors.

5.4. Concluding remarks and future outlook

Nigeria, one of Africa's largest economies, faces significant risks of failing to meet both its equitable development and decarbonisation goals. Despite having one of the lowest per capita GHG emissions globally, Nigeria was the 25th largest global emitter of GHGs in 2022 and the second highest in Africa after South Africa (European Commission *et al.*, 2023). Projected to become the world's third most populous country by 2050, Nigeria's demographic and economic growth is expected to drive a rise in its emissions, underscoring its critical role in global climate action.

The Paris Agreement, adopted in 2015, brought all countries together around the goal of limiting global warming to well below 2°C, while pursuing efforts to keep it to 1.5°C above pre-industrial levels. Achieving this target requires global greenhouse gas emissions to reach net zero around mid-century. The Agreement recognises that countries have different national circumstances and development priorities, and states that "developed countries should continue taking the lead" and that "peaking [of emissions] will take longer for developing country Parties". This shared but differentiated approach underscores the need for all countries to contribute to the global transition, while acknowledging varying starting points and capacities.

At the Conference of Parties in Dubai, in late 2023, and following the completion of the final research component in this thesis, the Nigerian government unveiled its Long-Term Low Emission Development Strategy (LT-LEDS), as part of its commitment to the Paris Agreement. The strategy's vision is as follows: "*By 2060, Nigeria will be a country of net-zero emissions across all sectors of its development and climate-resilient with high-growth circular economy in a gender-responsive manner* ". With this declaration, Nigeria not only reaffirmed its commitment to global climate goals but also asserted its role as a key player and agenda-setter in the global transition to sustainability.

This thesis provides evidence to demonstrate that Nigeria, as a significant economy and regional leader, possesses the potential to align its development goals with global net-zero targets. It also shows that the country stands to gain from putting an emphasis on climate policies that are pro-development, pro-health and pro-economic diversification. For this, sectoral transition strategies need to be integrated into a broader framework of cross-sectoral socio-economic transformation.

By focusing on three critical sectors of Nigeria's economy—electricity, cement, and cooking energy—this thesis provides a picture of which would be the concrete steps in the roadmap to harness the economic, development and health benefits of climate action while addressing the country's unique challenges and opportunities.

Achieving Nigeria's ambitious vision will require substantial financial resources and active participation from private investors. By highlighting the development and decarbonisation benefits within key sectors, this research provides a roadmap for aligning financial flows with national priorities. Mobilising domestic and international finance, coupled with creating enabling environments for private sector engagement, will be critical to driving the necessary systemic transformations and ensuring the delivery of Nigeria's long-term goals.

In 2024, global temperatures reached unprecedented levels, exceeding 1.5°C above pre-industrial averages for the first time. This milestone underscores the escalating climate crisis, which poses an unparalleled threat to all, with an urgent need for action. For developing economies—which have historically contributed the least to climate change but remain among the most vulnerable to its impacts— development, equity and climate goals are deeply interconnected and critical.

This thesis has important implications for the ongoing debate around the relationship between economic growth, inequality, and environmental sustainability. It illustrates how sectoral transitions can simultaneously generate significant development benefits (deliver access to electricity to homes and businesses, diversify the national economy and strengthen industry, or ensure clean air for all) and advance Nigeria's long-term climate strategy. It also highlights the risks of failing to achieve such a transition, reinforcing the urgency of setting a course towards sustainable development for all —before the consequences of inaction become more severe. Future research can build on this work to further strengthen the knowledge base needed to support sustainable transitions in Nigeria and beyond.

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Appendix: Full Articles

Article 1:

Yetano Roche, M., Verolme, H., Agbaegbu, C. Binnington,T., Fischedick, M., Oladipo, E. O. (2020): *Achieving Sustainable Development Goals in Nigeria's power sector: assessment of transition pathways*. Climate Policy, 20:7, 846-865, DOI: 10.1080/14693062.2019.1661818.

Article 2:

Yetano Roche, M. (2023). *Built for net-zero: analysis of long-term greenhouse gas emission pathways for the Nigerian cement sector.* Journal of Cleaner Production, 383, 135446, DOI: 10.1016/j.jclepro.2022.135446.

Article 3:

Yetano Roche, M., Slater, J., Malley, C., Sesan, T., Eleri, E. (2024). *Towards clean cooking energy for all in Nigeria: pathways and impacts*. Energy Strategy Reviews, 53, 101366, DOI: 10.1016/j.esr.2024.101366.

CLIMATE POLICY
2020, VOL. 20, NO. 7, 846–865
https://doi.org/10.1080/14693062.2019.1661818

RESEARCH ARTICLE

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Achieving Sustainable Development Goals in Nigeria's power sector: assessment of transition pathways

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ABSTRACT

Nigeria is Africa's largest economy and home to approximately 10% of the un-electrified population of Sub-Saharan Africa. In 2017, 77 million Nigerians or 40% of the population had no access to affordable, reliable and sustainable electricity. In practice, diesel- and petrol-fuelled back-up generators supply the vast majority of electricity in the country. In Nigeria's nationally-determined contribution (NDC) under the Paris Agreement, over 60% of the greenhouse gas emissions (GHG) reductions are foreseen in the power sector. The goal of this study is to identify and critically examine the pathways available to Nigeria to meet its 2030 electricity access, renewables and decarbonization goals in the power sector. Using published data and stakeholder interviews, we build three potential scenarios for electrification and growth in demand, generation and transmission capacity. The demand assumptions incorporate existing knowledge on pathways for electrification via grid extension, mini-grids and solar home systems (SHS). The supply assumptions are built upon an evaluation of the investment pipeline for generation and transmission capacity, and possible scale-up rates up to 2030. The results reveal that, in the most ambitious Green Transition scenario, Nigeria meets its electricity access goals, whereby those connected to the grid achieve a Tier 3 level of access, and those served by sustainable off-grid solutions (mini-grids and SHS) achieve Tier 2. Decarbonization pledges would be surpassed in all three scenarios but renewable energy goals would only be partly met. Fossil fuel-based back-up generation continues to play a substantial role in all scenarios. The implications and critical uncertainties of these findings are extensively discussed.

Key policy insights

- The 2030 electricity mix for Nigeria varies across the scenarios presented, with the most ambitious scenario achieving electricity access goals and partly meeting renewable energy goals.
- All three scenarios surpass the decarbonization targets of Nigeria's NDC for the power sector.
- The transformation of the power sector relies on a wide range of financial, policy and enabling environment-related conditions taking place in the near-term, some of which are in turn strongly influenced by larger political economy realities.
- Fossil fuel-based back-up generation plays a substantial role in all scenarios. Data availability for this technology remains a significant source of uncertainty.

ARTICLE HISTORY
Received 11 January 2019
Accepted 27 August 2019

KEYWORDS
Nigeria; SDG7; NDC; LEAP; energy access; electrification

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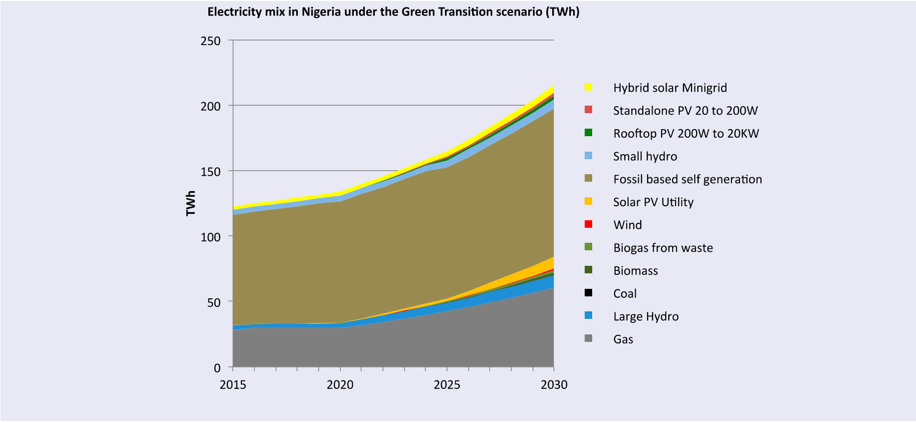
Supplemental data for this article can be accessed here https://doi.org/10.1080/14693062.2019.1661818.



1. Introduction

Nigeria has three key long-term ambitions for the electricity sector: a capacity expansion target, namely, 30 GW of installed on-grid capacity by 2030, of which 13.8 GW from grid-connected renewables (corresponding to 45% of total capacity and 30% of generation, respectively)[1]; the goal of universal electrification by 2040, and of 90% electrification by 2030; and the emission reduction targets in its nationally-determined contribution (NDC) under the Paris Agreement (FGN, 2015, 2016; FMPWH, 2016). Regarding the latter, Nigeria pledged a 20% unconditional reduction of its Business-as-Usual (BAU) greenhouse gas emissions (GHGs) by 2030, and a 45% reduction, conditional on financial, technical and capacity building support for implementation. Over 60% of these reductions are foreseen in the power sector.

There is a lack of scenario studies that look at the intersection of these three policy goals in Nigeria. Research in the area in general suffers from strong data inadequacies and limitations in gaining access to expert knowledge that is available but fragmented.

The goal of this study is to contribute to planning and decision-making by identifying and critically examining the possible pathways available to Nigeria to meet its electricity access, renewables and decarbonization goals in the power sector.

The following section presents the background on the challenges and opportunities in Nigeria's power sector and reviews key literature (Section 2). Section 3 presents the methodology including stakeholder validation, general scenarios, key assumptions and modelling approach. The following sections present the results (Section 4) and discussion (Section 5).

2. Background

Nigeria is a lower-middle income country, with annual per capita income of about US$2,500 (World Bank, 2018a). It is Africa's largest economy, and one in seven Africans is Nigerian. Despite Nigeria's significant human and natural resource capital, around a third of the 180 million Nigerians live below the national poverty line, with around another third just above (DFID, 2018). Nigeria is set to surpass the United States to become the world's third most populous country by 2050 (UNDESA, 2017).

According to official statistics, 77 million Nigerians have no access to grid power (IEA, 2018) and 80% of those with grid access use expensive diesel- and petrol-fuelled back-up generators as an alternative to the unreliable grid supply (IEA, 2017). Other surveys indicate that there could be as many as 120 million people, or 75% of the population, currently living without access to reliable and affordable power (de Boer, 2018).

Nigeria's insufficient generation and transmission capacity and the high costs of self-generation affect all aspects of the economy, from rural livelihoods to manufacturing and exports. Households and SMEs spend two to three times more on kerosene, diesel and petrol than they do on grid-based electricity (All On, 2016). In industry, government figures suggest that the cost of self-generating power makes Nigerian products about a third more expensive than imported products (FMITI, 2014).

Today's available on-grid peak generation averages 4 GW (NESISTATS, 2018) and the wheeling capacity of the grid is around 5.5 GW. Nigeria's on-grid generation is dominated by natural gas power stations (85% of available capacity) and three large hydropower plants (14%) (FGN, 2016). Currently, gas generation plants are severely constrained by availability of fuel. It is estimated that, with adequate gas supply, an average of 2 GW could be added to the country's daily peak generation (NESISTATS, 2018). In practice, diesel and petrol back-up generators supply the vast majority of power in the country. There is considerable uncertainty around the extent of fossil fuel-based self-generation but based on the number of generators imported annually it is estimated that there was around 15 GW of diesel and petrol-based generation installed capacity in the country in 2015 (FGN, 2016; Solar Plaza, 2017), with other estimates pointing at 16 GW just in the area of Lagos. Market segmentation data show a dominance of small and medium-scale generators in the 5–75 kVA range in terms of market volume (6WResearch, 2018).

The transformation of Nigeria's power sector faces various and interconnected challenges, some of which are common to both grid-based and decentralized electricity. The key challenges that they have in common are lack of finance, high investment risks and a poor enabling environment (World Bank, 2016b).

The grid-based sector suffers from: insufficient generation, transmission and distribution infrastructure (FGN, 2017), gas supply and water management bottlenecks (Occhiali & Falchetta, 2018), and corruption (Roy & Ibrahim, 2018; SERAP, 2017). In particular, the financial illiquidity of the market remains one of the most significant challenges for the sector (NERC, 2018a). This challenge is partly due to the lack of cost-reflective tariffs, high technical losses, and commercial losses of distribution companies under the prevailing practice of estimated billing. In addition, the potential of grid-based generation is constrained by a poor transmission and distribution grid. Its restoration and expansion are estimated to require an annual investment of US$1 billion for the next ten years (TCN PMU, 2017).

Recent policy developments geared towards tackling challenges in the grid-based electricity sector include new regulations on metering, rules allowing large consumers to buy electricity directly from generating companies (by-passing distribution companies), and feed-in tariffs for renewables (NERC, 2015, 2018b).

Different power generation technologies are at different levels of maturity in Nigeria, and there is a nascent market for renewables, both on- and off-grid. Fourteen solar PV companies signed power purchase agreements (PPAs) in 2016, with a combined capacity of 1 GW, though none have yet been commissioned.

Nigeria has a large potential off-grid market, be it through renewables-based mini-grids or through solar home systems (SHS) (All On, 2016; NESG & RMI, 2018). Standalone solar PV systems are already cost-competitive on a lifetime basis over diesel and gasoline generators (NESG & HBS, 2017). However, they have significant upfront costs and, without affordable financing, diesel generators are more accessible to households and small businesses. Hybrid (solar-battery-diesel) mini-grids have particularly high potential in Nigeria and thirty of them are currently in operation (RMI & REA, 2018). Some of the key barriers for investments in the off-grid electricity market are the lack of consumer affordability and financial viability of projects, the weak enabling environment, and the lack of data to make investment decisions. Recent policy developments geared towards tackling challenges in the off-grid-sector include regulations for mini-grids (NERC, 2018b), and a proposed bill for the removal of import tariffs on solar components. Moreover, a number of funds and financing partnerships have been launched to address key financing gaps in the deployment of mini-grids and SHS (GCF, 2018a; OGEF, 2018; World Bank, 2018b).

Despite its significant potential for savings, the role of energy efficiency in Nigeria is often overlooked and the market is in its infancy.

Nigeria's per capita GHG emissions are around 2 tCO_2e per capita (FGN, 2015), and the country represents around 1% of global GHG emissions. Nigeria, however, stands to suffer severely from climate change. The Climate Change Vulnerability Index consistently ranks Nigeria within the top ten most climate-vulnerable countries, and Lagos is the tenth most vulnerable city in the world (Verisk Maplecroft, 2013). The only comprehensive study on the economic costs of climate change in Nigeria points to losses in GDP of between 2–11% by 2020 if no adaptation measures are taken (ERM, 2009), a figure that is considered conservative judging by the economic losses caused by ongoing processes such as the shrinking of Lake Chad or crises such as the 2012 and 2018 floods. Costs associated with the 2012 floods alone amounted to around 2% of the annual GDP (FGN, 2013).

2.1. Modelling Nigeria's power sector transition

The last government-endorsed scenario study into Nigeria's energy future was carried out in 2014 by the Energy Commission of Nigeria (ECN, 2014). Since then, a number of other long-term scenario studies covering the Nigerian power sector, either partly or wholly, have been conducted (Cervigni, Rogers, & Henrion, 2013; FGN, 2015; Oxfam America, 2017; Oyewo, Aghahosseini, & Breyer, 2017; PwC, 2016). The most extensive one was carried out by the World Bank as part of a study on low-carbon development of the power, land use, agriculture, oil and gas sectors (Cervigni et al., 2013). It provided a 20-year outlook up to 2035, and identified the power sector as the key source for abatement of GHGs and consequent economic benefits of adopting low-carbon technologies. More recently, Oxfam and the University of California, Berkeley, modelled the Nigerian energy transition to reliable and affordable power by 2035 and explored the integration aspects of variable renewable resources (Oxfam America, 2017). Oyewo et al. (2017) modelled an energy transition from the current fossil fuel-based-system to a 100% renewable energy-based power system by 2050, where PV installed capacity reaches 400 GW by 2050 and battery storage dominates the balancing options. Finally, the modelling that supported the Nigerian NDC (FGN, 2015) pointed at efficiency of future gas power plants as holding the greatest potential for emission reductions, whereas the most cost-effective measure is the introduction of renewable energy into the mix, in particular in a decentralized manner.

In parallel to energy system models, a growing body of research uses geospatial data for electrification planning (Bertheau, Cader, & Blechinger, 2016; Mentis et al., 2015; Ohiare, 2015; World Bank, 2016a). Least-cost electrification studies address the economics of following different combinations of grid extension, mini-grids and standalone solutions to reach access goals. The literature for Nigeria indicates that, while grid extension is the least-cost solution in the long term, off-grid solutions have an essential role to play during the transition, bringing about important socio-economic benefits. Currently, no official strategy exists in Nigeria to harmonize grid extension plans with the deployment of off-grid solutions.

3. Method

3.1. Stakeholder validation

Consultation with representatives of stakeholder groups was central to the design of the scenarios presented in this paper. Stakeholders in the main segments of the power sector (policy, regulation, finance, technical assistance, private firms, advocacy) were involved through interviews in the development of the scenarios, validation of the underlying assumptions and assessment of their critical implications and uncertainties. A total of 28 expert interviews and small-group discussions were held. Key government institutions consulted included the Federal Ministry of Power, Works and Housing, the Energy Commission of Nigeria and the Rural Electrification Agency. Information on the investment pipeline was complemented by interviews with international development partners and private sector actors. The interviews resulted in valuable expertise on a range of issues, including underlying conditions and scenario storylines, demand forecasts, on-grid value chain, and off-grid market developments. It is worth noting that many experts found it difficult to estimate demand and supply figures beyond 2025. As a result, 2030 figures were often extrapolations of estimates they provided for 2020 and 2025, showing the difficulty of making long-range projections especially due to data constraints, political uncertainties, and a lack of long-term integrated planning for the sector.

Stakeholders were engaged via semi-structured interviews, and in some cases, small focus groups of experts focusing on a single issue such as, for example, mini-grids. The interviews were conducted between September 2018 and January 2019. Further information was obtained during several workshops of sectoral experts organized by third parties. The final results of the study were validated during a half-day meeting by government stakeholders, with a view to securing their inclusion in the 2020 NDC update. Overall, a balance was maintained in the number of interviews with government stakeholders (13) and those from the private and other sectors (15). Some stakeholders commented only on specific technologies.

Stakeholder validation and, more broadly, stakeholder participation and engagement, are increasingly used in scenario building with the aim of improving the effectiveness and transparency of public policy as well as the acceptance of, and engagement in, long-term strategies. In the realm of energy and climate change mitigation, stakeholder-based scenario building has emerged recently as a method for eliciting required data and for improving interpretations of model outputs, as well as for translating the results of the analysis into strategies (Mathy, Fink, & Bibas, 2015; Schmid & Knopf, 2012; Wiebe et al., 2018). From a theoretical point of view, collaboration between researchers and stakeholders is seen as a prerequisite for trans-disciplinary research that enables societal transitions (Brandt et al., 2013). There is a broad set of methods for stakeholder engagement and no consensus on what degree of stakeholder involvement constitutes real engagement and empowerment. Stakeholder-based approaches are not common in scenario studies for developing countries.

3.2. The scenarios

Taking into account the background realities sketched out above, and in consultation with stakeholders, we drafted three possible scenarios and developed accompanying assumptions. The scenarios depict futures in which Nigeria either meets or fails to meet its electricity access goals, with the aim of exploring the potential effects of near-term developments. The scenarios hinge on the key challenges and opportunities faced by different segments of the power sector: grid-based electricity, sustainable off-grid solutions, and fossil fuel-based back-up generation. The three scenarios can be summarized as:

- **BAU:** a pessimistic scenario where sector transformation is slow, national plans are weakly implemented and development continues along historical trends. A significant share of the population (46.7%) remains unelectrified and/or continues to rely on diesel and petrol generators in 2030. The underlying driver is the lack of significant mitigation of investment risks (via finance, policy and enabling environment) for both on-grid (generation, transmission, distribution) and sustainable off-grid investments (mini-grids and standalone systems).
- **Green Transition:** a best-case and relatively disruptive scenario where all current plans are fully implemented, leading to substantial transformation of the power sector. Both the on-grid and the sustainable off-grid sectors develop at a fast pace, and by 2030, 90% of the population has access to electricity. Those connected to the grid achieve a Tier 3 level of access (in line with the World Bank's Multi-Tier framework (MTF) for electricity access (Bhatia & Angelou, 2015)[2]), and those served by sustainable off-grid solutions achieve a Tier 2 level of access (including residential, productive and public services use). This scenario relies on investment risks in the on-grid and sustainable off-grid sector being strongly mitigated through finance, policy and enabling environment measures, and there being a strong drive from the government for renewables-based generation. The electricity mix diversifies away from fossil fuel-based back-up generators, though these continue to play an important role.
- **Moderate Change:** a scenario that sees incremental improvements, mainly on gas-based and centralized solutions, and where the scale-up of decentralized and renewable energy markets is delayed. The roll out of the grid and gas pipeline network proceeds at a slow pace. A relatively high share of the population (34.1%) does not have access to electricity by 2030. There is no strong drive for renewables-based on-grid projects but continued reductions in the cost of renewable energy technologies eventually bring about their presence in the mix.

Each scenario is underpinned by more detailed qualitative assumptions about near-term developments in finance, policy and enabling environment that would drive the scenario. Examples of such near-term developments are the resolution of the liquidity challenges facing the on-grid sector (via roll out of meters, or the review of electricity tariffs scheduled to take place in 2019–20), and the greater availability of finance for decentralized solutions. The underlying assumptions for each scenario are described in the Supplementary Material. It is important to note that the individual statements listed on this table do not lead to specific quantitative effects in the model. Rather, they underpin the storylines of each scenario and, taken individually or as a whole, facilitated the elicitation of expert views on the quantitative demand and supply assumption values that are explained in the following sections. Moreover, the scenarios as a whole, as well as the individual statements listed in the Supplementary Material, were to a large extent refined and improved on the basis of stakeholder interviews.

3.3. Demand assumptions

For each of the three scenarios, different quantitative assumptions were developed for potential pathways for electrification and growth in demand for electricity. We explicitly chose to avoid deriving demand assumptions from macroeconomic assumptions. The model underlying Nigeria's NDC (FGN, 2015) incorporated the government's projections of 5% annual GDP growth rate. The NDC (initially presented as Nigeria's Intended NDC in the run-up to the 2015 Paris Climate Conference) was prepared before the 2016–7 economic recession, during which the Nigerian economy contracted by 1.6%, after having grown at an average of 5.7% over the previous decade (2005–2015) (World Bank, 2018a). Slow economic recovery is forecast in the coming years, with the IMF reporting a GDP growth of 0.8% in 2017 and projecting a 2% growth in 2018 and coming years (IMF, 2018). The NDC's demand scenarios assume that Nigeria would reach a per capita electricity consumption of around 2,000kWh by 2030 (including industrial demand), in line with similar lower-middle income countries (Cervigni et al., 2013). This equates approximately to Tier 5 of the World Bank's MTF for electricity access (Bhatia & Angelou, 2015) in 2030. The scenario contained in Nigeria's Sustainable Energy for All (SEforALL) Action Agenda, in turn, projects an annual consumption per capita of 1,126 kWh by 2030 (FGN, 2016; FMPWH, 2016).

Based on stakeholder consultations, this study took a more conservative view on what level of access could be achieved by 2030. It is important to note that this assumption is not broken down into demand sectors (i.e. buildings, industry, agriculture) and is not split into urban vs. rural segments of the population. Moreover, for simplicity, energy efficiency improvements are not taken into account (both the SEforALL Action Agenda and the NDC assume efficiency improvements of between 0 and 2% per year). In our study, the main drivers for demand are:

- Population growth, assumed at around 2.5% per year, in line with UN projections (UNDESA, 2018).
- Electrification pathways, based on least-cost electrification plans carried out for five states in Nigeria (Blechinger, Cader, & Bertheau, 2019; NESP, 2017) and refined via stakeholder consultations. Based on existing electrification rates, population density, distance from the grid and other indicators, these studies modelled the optimal pace at which grid extension and densification investments should proceed, as well as the areas where mini-grids and SHS were viable over the transition period.
- A purpose-built definition of Nigeria's 2030 access goal in terms of the World Bank's MTF (Bhatia & Angelou, 2015), whereby those connected to the grid achieve a Tier 3 level of access, and those served by sustainable off-grid solutions (mini-grids and SHS) achieve a Tier 2 level of access, including residential, productive and public services use (Table 1). It is important to note that such a definition does not yet exist in Nigeria's national electricity access goals, and that it has been proposed as a framework assumption in this study on the basis of stakeholder consultations and model iterations. Official goals refer only to the proportion of the population that would have access to electricity. The electrification pathways for each scenario are depicted in Figure 1.
- An estimate of what demand there will continue to be for fossil fuel-based back-up generation in each of the scenarios (Table 2).

The resulting electricity demand assumptions for each scenario are depicted in Figure 2.

3.4. Generation and transmission capacity assumptions

The assumptions for the development of generation capacity are shown in Tables 3 and 4, whereas those for transmission and distribution are shown in Table 5. In correspondence with the general storylines for the

Table 1. Assumptions for level of access achieved.

	2015	2020	2025	2030
Off-grid (kWh/year/person with sustainable off-grid access)	0	20	50	100
On-grid (kWh/year/person with grid access)	243.4	250	350	500

Note: Base year values derived from FGN (2016). Note that the yearly per capita values include residential, productive and public services use.

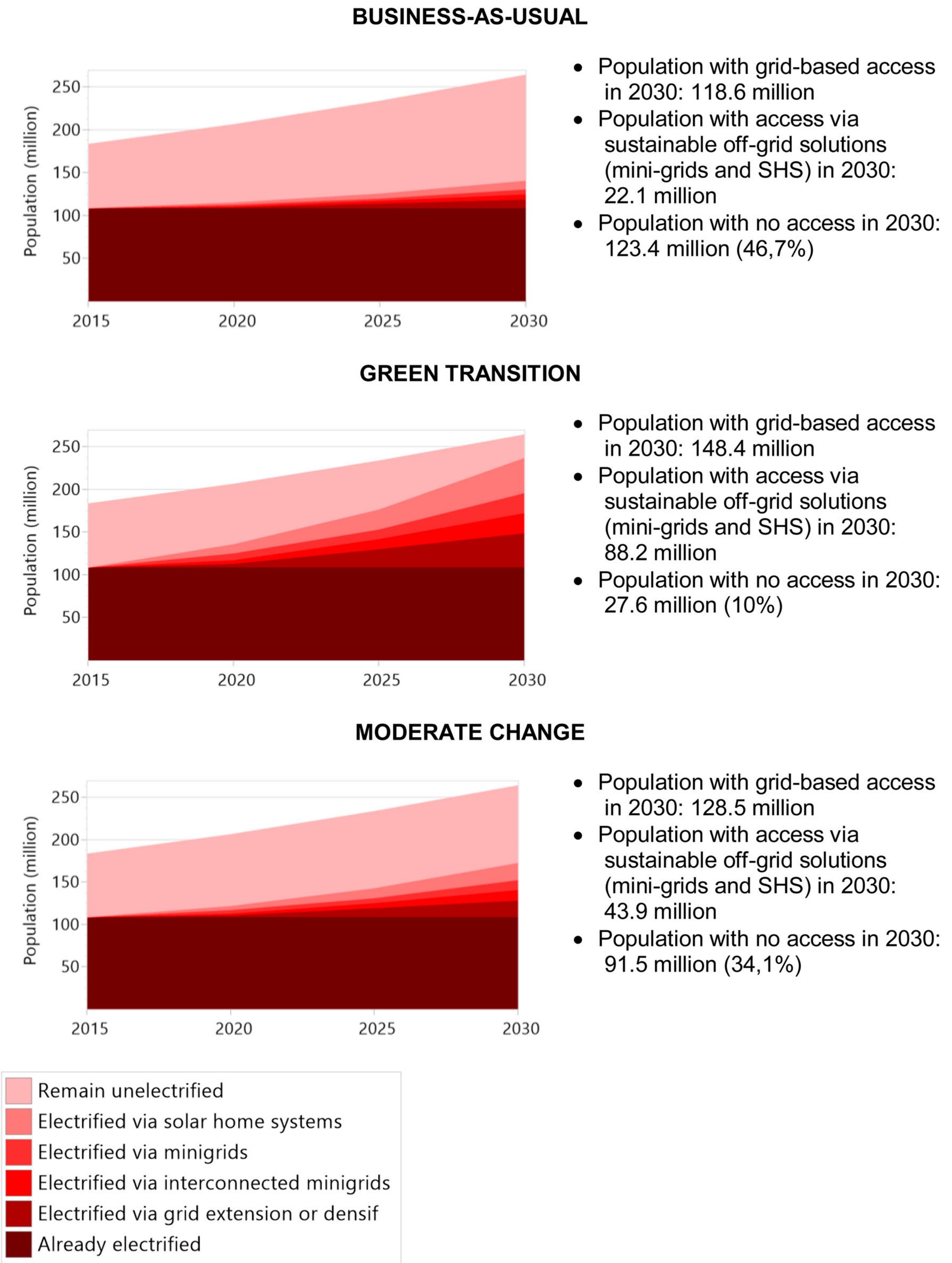
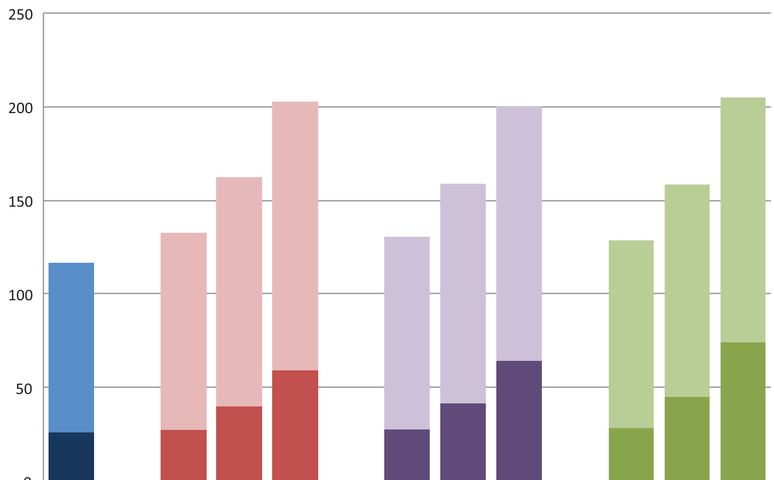


Figure 1. Electricity-access pathways for each scenario. Sources: NESP (2017) and stakeholder consultations. The pathways form the basis for the demand assumptions that were inputted into the model.

Table 2. Assumptions for growth in demand for fossil fuel-based back-up generation for each scenario.

Demand for fossil-based back-up generation (TWh)	2015	2020	2025	2030
BAU – 3% annual growth rate	90.6	105.0	121.8	141.2
Green Transition – 2% annual growth rate	90.6	100.0	110.4	121.9
Moderate Change – 2.5% annual growth rate	90.6	102.5	116.0	131.2

Note: Base year values derived from FGN (2016). Projected growth rates based on stakeholder consultations and (6WResearch, 2018).



	Baseline	BAU 2020	BAU 2025	BAU 2030	MOD 2020	MOD 2025	MOD 2030	GREEN 2020	GREEN 2025	GREEN 2030
Off-grid demand (TWh)	90.6	105.1	122.3	143.4	102.7	117.1	135.6	100.5	112.8	130.8
On-grid demand (TWh)	26	27.4	39.9	59.3	27.7	41.7	64.3	28.2	45.4	74.2

Figure 2. Electricity demand assumptions for each scenario, based on electricity access pathways and assumptions on development of fossil fuel-based back-up generation. Sources: baseline values derived from FGN) (2016).

Note: Off-grid demand includes both fossil fuel-based back-up generation and sustainable solutions (mini-grids and SHS).

Table 3. On-grid generation capacity assumptions for each scenario.

	Scenarios									
		BAU			GREEN			MODERATE		
On-grid Generation Capacity (GW)	Base year 2015	2020	2025	2030	2020	2025	2030	2020	2025	2030
Gas	5.845	5.845	6.500	7.500	6.200	7.500	10.000	6.000	7.000	8.500
Large Hydro	1.383	1.383	1.890	1.890	1.890	3.000	4.000	1.600	2.000	2.500
Coal	–	–	0.400	0.400	–	–	–	–	0.400	0.400
Biomass	–	–	–	0.050	0.020	0.100	0.500	–	0.020	0.100
Biogas from Waste	–	–	–	0.050	0.020	0.100	0.500	–	0.020	0.100
Wind	–	–	0.010	0.100	0.010	0.200	0.500	–	0.050	0.150
Solar PV Utility	–	0.070	0.200	0.500	0.120	1.080	5.000	0.120	0.500	1.000

Note: Base year and projections based on public sources (Future Energy Nigeria, 2017; Office of the VP & Power Africa, 2015) that were then refined via stakeholder consultations.

scenarios, in the Green Transition scenario, both on- and off-grid technologies scale up at what sector experts consider to be the fastest possible pace. This means, for example, that natural gas installed generation capacity increases to 6.2 GW by 2020, mainly due to refurbishment of existing plants, and that 10% of the approximately 13 GW pipeline of natural gas projects currently planned or under construction in Nigeria is actually realized by 2025. A further 2.5 GW comes online during the following five-year period (2025–2030), meaning a doubling of the capacity installed over the previous five years. The rates of implementation are considerably lower in the

Table 4. **Off-grid generation capacity assumptions for each scenario, including both fossil fuel-based self-generation and sustainable off-grid solutions.**

Off-grid Available Generation Capacity (MW)	Base year 2015	Scenarios: BAU 2020	BAU 2025	BAU 2030	GREEN 2020	GREEN 2025	GREEN 2030	MODERATE 2020	MODERATE 2025	MODERATE 2030
Fossil-fuel based Self-Generation	25,000	28,981	33,597	38,949	27,602	30,474	33,646	28,285	32,002	36,207
Small Hydro	45.0	46.0	50.0	53.0	50.0	65.0	80.0	46.0	53.0	60.0
Rooftop PV (Residential, C&I, Public – 200W to 20 kW)	10.0	20.0	40.0	80.0	20.0	70.0	170.0	20.0	70.0	170.0
Standalone PV (20W to 200W)	1.0	4.5	7.0	10.0	7.0	20.0	35.0	6.0	10.0	20.0
Hybrid Solar Mini-Grid	–	1.2	3.6	7.2	2.0	20.0	100.0	2.0	5.0	10.0

Note: Base year and projections based on public sources (6WResearch, 2018; GOGLA et al., 2019; HBS & CSJ, 2017; UNIDO, 2016) that were then refined via stakeholder consultations.

Table 5. Transmission and distribution capacity assumptions for each scenario.

Transmission and Distribution capacity (GW)	2015	2020	2025	2030
BAU	5.5	6.0	7.0	8.0
Green Transition	5.5	7.5	10.0	15.0
Moderate Change	5.5	6.0	8.0	10.0

Note: Base year and projections based on stakeholder consultations.

BAU and Moderate scenarios. All scenarios assume, based on the evaluation of the investment pipeline, that the gas power plant fleet continues to be dominated by single-cycle turbines. We note the NDC assumes an increase in investment in combined cycle technology.

Large hydropower sees around a third of the 6GW pipeline realized by 2025, whereas in the BAU scenario only 500 MW are added. For grid-connected solar PV, the Green Transition scenario assumes that two of the fourteen PPAs that were signed in 2017 reach financial close by 2019 (CSEA Africa, 2019; Nextier Power, 2018), bringing the installed capacity to 120 MW in 2020, then increasing to 1.1 GW in 2025 and 5 GW in 2030.

The on-grid investment pipelines (projects planned or being commissioned) were estimated from publicly available sources (Future Energy Nigeria, 2017; Office of the VP & Power Africa, 2015) and refined via stakeholder interviews. For off-grid generation, data scarcity meant that most baselines and scale-up projections were developed on the basis of stakeholder interviews only. For example, the status of functioning mini-grid projects by 2015 and the possible scale-up rates were estimated during interviews with private mini-grid developers and development organizations active in the energy access space.

In the Green Transition scenario there is a disruptive scale-up of off-grid renewables-based solutions: over 1 million solar standalone systems are installed by 2023. This is in line with the goals of the Nigeria Electrification Project (World Bank, 2018b) and was checked against the latest market trend data (GOGLA et al., 2019). For mini-grids, we assumed that there would be a gradual implementation of the various funds currently being pledged over the next 10 years, which would result in around 100 MW of mini-grid projects being successfully implemented by 2030. The baseline values and projections for small hydro, commercial and industrial PV, and fossil fuel-based self-generation (i.e. diesel and petrol generators) were based on existing studies (6WResearch, 2018; HBS & CSJ, 2017; UNIDO, 2016) but extensively refined as a result of stakeholder consultations. There remain high levels of uncertainty in the assumptions for these technologies.

The assumptions for transmission and distribution (Table 5) were developed through stakeholder consultations. The government's grid expansion goals are significantly higher than our assumptions (e.g. 10 GW of wheeling capacity are targeted by 2020), but the sector is inadequately funded (TCN, 2018; TCN PMU, 2017). There is currently no official strategy to harmonize grid expansion plans with the roll-out of off-grid solutions.

As well as capacity assumptions, other technical variables such as process efficiency, capacity credit and capacity factors were derived from previous studies (FGN, 2015; NESG & HBS, 2017) and are available on the full data set that is made available with the paper (LEAP, 2019). The sources used in those studies are Nigerian public documents (e.g. Cervigni et al., 2013; NERC, 2012, 2015; Oladokun & Asemota, 2015), complemented with international sources where necessary.

3.5. Model

We simulate the resulting electricity supply mix and emissions of the three scenarios with the help of the LEAP (Long-range Energy Alternatives Planning) tool (Heaps, 2016). LEAP, a medium- to long-term modelling tool for energy policy analysis and climate change mitigation assessment, was also used to inform Nigeria's NDC, as well as the NDCs of 34 countries, especially in the developing world (GIZ, 2017).

Our study uses LEAP as an energy accounting tool, which is one of several modelling methodologies it can support.[3] First, we used LEAP to develop a model of Nigeria's on- and off-grid electricity systems. The tool allows for flexibility in the structure and hierarchy of final demand and energy supply modules. This proves important in the Nigerian context, where severe data shortages exist, and where electricity supply technologies that are not subject to transmission losses (i.e. off-grid technologies) play an important role in the system.

The model's key exogenous assumptions are the final electricity demand, the maximum installed capacity of different generation technologies and the transmission capacity of the grid (Figure 3). With these, and using its rules-based algorithms, LEAP determines endogenously the future capacity additions and electricity production that will meet demand under each of our scenarios, and estimates the resulting GHG emissions.

4. Results

The results indicate that in 2030, Nigeria's electricity mix continues to be dominated by fossil fuel-based self-generation (between 53 and 62% of the mix, depending on the scenario) and natural gas generation (26–29%) (Figure 4). The Green Transition scenario achieves a total output of 215,03 TWh, which in per capita terms

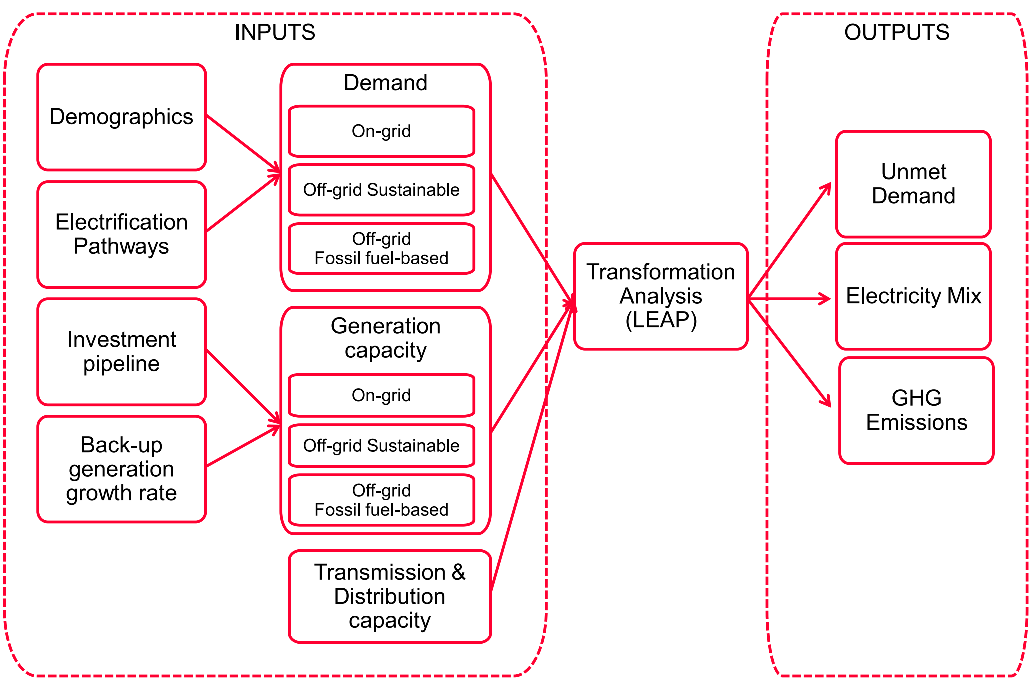


Figure 3. Schematic view of model assumptions (inputs) and results (outputs). Expert stakeholder views informed the inputs.

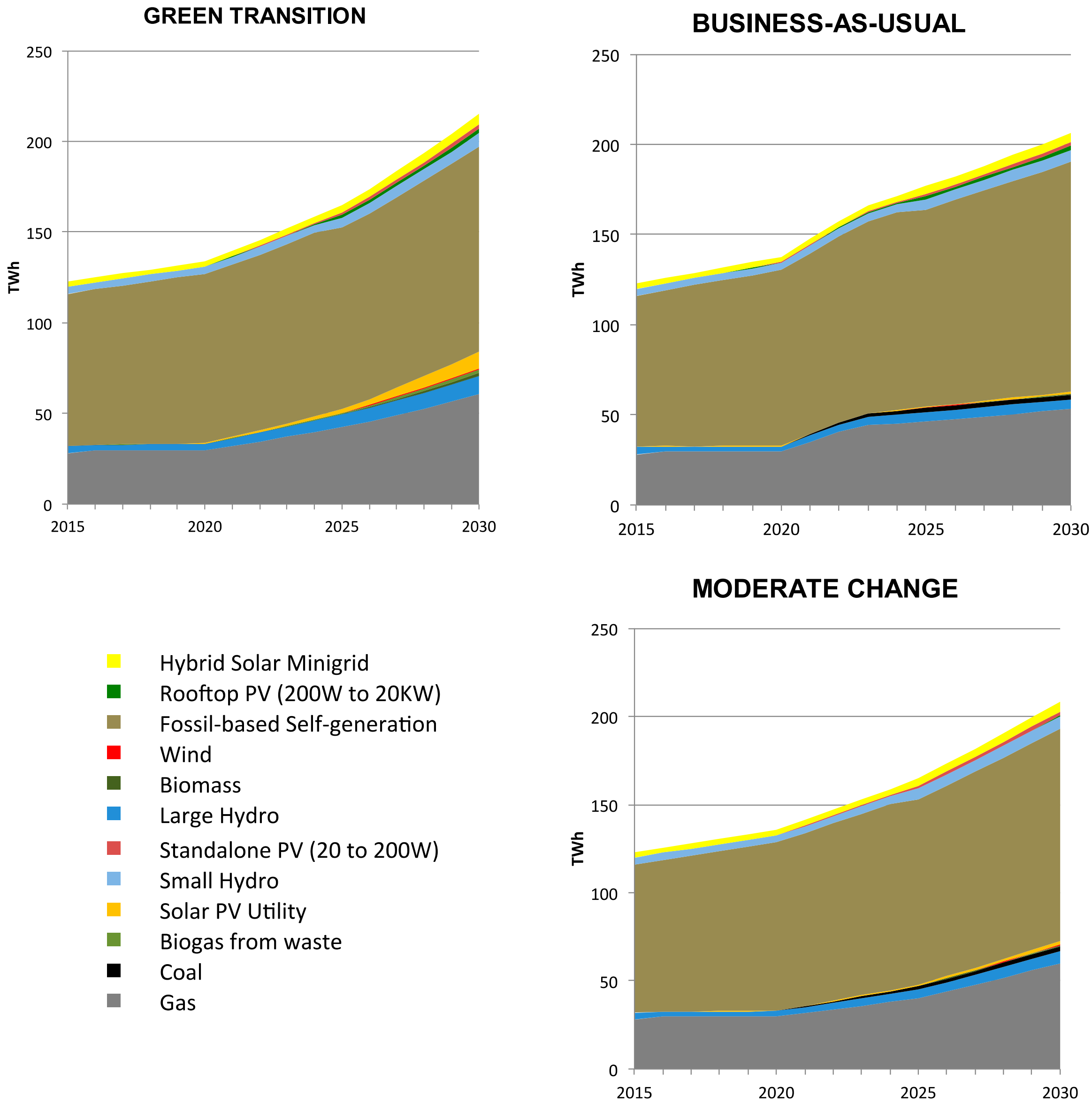


Figure 4. Electricity mix for each scenario (TWh).

equates to 814 kWh per person per year, or 386 kWh per year if the fossil fuel-based generators are excluded. This is significantly below the yearly demand projected by Nigeria's NDC and SEforALL Action Agendas of around 2,000 kWh and 1,000 kWh per capita by 2030, respectively.

4.1. Access goals

On the basis of our assumptions on supply (generation, transmission and distribution capacity), the demand in the Green Transition scenario is met. In other words, the Green Transition scenario meets the '90% electricity access by 2030' goal as defined in this study. Specifically, this means that 148.5 million people would be connected to the grid by 2030 and would have a Tier 3 level of energy access (500 kWh per capita per year) and that those with sustainable off-grid access would shift from zero to Tier 2 (100 kWh per capita per year).

The BAU and Moderate scenarios are also able to meet demand, which in these cases was much lower given the lower assumed electrification rates (53.3% and 65.9%, respectively).

It is important to recall that the electrification pathway underlying the Green Transition scenario sees 88.2 million people receiving electricity from sustainable off-grid solutions by 2030, including over 40 million from standalone systems. While this was considered feasible by some of the experts consulted, it would entail an unprecedented speed and scale of transition in the off-grid sector. Moreover, the scenarios remain rather reliant on the assumptions on the scale-up of mini-hydropower, with almost half of the demand for sustainable off-grid electricity being met with these solutions.

4.2. Renewable energy goals

The Green Transition scenario would result in a 14.7% share of renewables in the energy mix by 2030, when excluding large hydropower. This is in line with the government's goal of 15%. However, when large hydropower is included, the share of renewables in the mix is only 19.3%, far from the 30% government goal. In other words, the renewable energy targets are only partly met. Nonetheless, this substantial share would contribute greatly to accelerating the transition towards meeting longer term goals beyond 2030. The BAU and Moderate scenarios result in a share of approximately 9% for renewables in the mix excluding large hydro, and 12% when including large hydro.

4.3. Emissions goals

Nigeria's NDC does not have a specific emissions goal for the power sector, but its most ambitious, i.e. 'conditional', scenario sees power sector emissions roughly doubling from 164.5 $MtCO_2e$ in 2015 to around 300 $MtCO_2e$ by 2030. The emissions of all three scenarios in our study are significantly lower than that level, ranging from 146 to 153 $MtCO_2e$ in 2030 (Figure 5). In other words, according to our assumptions, the NDC's pledges for the power sector would be comfortably met in all three scenarios. It is important to note that this study used the same modelling tool and a similar model structure as the NDC, considered the same GHGs (CO_2, methane and nitrous oxide) and used the same Tier 1 emission factors for electricity generation.

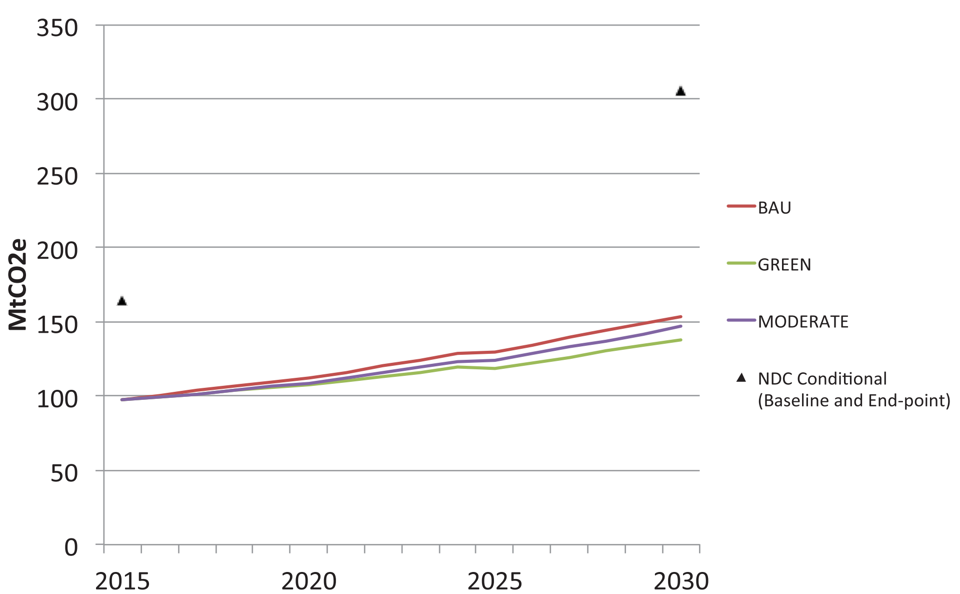


Figure 5. Emission pathways for all scenarios ($MtCO_2e$). Emission factors based on IPCC guidelines (2006)

The difference between the NDC emission pathways and this study's is due to the underlying demand and supply assumptions. Specifically, we can distinguish the following drivers for the differences:

- 2015 baselines: the NDC assumed significantly higher installed capacity for gas stations. In our study we used only operational (rather than nameplate) plant capacity and refined the values through expert interviews.
- Emission pathways: demand assumptions were the main reason for the difference. The NDC assumed a 5% rate of growth in GDP per annum, whereas our study avoided macro-economic drivers of demand and built demand on the basis of feasible electrification rates, as revealed by least-cost electrification studies. Supply assumptions also played a (smaller) role in the difference between the emission pathways.

The differences in emissions between the Green Transition, Moderate and BAU scenarios are mostly driven by the different role of fossil fuel-based back-up generators in each scenario. Incorporating other gases would likely make these differences larger, particularly in the case of diesel generators, which are important sources of black carbon and other short-lived climate pollutants (SLCP). A study into Nigeria's SLCP emissions and their health and economic costs is currently underway (CCAC, 2018).

5. Discussion

One of Nigeria's most demanding challenges today is to deliver electricity access to millions. Despite the recent privatization of generation and distribution, the establishment of a grid management company, and the adoption of accompanying legislation, Nigeria is considered to have one of the least developed policy environments to support energy access (World Bank, 2016b). Moreover, Nigeria's power sector has recently faced a national economic recession. This study aimed to explore the feasibility of a power generation mix that would meet electricity access, renewables and emissions reduction goals by 2030. We determined that under certain assumptions the targets can be achieved through a combination of on- and off-grid solutions.

5.1. Off-grid sector

On the off-grid side, a fast but plausible growth of the market for standalone PV and hybrid mini-grids could deliver a Tier 2 level of access (approximately 100 kWh per capita per year) to over 88 million people by 2030. Key underlying conditions for this would include: rapidly shifting financial flows from grid-connected investments to off-grid systems (SEforALL, 2018), coordinating grid expansion plans with roll-out of off-grid solutions (World Bank, 2016b), and improving capacity and standards. The BAU and Moderate scenario also see some growth, driven by the reduction in costs. However, they fall short of delivering on the access goals as defined in this study.

Stakeholders consistently highlighted the role that emerging financing tools and funds can play in triggering this rapid transition. Several development finance institutions have recently set up funds that underwrite or derisk off-grid investments in Nigeria, provide guarantees to mini-grid and SHS system developers and financiers, or take a direct stake in investments. Commercial banks have also been targeted through finance programmes, with the Central Bank of Nigeria and the African Development Bank (AfDB) now supporting a commercial bank in the provision of preferential loan terms to renewable energy developers (Anyaogu, 2018). The French Development Agency (AFD) has also partnered with two Nigerian commercial banks to set up a credit facility for investments into renewables (SUNREF, 2018). The AfDB is also an investor in the Off-Grid Energy Access Fund (OGEF, 2018). The Green Climate Fund is supporting additional blended finance investments into Nigeria, by consortia led by AFD and FMO, the Dutch development bank (GCF, 2018b). The portfolio of the domestic sovereign green bond launched in 2017 includes NDC-compliant renewable energy projects (DMO, 2017).

Expert interviews revealed that there are currently about 100,000 PV standalone systems deployed in Nigeria (excluding solar lanterns and products below 20Wp) and around 30 operating hybrid solar-diesel mini-grids. This is a very small fraction of the very large market potential (GOGLA et al., 2019; NESG & RMI, 2018). A considerable number of international and national investors are currently active in the Nigerian market, but even for them, predicting the pace of market scale-up is very challenging, in particular for small-scale solar systems. Stakeholders have a wide range of views as to the speed with which off-grid can be scaled up, and the impact the investments will have on electrification pathways. In view of the limited experience in the scaling up of off-grid operations in the country and an evident lack of capacity among project developers, concern has been expressed that a sudden large inflow of investment, into what is arguably an immature market, may lead to sub-standard projects.

Our quantitative scenarios do not fully capture the interaction between the off-grid and on-grid sectors, and how the development of one sector might influence the other. For example, there is high uncertainty around how a strengthened grid supply and availability of sustainable off-grid solutions would affect the rate of replacement of diesel and petrol back-up generators (Farquharson, Jaramillo, & Samaras, 2018). Another example is inter-connected mini-grids, which were seen by stakeholders to play a crucial role in certain segments of the market during the transition. Mini-grids may actually develop much faster in rural and peri-urban areas that are already grid-connected but are loss-making for the on-grid distribution companies (Graber, 2018).

The Green Transition scenario sees a relative deceleration in the growth of the petrol and diesel back-up generator market, due to the emergence of sustainable access solutions. However, there would still be a very large share of fossil fuel-based back-up generation in the mix (53% of the total output in 2030, compared with 58% and 62% in the Moderate and BAU scenarios, respectively). In the absence of sufficiently large sustainable off-grid markets, or of clear policy signals (e.g. fuel price reform, import duties) – which are unlikely to be put in place in the near-term – the high willingness to pay for power will continue to drive this part of the electricity mix and many millions of households and businesses will still depend on diesel and petrol back-up generators.

A number of studies point towards the significant health impacts and costs to the economy of petrol and diesel generators in Nigeria (Awofeso, 2011; Climatters, 2018; Oguntoke & Adeyemi, 2017). Exposure to fine particulate matter accounted for 22% of infant deaths in Sub-Saharan Africa (Heft-Neal, Burney, Bendavid, & Burke, 2018). The contribution of emissions from diesel generators to this has not been established (Farquharson et al., 2018), but reducing reliance on back-up generation is likely to accelerate the achievement of health-related sustainable development goals (SDGs) in Nigeria (especially SDG-3).

This study purposely omitted energy efficiency improvements from the demand assumptions, with the aim of reducing complexity and therefore engaging more effectively with stakeholders who are unfamiliar with energy modelling and scenario building. However, it is widely acknowledged that energy efficiency is set to be a catalyst for off-grid electrification (GOGLA et al., 2019). The growth of markets for energy-efficient appliances such as televisions and fans in Nigeria will be an important factor in the successful realization of the off-grid electrification pathway in the Green Transition scenarios. Future studies should address the role of efficiency in off-grid electricity demand.

5.2. On-grid sector

Based on the assumed rates of growth in gas-based generation, coupled with significant improvements in the grid, a moderate increase of large hydropower and introduction of non-hydro renewables-based generation, particularly solar PV, the current level of access could increase significantly. However, this does not mean that the electricity mix changes dramatically from the current relative shares. The Green Transition scenario sees 28% of the 2030 output coming from natural gas, 5% from large hydropower and 4% from utility scale solar. In the case of gas or hydro, this only slightly surpasses the 2015 shares (23% and 3%). It is important to remember that this scenario relies on there being wide-ranging improvements in financial, policy and enabling environment-related conditions in the near-term, including the restructuring of distribution companies that are currently not creditworthy. A very important assumption in the Green Transition scenario is that the regulated electricity tariffs are reviewed as scheduled in 2019–20.

It is important to note that this study does not take into account potential gas supply bottlenecks. Nigeria's plan to unlock its domestic gas market is hindered by high cost of finance for gas transport infrastructure as well competition with the export market (Occhiali & Falchetta, 2018). Similarly, the potential expansion of hydropower in Nigeria must be understood in the context of a poor track record of project completion. Many of the large hydropower projects in Nigeria have faced significant overruns and increases over the planned costs.

The non-hydro renewable energy resource that is currently of most interest in Nigeria is solar PV. At present, there is no significant utility scale PV generation, but it is of high priority for the government due to its potential to stabilize the grid in the North of the country and reduce transmission losses. Predicting what will be the share of biogas, biomass and wind-based electricity in the mix by 2030 is highly challenging. Both Nigerian and international data show good prospects for biomass-based generation. However, the market is particularly immature and there is a significant lack of knowledge regarding the most promising feedstock and conversion technologies, and the effects of competition with agricultural land use.

Although our study did not explicitly consider energy efficiency, in reality, there are likely to be efficiency gains even if no measures are taken, due to the reduction in costs of energy efficiency innovations. There is moreover a large efficiency potential to exploit in all demand sectors (GIZ NESP, 2015), which is likely to bring about significant savings and productivity gains. Suitable policies and standards (e.g. building code, Minimum Energy Performance Standards for lighting and air conditioners, ISO 50001) and a number of capacity-building initiatives are in place in Nigeria, but there are also large gaps in enforcement and monitoring, and an almost total lack of financing. The National Energy Efficiency Action Plan (NEEAP) sets several ambitious targets for 2030, such as increasing the share of new energy efficient buildings by 30% and almost 100% efficient lighting in housing by 2030.

5.3. Methodological implications

The design of the qualitative scenarios in this study relied on a deep understanding of the realities of the sector based on numerous stakeholder interviews. This approach is, however, not without its limitations. The set of underlying conditions (financial, policy and enabling environment-related) that underpin the scenarios are very dynamic and uncertain, and were a source of much debate during stakeholder discussions. Moreover, their effect is strongly influenced by larger political economy realities and they are themselves strongly interconnected.

The two exogenously defined drivers of this scenarios – demand and capacity installed – were also co-created with the support of experts and validated by numerous stakeholders of the power sector (policy, regulation, finance, technical assistance, private firms, advocacy). Finally, the preliminary outputs from the simulation were fed into some of the stakeholder interviews.

This study sheds light into the use of LEAP as a tool in the emerging field of energy transition analysis in developing countries, and has striven to address some of the gaps in the application of energy planning models in developing economies (Debnath & Mourshed, 2018). One advantage of the tool is that it is flexible enough to use in environments with severe data shortages. Moreover its transparency and accessible interface suits stakeholder engagement processes. LEAP has been used before in Nigeria (e.g. Emodi, 2016; Ibrahim & Kirkil, 2018).

Nigerian on-grid power generators have not met natural customer demand since the 1990s, hence historic statistics are insufficient to understand the level of suppressed demand. To compensate for this, the scenarios used the standard Tier system and proposed that different segments of the population realize a different share of the suppressed demand by 2030. In terms of kWh, rural and low income segments would realize relatively less than those connected to the grid, but probably with comparatively greater socio-economic impacts. The approach allows us to introduce a measure of inclusivity into the scenarios (Practical Action, 2018).

Climate change impacts are not considered directly in the study, but influenced the assumptions on installed capacity for large hydropower. There is scarce information on the vulnerability of hydropower to climate change in Nigeria. Given Nigeria's high vulnerability to climate change, water needed in both thermal and hydroelectric generation could become a limiting factor in the future.

Paucity of data remains a critical barrier to meaningful planning. In particular, some of the key areas of uncertainty include the 2015 baseline for fossil fuel-based back-up generators, as well as their pace of scale-up and the relationship between scale-up of sustainable off-grid access solutions and the shift away from back-up generators. The figures on techno-economic potential for small hydropower in Nigeria also warrant further investigation.

There is great convergence across SDGs when it comes to access to energy and mitigation of climate change (Antwi-Agyei, Dougill, Agyekum, & Stringer, 2018; McCollum et al., 2018; Nerini et al., 2019). The implementation of the pledges contained in developing country NDCs will be driven largely by the synergies between low-carbon transitions and the SDGs. Next steps stemming from this study could therefore include an assessment of the scenarios in terms of their impacts on goals other than SDG7 (Affordable and Clean Energy) and 13 (Climate Action), such as poverty alleviation, food security, job creation, gender, social inclusion and air quality (Markkanen & Anger-Kraavi, 2019; Nerini et al., 2018; Power for All, 2019; Verolme, 2017). Future research could moreover focus on testing the sensitivities of the results to the most critical demand and supply assumptions.

The present study does not invoke LEAP's cost modelling capabilities. Including cost assumptions into the LEAP tool or complementing the use of LEAP with other geo-spatial analysis tools would provide further insights into the potential of different technologies (Moksnes, Korkovelos, Mentis, & Howells, 2017).

Deepening the detail of NDC emissions scenarios is of great importance to accelerate their implementation. Our research also has the potential to make a significant contribution to the enhancement of Nigeria's NDC, in a context where the current set of NDCs have been deemed inadequate for meeting the 'well-below 2°C' goal of the Paris Agreement (Rogelj et al., 2016). Moreover, our study contributes to the emerging field of energy transition analysis and stakeholder-based scenario-building in developing countries (Osunmuyiwa, Biermann, & Kalfagianni, 2018; Palazzo et al., 2017; Waisman et al., 2019).

6. Conclusion

Drawing on published data and stakeholder interviews, we identified pathways along which Nigeria's power sector might transition up to 2030. The results reveal that, in the most ambitious Green Transition scenario, Nigeria could meet its electricity access goals and decarbonization pledges, and partly meet its renewable energy goals.

In contrast, the BAU and Moderate scenarios point towards a delay in the transition of the power sector, where population growth overshadows the impact of policies and investments, and access to electricity stagnates or decreases by 2030. It is worth noting that all three scenarios in this study surpass the decarbonization targets of Nigeria's NDC. Moreover, fossil fuel-based back-up generation (chiefly small-scale diesel and petrol-fuelled generators) plays a substantial role in all three scenarios. Data availability remains a significant source of uncertainty for this generation technology and warrants specific research.

A better understanding of the links between electrification strategies, capacity expansion and mitigation pathways, as described here, can support the planning process and make a significant contribution to the updating of Nigeria's SEforALL Action Agenda and its NDC. This improved understanding can also, to some extent, support policy and investment decisions.

Notes

1. Goals for grid-connected renewables include medium and large hydropower. When excluding them, the targets are 9.1GW of installed capacity by 2030, generating around 25 TWh/year. This corresponds to 30% of total capacity and 15% of total generation. Other targets include the proportion of the rural population that are served with off-grid renewables (25% by 2020 and 40% by 2030).
2. The Multi-tier Framework (MTF) was designed in 2015 under the SEforALL initiative, and provided a new definition and metric of energy access that is broader than binary metrics (electricity connection vs. no connection), and takes into account the quantity and quality of energy being accessed. The framework has proven to be a useful tool for measurement, goal-setting, investment prioritization, and tracking progress. The MTF follows a multidimensional approach. For example, where it concerns electricity supply, the following attributes are taken into account: capacity, duration, reliability, quality, affordability, legality, and health and safety. Our study built its demand assumptions with the goal of providing some degree of comparability with the MTF, so as to be of greater relevance in the light of upcoming MTF-based measurements and targets in Nigeria. To this end, some attributes of the MTF, chiefly the yearly consumption and supply levels, were used as criteria for defining tiers of access in our scenarios. Some important differences between the MTF's approach and our study's are: we summed annual household electricity consumption levels (as defined Table ES.3 of Bhatia and Angelou (2015)), productive use supply levels (Table ES.6) and public community infrastructure levels (Table ES.8). Moreover, for ease of comparison with available Nigerian statistics, we converted the metric from a 'per household' to a 'per capita' metrics. The result is an approximate yearly per capita values for Tier 2 (100 kWh) and Tier 3 (500 kWh). It is important to remember that Nigeria's current national electricity access goals do not follow this approach and refer only to the proportion of the population that has access to some source of electricity.

3. LEAP is a scenario-based modelling tool that supports a wide range of different modelling methodologies, from bottom-up accounting techniques to top-down macroeconomic modelling. LEAP can also accommodate a variety of cost-related inputs, which opens the door to a broader set of modelling methodologies (such as optimal dispatch and capacity expansion for power sector modelling). This study does not invoke LEAP's cost modelling capabilities. As a result, any mention of technology costs or financial barriers is part of the narrative description of each scenario only.

Acknowledgements

We thank all the stakeholders and experts interviewed, in particular Christine K, Ifeoma Malo, Luis Carlos Miro Baz and Chineme Okafor.

Disclosure Statement

No potential conflict of interest was reported by the authors.

Funding

This work was supported in part by the Nigeria office of the Heinrich Böll Foundation under [grant number 12331123/18]; Heinrich Böll Stiftung

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Journal of Cleaner Production 383 (2023) 135446

Contents lists available at ScienceDirect

Journal of Cleaner Production

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

Built for net-zero: analysis of long-term greenhouse gas emission pathways for the Nigerian cement sector

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A R T I C L E I N F O

Handling Editor: Zhifu Mi

Keywords:
Cement
Nigeria
Long-term scenarios
Industry decarbonisation
Net-zero
Energy transition

A B S T R A C T

Nigeria is Africa's top cement producer and could be on course to be one of the top producers globally. The goal of this study is to identify and critically examine the pathways available to Nigeria to meet its decarbonisation goals in the cement sector. Based on a literature review, the study assesses demand drivers and decarbonisation potentials for the sector. It then presents two different quantitative pathways for growth in production of cement by 2050, and three different pathways for decarbonisation of the sector. Using published data and a scenario analysis tool, the study calculates how the sector's emissions might evolve under each of these pathways. The results indicate that, in the most ambitious scenario, emissions from the sector can plateau by the late 2030s, resulting in an overall increase of 21% by 2050 (compared to 2015 levels). Achieving this scenario is necessary in order to put the sector on a path to net zero emissions beyond 2050. The scenario is driven by reductions in both energy-related and process emissions, as well as a small share of carbon capture and storage and demand management. A moderately ambitious scenario that relies mostly on savings on energy-related emissions results in an 84% increase in emissions by 2050. Finally, the Business-as-Usual scenario results in an almost tripling of emissions by 2050. The results indicate a strong potential for policies to drive improvements in energy efficiency and clinker-to-cement ratio. Critical areas of uncertainty within the assumptions include the production rates (including the evolution of the export market) and the fuel mix.

1. Introduction

The industry sector was the leading source of greenhouse gas (GHG) emissions worldwide in 2019, once indirect emissions are considered (Bashmakov et al., 2022; Bataille et al., 2018). Industry decarbonisation is now considered one of the next frontiers in the fight against climate change. Across the world, ambitious long-term transition plans for industry decarbonisation are being developed, such as the G7 Industrial Decarbonisation Agenda (G7 Germany, 2022) or the Industrial Deep Decarbonisation Coalition (UNIDO, 2022).

Cement production is one of the key contributors to emissions from the industry sector. It is the fastest-growing industry sub-sector in terms of emissions, currently accounting for up to 8% of global emissions (Bashmakov et al., 2022; Minx et al., 2021). Decarbonising the cement sector poses a challenge in the transition to a net zero world due to process emissions, which are particularly difficult to avoid (ETC, 2018). A radical reduction in emissions from the cement sector will entail making use of different decarbonisation levers, including energy efficiency, fuel switching and demand management. To this end, cement producers and governments are devising sectoral strategies and commitments. Key ones include the 2050 Net Zero Global Industry Roadmap of the Global Cement and Concrete Association and the World Economic Forum (GCCA, 2021; Mission Possible Partnership, 2022). Cement decarbonisation has been a key focus of the 2022 COP 27 Summit (Conference of Parties) (WEF, 2022), building on the success of the international commitments of the steel industry that were reached at COP26.

A range of long-term scenario studies for the cement sector project that, with ambitious measures, achievement of net zero emissions in the sector in the long term is within reach (Cembureau, 2020; ETC, 2018; GCCA, 2021; IEA, 2018, 2021). However, the majority of the research is centered around developed countries and China, where cement production is projected to stay relatively flat or decline in the next decades. Countries such as India, and other emerging and developing Asian and African countries, are still in the process of urbanising and building up key infrastructure. In these countries, cement demand is projected to grow significantly and begin to stabilize only around 2050 (IEA, 2020a). Achieving emission reductions in the sector in emerging and developing economies is projected to be far more challenging than in the industrialised economies.

In Africa specifically, cement demand per capita is projected to

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https://doi.org/10.1016/j.jclepro.2022.135446
Received 17 June 2022; Received in revised form 15 November 2022; Accepted 28 November 2022
Available online 2 December 2022
0959-6526/

List of abbreviations

BAU	Business as Usual
GNR	Getting Numbers Right
BECCS	Bioenergy with Carbon Capture and Storage
IEA	International Energy Agency
BIP	Backward Integration Policy
GDP	Gross Domestic Product
GHG	Greenhouse Gas
CCS	Carbon Capture and Storage
NEEAP	National Energy Efficiency Action Plan
COP	Conference of Parties
NDC	Nationally Determined Contribution
ETP	Energy Transition Plan
EU	European Union
SSA	Sub-Saharan Africa
GCCA	Global Cement and Concrete Association
TNZ	Towards Net Zero

double or triple in the mid-term, and local production is expected to increase greatly as well (IEA, 2019). There is however a lack of detailed emission scenario studies that assess the feasibility and pathways for achieving deep decarbonisation of the sector in specific African countries. Despite the rapid ramping up of investment and cement production capacity, the prospects for demand growth and the potential for carbon mitigation measures in African countries are not well understood. In general, research in the area suffers from strong data inadequacies and limitations in gaining access to expert knowledge that is available but fragmented. The following sections describe the novelty of this study and its key goals.

1.1. Novelty of the study

The novelty of the present study against existing studies in the field is that it is the first study to provide a detailed analysis of the prospects for cement sector decarbonisation at the national level for a country in the African region. It focuses on Nigeria, already the top cement producing country in the region and on course to becoming one of the top producers worldwide. The analysis is more in depth than previous studies, because it considers the underlying drivers of cement demand for Nigeria, as well as the full range of decarbonisation options for the sector, including demand-side measures. The assumptions regarding the evolution of these drivers are based on a review of existing historical data, literature regarding decarbonisation potentials, and expert opinion.

1.2. Motivation and objective of the study

The goal of this study is to identify and critically examine possible pathways available to Nigeria to transition to a decarbonised cement sector, in the context of the country's recently announced net zero targets (Climate Action Tracker, 2022; FGN, 2021b, 2021a). Drawing from socio-technical transition studies, and using the method of scenario analysis, the study identifies plausible future changes in underlying drivers of cement production (e.g. demographics, economic growth) and cement decarbonisation (e.g. technological improvements, policies, investments) and tests how they would interact and lead to outcomes in terms of the GHG emissions of the sector in the long-term.

1.3. Research gaps

The study aims to address the following research gaps:

- Lack of validated historical data regarding cement demand, sector energy intensity and emissions from the sector in Nigeria, Africa's top cement producer.
- Poor understanding of the prospects for growth in demand for cement and the potential for different decarbonisation measures in the specific context of Nigeria, which differs from the context of industrialised economies. Key differences between Nigeria and these more widely studied contexts include the prospects for rapid demand growth in the short term, the young cement production infrastructure fleet, the technological maturity of the sector, a distinct energy mix, and the market characteristics, among others. Knowledge in this area is strongly limited by data inadequacies and limitations in gaining access to expert knowledge.
- A scarcity of coherent and published datasets available for use in the analysis of future scenarios in the sector.

1.4. Study contribution

This study contributes to:

- Advancing scientific knowledge on the Nigerian cement sector structure, dynamics, prospects for growth and the pathways available for this key sector to contribute to the goal of achieving net zero emissions by mid-century.
- Enhancing the understanding of the sector in comparable African economies: Nigeria, Africa's top cement producer, provides a suitable case study of the prospects of growth in demand in Sub-Saharan Africa (SSA) as well as possible approaches to decarbonisation in the region.
- Providing an evidence basis for national strategy development, in particular to inform:
  - A roadmap that can guide the transformation of the sector and prepare it to comply with more stringent climate regulation in the future, and therefore remain competitive in international markets.
  - An investment plan that can prioritise and help attract the considerable financing needed both in mature technologies (e.g., clinker substitutes), non-commercial technologies (e.g., Carbon Capture and Storage (CCS)), and new value chains (e.g., bioenergy).
  - Goal setting for the sector, as part of the country's climate commitments under the Paris Agreement (Nationally Determined Contribution (NDCs), and long-term decarbonisation goals).
  - Policy and regulation for the sector, including standards and financial incentives.
- Identifying key areas of uncertainty and remaining data gaps, that can guide future research efforts in this field.

1.5. Orientation of the manuscript

The following section reviews relevant recent cement decarbonisation scenario studies as well as literature regarding demand projections and decarbonisation potentials for the Nigerian cement sector. Section 3 presents the methodology including the scenarios, key assumptions, and modelling approach. Sections 4 and 5 present the results and discussion, respectively.

2. Literature review

2.1. Scenario studies on cement decarbonisation

A small number of studies analyse decarbonisation scenarios in the African and Nigerian contexts specifically. These are summarised in Table 1 below, together with a set of key global studies.

In its decarbonisation pathways study for African industry, McKinsey (2021) finds that the cement sector can potentially reach net-zero by 2050. For this, three strategies (Bioenergy with Carbon Capture and

Table 1
Review of recent relevant scenario studies on long-term cement sector decarbonisation.

Reference and *Geographical scope*	Key mitigation levers	Key results	Net-zero sector by 2050?
Climate Action Tracker (CAT, 2017), *Nigeria*	• Demand reduction by 20% by 2050 via material substitution • 100% decarbonised power and fuels by 2050 • Reduction of the clinker/cement ratio to 70% • No CCS	Sector emissions continue to increase in 2050, even in most ambitious scenario	No
Energy Transition Plan (FGN, 2021b, 2021a), *Nigeria*	• Clinker substitution with calcined clay by 50% • Applying biomass combustion and CCS (BECCS) to 50% of production post 2030 • No demand-side measures	Emissions reduced by 92% against BAU in net-zero scenario (62% via BECCS and 30% via clinker substitution)	No (but yes by 2060)
Africa green manufacturing (McKinsey, 2021), *Africa*	• BECCS (most kilns fired by biomass and fitted with CCS in 2050) • Demand reduced by 40% in 2050 due to uptake of cross-laminated timber in commercial and residential construction • Clinker substitution with energetically modified cement where available, 50% calcined clay elsewhere	Emissions reduced by 91% against BAU in net-zero scenario (62% via BECCS and 30% via clinker substitution)	Yes
Africa Energy Outlook (IEA, 2022a), *Africa, SSA*	• Fuel mix (coal and gas) for cement production remains largely stable, but bioenergy and waste replace some of the coal • Substantial use of calcined clay as substitute	Production per capita in Africa and SSA increases to 100–150 kg by 2030 and then slows down	No
World Energy Outlook (IEA, 2022b), *Global*	• Clinker-to-cement ratio 0.56 b y 2050 (globally) • Use of coal, oil and natural gas in cement production is fully replaced by bioenergy, electricity and hydrogen between 2030 and 2050 (globally) • 8% of emissions from cement are captured by 2030, and 95% by 2050 (globally)	Africa sees overall increase in demand industrial materials but material efficiency tempers growth in net-zero scenario	Yes in Net-Zero scenario (globally)
Concrete Future Roadmap (GCCA, 2021), *Global*	• Largest share of emission reductions (36%) achieved via CCS, starting post 2030 • Demand-side measures, e.g. efficiency in design and construction, also contribute a very significant share (22%) • Smaller role for other measures: efficiency in production, fuel switching, etc. • Cement as a carbon sink (recarbonation)	Global demand increase from current 14.0 billion m^3 of concrete to 20 billion m^3 in 2050, taking into account large increases in Africa, India and Latin America	Yes
Cement industry roadmap (IEA, 2018), *Global*	• Global cement production is set to grow by 12–23% by 2050 from the current level. • Africa more than triples its current cement production by 2050 • Carbon capture and reduction of clinker content provide largest emissions reductions by 2050, complemented by fuel switching and energy efficiency • Material efficiency and demand management only marginal	By 2050, sector's direct emissions reduced by 24% compared to current levels (in most ambitious scenario)	No
Mission Possible (ETC, 2018), *Global*	• Full spectrum of measures required to reach net zero: • Demand management: improved demand management and material efficiency, circularity, use timber as a substitute. • Energy efficiency: especially clinker-to-cement ratio • Switch from coal to gas (particularly in China), use of biomass and hydrogen. • Innovations: new cement chemistries, use of carbon capture and heat electrification	Sector decarbonisation will imply a significant increase in cement prices and could account for circa 60% of the global costs of decarbonizing all the harder-to-abate industrial sectors	Yes
Indian cement decarbonisation roadmap (WBCSD, 2018) - *India*	• Demand for cement expected to increase three- to six-fold • Roadmap's goal is to reduce emissions intensity to 0.35 tCO2 per tonne of cement	Direct emissions can be reduced by 45% compared to 2010 levels by 2050	No
Indian cement sector 1.5 °C scenario (Dhar et al., 2020), *India*	• Industrial GDP growth as driver for cement demand growth • In BAU scenario, demand increases 5-fold from current levels by 2050 in, but in 1.5 scenario it is 25% lower than BAU, thanks to demand management • Significant role for material efficiency and demand management in order to meet 1.5 goal • Widescale deployment of CCS	Most ambitious scenario results in a 30% increase in emissions by 2050, compared to the base year.	No

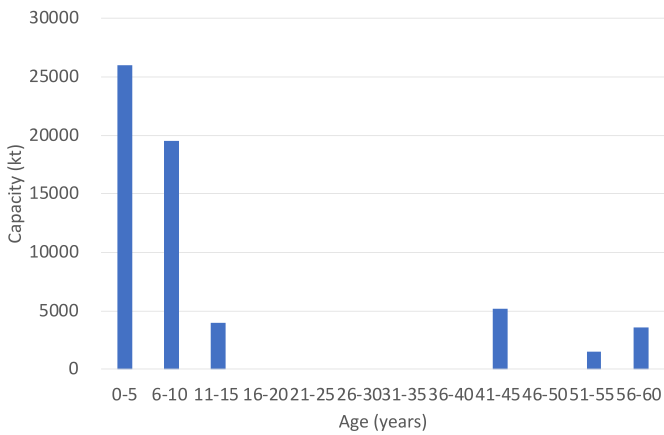


Fig. 1. Plant installed capacity by age. Source: GID (2021).

Storage (BECCS), clinker substitution, and demand reduction) would need to be pursued aggressively in the sector. More recently, Nigeria's Energy Transition Plan (ETP) (FGN, 2021b, 2021a) highlights two key levers for the full decarbonisation of the sector by 2060. On the other hand, it assumes a strong reduction of the clinker-to-cement ratio through the substitution of 50% of clinker with calcined clay. This assumption would drive 30% of the emissions reductions by 2060. The ETP also identifies BECCS as an option for the cement sector post-2030, and estimates that applying it to half of Nigeria's cement production could abate 62% of emissions from the sector. Finally, an earlier scenario study by CAT (2017) found that emissions in Nigeria's cement sector would be in the range of 110MtCO_2 by 2040 in an ambitious scenario that considers material efficiency, and around 200 MtCO_2 under a Business-As-Usual (BAU) scenario.

The next section sums up the state of knowledge on the Nigerian cement sector, to provide the needed context for the scenarios.

2.2. Nigeria's cement industry

Nigeria produced 21.5 million tonnes of cement in 2015 (FMEnv, 2018). It is unclear how much of this was destined for export. Cement production in the country grew at an average rate of 18% per year between 2000 and 2015. As a point of comparison, China's production between 1990 and 2014 grew at an average rate of 11% per year (CAT, 2017).

Current production capacity is estimated to stand at 56.8 Mt, making it the second-largest installed capacity in Africa after Egypt. The capacity utilisation level thus stands at around 40%, slightly lower than the world average (CemNet, 2021b, 2022; United Capital, 2019). As can be seen in Fig. 1, 44% of installed capacity has been installed in the last 5 years, and 83% in the last 15 years (Fig. 1). The average age of the fleet is thus lower than the Chinese and Indian average of 12–13 years (IEA, 2020a; Tong et al., 2019). Major plants are listed in Table 2 and mapped in Fig. 2.

Nigeria's manufacturing and construction sectors currently contribute around one-tenth of the nation's Gross Domestic Product (GDP) (CBN, 2022). The sector's contributions to foreign exchange earnings, employment and government revenue remain relatively low, in particular in comparison to the oil sector. The contribution of non-oil sectors to the economy has consistently grown in the last fifteen years, though at a relatively slower rate since the 2016 recession. Within the manufacturing sector, the cement sector is one of the main contributors to growth in GDP terms (CBN, 2022).

The current market in Nigeria is oligopolistic in nature and dominated by three key players: Dangote Cement Plc is the leader with 32.3 Mt per year of installed capacity (concentrated in just two plants, Obajana and Ibese), followed by Lafarge Africa Plc and the BUA Group (BUA Group, 2022; Dangote Cement Plc, 2020). This is in line with a global trend, where large companies dominate the market. It is estimated that over half of African production capacity is owned by nine pan-regional firms (Byiers et al., 2017).

Table 2
Cement production plants in Nigeria and estimated capacities. Sources: CemNet (2021a), GID (2021), SFI-ALD (2021).

Main owner	City and state	Capacity (Mt/year)
BUA	Okpella 1 and 2, Edo	3
	Kalamaina, Sokoto	5
Dangote Cement PLC	Gboko, Benue	4
	Ibese, Ogun	12
	Obajana, Kogi	16.3
Lafarge Africa PLC	Ashaka, Gombe	1
	Ewekoro 1 and 2, Ogun	2.7
	Sagamu, Ogun	1.8
	Mfamosing, Cross River	5
	Calabar, Cross River	3

1 All plants are integrated (meaning they include clinker production), and all are in operation except Calabar which is under construction.

The oligopolistic nature of Nigeria's cement industry has been criticized for causing price rises and obstructing economic recovery, calling for new policies to attract new entrants (Reuters, 2021). The current dominance of the three large firms is indeed a result of previous policies: in 2002, when domestic production was unable to meet demand and the country relied on the importation of cement to meet domestic construction needs, the government implemented the Backward Integration Policy (BIP), requiring cement import licenses be allocated only to importers who could prove they were building factories for local cement manufacturing in Nigeria. Incentives under the policy include waiver of VAT and custom duty for importation of cement production equipment (Akinyoade and Uche, 2016).

The following two sections delve into the key drivers for cement demand and the potentials for decarbonisation in the sector.

2.3. Drivers of demand

The relationships between cement demand, economic development and urbanisation are complex, but some patterns can be distinguished (Zhang et al., 2018). Cao et al. (2017) identified an S-shaped evolution of cement stock per capita as a function of income and urbanisation, where four stages can be distinguished: an initial stage with a slow linear growth in developing economies, an accelerated "take-off" stage, a slowdown stage, and finally a shrinking stage (found in a limited number of countries with very high incomes and urbanisation levels). Van Ruijven et al. (2016) tested different linear and non-linear models for GDP growth and also found that an S-shaped relation is the best fit to historical data. Bleischwitz et al. (2018) also find that historical data from developing economies tend to show a linear fit, and that at higher levels of GDP per capita consumption tends to decouple. However, they find the decoupling pattern can vary considerably, depending on the infrastructure intensity, consumption patterns and technological choices of developed economies. Three areas of relevance for cement demand are analysed below: demographic changes, economic development, and infrastructure growth drivers.

2.3.1. Demography and urbanisation

Extended demographic changes are expected over the coming decades in SSA countries. The projected growth in population is led by West Africa. Between 2020 and 2050, Nigeria's population will have doubled in size, reaching 401 million and making it the world's third most populous country (Fig. 3).

Regarding urbanisation, Nigeria is expected to show growth rates that are above the regional averages (Fig. 3). Urban population in SSA has more than doubled since 2000 to reach 440 million today. The share

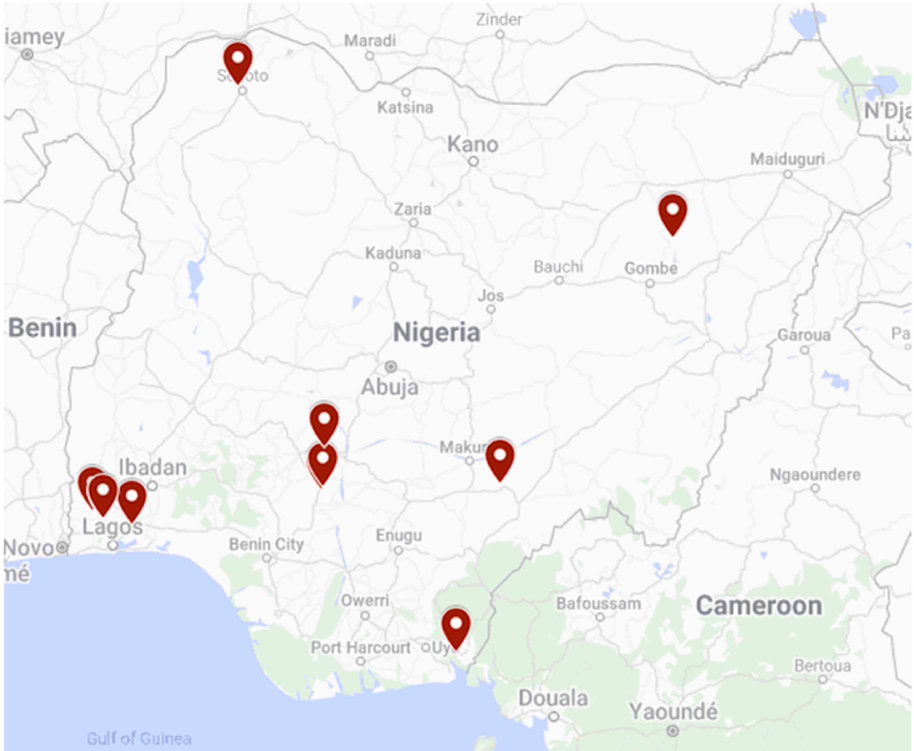


Fig. 2. Location of cement plants. Source: SFI-ALD (2021) (created with Google Maps).

of population currently living in cities in SSA is now 40.4%, up from 31.4% in 2000. In Nigeria, this proportion is now well over 50%. By 2040, there will be 520 million more people in cities in SSA than there are today. Around 115 million of these will be in Nigeria. For comparison, between 1990 and 2010 China saw the population of cities increase by 360 million (and cement production grow nine-fold). Urbanisation of this scale and speed has never been seen before, and is expected to be twice as large as the projected growth of urban population in India over the next two decades (IEA, 2019).

2.3.2. Economic growth and industrialisation

In the period 1990–2020, Nigeria's average GDP per capita growth rate was 1.4% per year (World Bank, 2022a). There is currently strong uncertainty on economic trends in Nigeria and no studies on how they would affect cement demand. Despite being Africa's largest economy in terms of size of GDP, Nigeria is not likely to be among the fastest growing economies in SSA in the next years (World Bank, 2022b). Mid-term estimates for growth of GDP in Nigeria are highly uncertain. The government's post-pandemic recovery economic plan foresees an average GDP growth rate of between 3 and 5% per year could be achieved by 2025, depending on different oil price and economic stimulus scenarios (ESC, 2020; FMFBNP, 2021).

Regarding industrialisation, SSA is projected to increase its global share of manufacturing, although the timeframe and speed of this increase are debated. Some of the factors that could make SSA manufacturing more globally competitive include: an increase in wage levels in Asia, suitable skill base development, and growing trade between SSA and other emerging economies (Hogarth et al., 2015).

2.3.3. Infrastructure and housing

Cement use for infrastructure, and particularly transport infrastructure, is expected to be a key driver of cement demand in emerging economies up to 2050 (IEA, 2020a). Infrastructure deficit severely undermines the prospects for economic growth in Sub-Saharan Africa. For example, Nigeria's road network spans around 195,000 km, of which an estimated 81% are unpaved (Bello-Schünemann and Porter, 2017; Ubi and Udah, 2019). Both paved and unpaved road network density in Nigeria is more than twice as high as those of the peer group of resource-rich African countries, although still only half of the levels found in Africa's middle-income countries.

As a result of demographic trends, demand for housing in Nigeria is also high. It is estimated that up to 780,000 housing units in different market segments are needed annually in Nigeria to keep up with demand (OBG, 2018b; Wong et al., 2016). However, current production is below 100,000, resulting in an overall accumulated deficit of around 17 million units as of 2013. As a result, it is estimated that Nigeria would need to build 1.5 million new units per year to meet its needs.

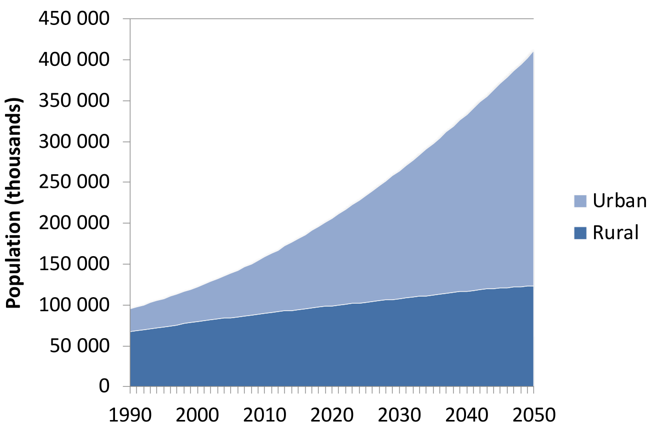
2.4. Decarbonisation potentials

Historically, Nigeria has contributed very little to climate change. Nevertheless, in 2021, Nigeria passed the Climate Change Bill which includes a net zero target for 2050 to 2070 and has since further committed to net zero emissions by 2060 (Climate Action Tracker, 2022; FGN, 2021a, 2021b).

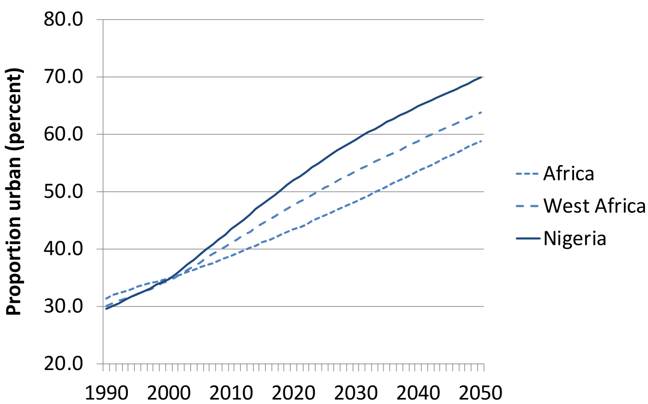
There are three key levers for decarbonisation of the cement sector: (1) reducing demand for cement (chiefly through material efficiency and material substitution); (2) improving energy efficiency (including reducing the clinker-to-cement ratio), and (3) deploying decarbonisation technologies such as cleaner fuels or carbon capture and storage (ETC, 2018; Korczak et al., 2022). The following sections sum up existing knowledge on their potentials as well as ongoing initiatives and example projects in Nigeria.

2.4.1. Demand management

The IEA (2019) assumes that Africa could follow a different trajectory for cement demand than China and other emerging economies thanks to demand-side measures. While no studies could be found regarding the potential of demand-side measures for SSA and Nigeria, the greatest opportunities are likely to lie in material efficiency and



(a)



(b)

Fig. 3. Population projections for Nigeria (a) and projections for proportion of urban population in Nigeria compared to the region (b). Source: UNDESA (2018).

circularity.

Regarding material efficiency, measures to extend the lifetime of buildings account for the largest reductions in demand from material efficiency in global scenarios, followed by improved building design and construction and reduced material losses (IEA, 2020a). Recycling of cement is currently challenging but innovation efforts are underway to recycle production waste and end-of-life cement.

Usage of alternative low-carbon building materials could impact cement demand in the long term. There is a large potential for use of engineered timber and traditional materials (e.g. adobe) rather than concrete in construction. This could not only deliver net reductions in emissions, but also potentially constitute a permanent carbon sink, offset some of the growth in demand for cooling and make cities more resilient to climate change (ETC, 2018; IEA, 2019). McKinsey's net-zero decarbonisation path for Africa suggests that cement demand could be reduced by 40% against business-as-usual by 2050 due to the uptake of cross-laminated timber (McKinsey, 2021) and adds that job creation in this sector would compensate for the job losses in the cement sector. However, there are no studies examining the cost or available supply of timber or other materials for this purpose in Nigeria nor its potential impact on water or biodiversity (Klasa, 2018).

2.4.2. Energy efficiency

Cost of energy is a strong driver for energy efficiency in Nigeria, with energy costs being the single largest variable production cost at a cement plant (Oni et al., 2017). As depicted in Fig. 1, most capacity has been installed in the last 10 years. Full refurbishments of these young kilns are unlikely. However, there is a large potential to improve energy efficiency of existing kilns in the next investment cycle (the typical lifetime of a cement kiln is 40 years). Njoku et al. (2017) constructed energy conservation supply curves for three Nigerian cement manufacturing plants and showed that thermal energy savings of between 19.8 and 52%, and electrical energy savings of between 35.2 and 43.1% were possible with respect to the global benchmark plants. With respect to Chinese benchmark plants, thermal energy savings of 10.7–47.3%, and electrical energy savings of 20.9–30.2% could be achieved.

Moreover, studies show a large room for cost-effective investments in partial retrofits. A recent audit in a major plant indicates there is potential for 10% savings in primary energy consumption against the benchmark, with an average payback of four years for the necessary investments. The calcination process is the biggest energy consumer and has the highest potential for savings, followed by the on-site electricity generation losses (NESP, 2020).

It is important to remember that energy efficiency improvements may be partly offset by additional energy requirements related to the use of other carbon mitigation measures, for example, use of alternative fuels or installation of carbon capture equipment. Policies and standards may also impede efficiency improvements (for example, electricity consumption in cement grinding is very dependent on grain size requirements).

Clinker production is the most energy- and emission-intensive process of cement production. Decreasing the clinker-to-cement ratio through the use of blended cements and clinker substitutes can substantially reduce the energy requirements and direct emissions of cement production. The "Getting Numbers Right" (GNR) project of the Global Cement and Concrete Association (GCCA, 2022) estimates the average clinker-to-cement ratio for Africa was 79–75% over the 2012–2019 period. Most decarbonisation scenarios for the sector rely on the clinker-to-cement ratio declining to between 60 and 70% in the mid-term (Cembureau, 2020; IEA, 2018; WBCSD, 2018), though the lower range is not yet commercially viable.

In Nigeria, Lafarge cement has implemented projects (including some with CDM finance) to reduce the clinker to cement ratio and introduce a new blended cement standard (FMEnv, 2021), but there is no recent information on their progress. Almost all the steel production in Nigeria is through scrap steel recycling and therefore the potential of Nigeria's steel sector to provide slag to the growing cement sector is likely to be very limited.

Nigeria has abundant deposits of kaolin clays (Raheem et al., 2021). Their use for replacing up to 50% of the clinker in cement has been successfully tested though not developed (Akindahunsi et al., 2020). There are other viable natural clinker substitutes available, such as rice husk ash, but they are presently not used (Abubakar, 2018; Tijani et al., 2022). The development of sustainable supply chains, standards for alternatives to clinker, and construction standards has an important part to play in unlocking the potential of clinker alternatives.

2.4.3. Decarbonisation technologies

Two key levers to reduce the emission intensity of cement production are fuel switching and CCS.

The IEA projects that the share of gas in the calcination process across Africa will grow significantly, in line with global trends (IEA, 2019). Nigeria's IEA balances state that coal represents 100% of the direct energy input in the cement industry (IEA, 2020b). These national statistics stand in contrast with company reports that indicate a mix of fuels. For example, the market leader Dangote (Dangote Cement Plc, 2020) reports that its plants currently use between 30% and 50% local coal, with the rest being supplied by gas. In one plant, petroleum coke represents about 10% of the fuel mix. According to one report (United Capital, 2019), key Dangote plants (Obajana and Ibese) which were originally designed to run on gas were retrofitted to operate with coal.

Despite the lack of coherent data, there are indications that in recent years cement manufacturers in Nigeria are increasingly using locallymined coal in heat-related processes. This is because oil products and gas have proven to be more expensive and, in the case of gas, susceptible to foreign exchange volatility and supply disruptions (United Capital, 2019). Moreover, earlier studies suggest that the shortage of natural gas supply in the northern part of the country may have restricted its use in plants located in this region (Ohunakin et al., 2013).

One other major player, Lafarge Africa, currently leads in the use of alternative fuels, which they use at four of their five plants (NIRAS-LTS et al., 2021). Alternative fuels currently account for 45% of energy supply at its Ewekoro plant, and a reliable supply chain has been set up over the last decade. The feedstock is almost entirely from palm kernel shells, with some limited use of palm fruit fibre. A recent study estimates that these two bioenergy feedstocks, together with peanut shells, rice husk, and wood processing residues (all of which also have relatively established supply chains) could meet up to 70% of the energy demand of the current Nigerian cement plant installed capacity. The use of waste as a fuel source, such as tyres, seems to be minimal in the Nigerian cement sector.

Technology developments may allow increasing the electrification of kilns in the mid-term. The lack of sufficient power from the grid drives all Nigerian cement plants to install their own power generation plants on site. This is potentially an opportunity for increasing the share of renewables-based electricity in heat-related processes as well as in general operations.

CCS is likely to be the only route to achieving total decarbonisation of cement production (ETC, 2018). The IEA's latest net-zero scenario projects that by 2070, about 90% of all the CO_2 emitted globally in cement sector is captured (IEA, 2021). However, the first commercial applications in the cement sector are not expected until 2024–2026 (IEA, 2020a).

In Nigeria, carbon capture has mainly been studied for the oil and energy sectors. The biggest bottleneck for use of CCS in Nigeria is likely to be storage and transport. The Oil and Gas Climate Initiative (IEA and OVP, 2021) has identified four storage hubs in Nigeria amounting to ~42 Mt/year of CO_2, but the feasibility of their use for the cement sector has not been investigated.

With regards to capture technology, investment costs in Nigerian cement plants are high (Betiku and Bassey, 2022), which suggests that pilot projects are very unlikely to start in the next ten years. It is likely that only new plants in future investment cycles will incorporate capture technologies, due to the high costs and efficiency losses related to retrofitting options. Moreover, Nigeria will need strong policy and regulatory frameworks for CCUS deployment.

Based on the data and trends reviewed in this section, the next section describes the approach to developing the scenarios and accompanying assumptions.

3. Method

3.1. Scenario analysis

The study draws from socio-technical transition studies, and other theoretical frameworks that delve into the management and governance of complex transitions toward sustainability, including transition management, strategic niche management, and the multi-level perspective (Markard, 2018; Markard et al., 2012). Nigeria's cement sector is a socio-technical system that consists of different elements: infrastructure, knowledge, markets, regulation, etc. Scenarios are a tool used within transition studies to improve the understanding of the complex interactions within socio-technical systems and the dynamics of the transition from one system state to a future one. The long-term, system-level foresight provided by scenarios can anticipate key features of transitions, as well as key risks and uncertainties. A scenario is a coherent and plausible description of a possible future state of a socio-technical system. It incorporates internally-consistent assumptions about the drivers, relationships, and constraints in the system (Thompson et al., 2012). Scenario analysis in climate change mitigation research in general, and in this study in particular, helps to evaluate the implications of different approaches to mitigation as well as critical areas of uncertainty (Moss et al., 2010).

This study analyses three possible transition scenarios for Nigeria's cement sector:

- Business-as-Usual: a pessimistic scenario where decarbonisation potentials are not pursued.
- Ambition: a scenario that sees significant improvements, but does not put the sector on the path towards deep decarbonisation.
- Towards Net-Zero (TNZ): a best-case scenario where all current decarbonisation levers are used to a high degree, leading to a substantial transformation of the sector. This scenario relies on significant investments, improvement in finance, policy, and enabling environment measures as well as continued reductions in the cost of decarbonisation measures that are not currently cost-competitive in Nigeria.

The following sections delve into the rationale behind the chosen cement production and decarbonisation pathways.

3.2. Production pathways

As a basis for the development of the transition scenarios, two different quantitative pathways for growth in production of cement were developed (Fig. 4). The baseline scenario follows a 3% growth rate consistently until 2050. This is based on a mid-point of current GDP growth projections. It is slightly lower than the 3.75% rate of urbanisation that UNDESA projects for Njoku et al. (2017) and the 3.5% yearly growth rate that the top-down model by van Ruijven et al. (2016) obtained for growth in cement demand in West Africa, and which was used in an exploratory modelling exercise for the Nigerian cement sector (CAT, 2017).

The second production scenario assumes that cement production starts to slow down from 2035 onwards and settles at a 1.5% growth rate. This is based on the decoupling of demand from economic growth that has been identified by global models (reviewed in section 2) as well as on the introduction of demand-side measures that drive down demand for cement.

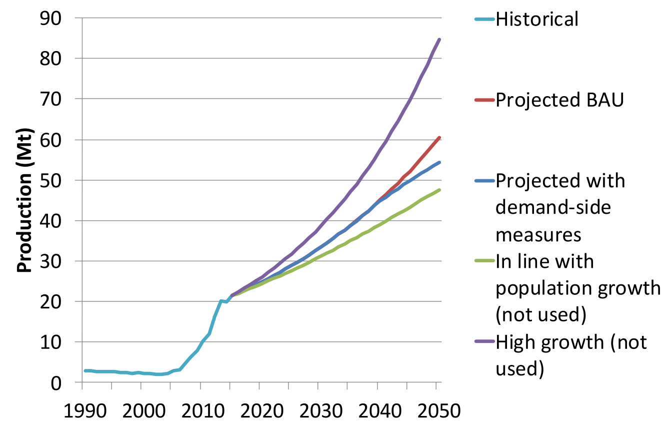
A further two projections are given in Fig. 4 for illustration purposes: one assumes a production growth rate that only follows population growth (2.5% per year). The other one assumes a significantly higher growth rate (of 5% per year) and illustrates a potential path where domestic production grows faster than GDP and where Nigeria significantly increases its exports of cement to the region. It is interesting to note that some market analysis studies foresee higher demand growth in the short term (of up to 6% in total) (ARM, 2018; Research and Markets), but it is unclear whether this would be the case for Nigeria nor for how long.

It is important to note that the growth rates chosen do not dramatically increase production on a per capita basis. As Fig. 4(b) shows, the current low levels of 120 kg per capita would increase by 27%, to 151 kg per capita, in 2050 (and only 14%, or 135 kg per capita, in the scenario with demand-side measures). These values are still significantly lower than emerging economies (e.g., per capita cement consumption in India currently stands at around 200 kg).

3.3. Decarbonisation pathways

The three scenarios hinge on different key strategies for emission reductions from the sector. The key assumptions for each scenario are shown in Table 4 below.

The assumptions on historical values, potential fuel mix and energy efficiency improvements (including clinker-to-cement ratio) draw strongly on the GNR database (GCCA, 2022), the IEA National Energy



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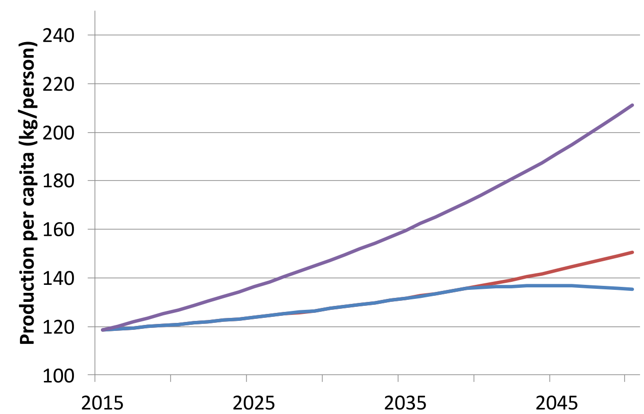

(b)

Fig. 4. Cement production (historical data and assumptions under the scenarios), total (a) and per capita (b). Source of historical data: 1990–1999 from Ohimain (2014), 2000–2015 from FMEnv (2018).

Balances (IEA, 2020b), and the IEA's regional estimates for cement decarbonisation potentials (IEA, 2018). However, the values derived from these datasets are qualified in light of the literature reviewed and expert interviews.

3.4. Scenario simulation tool

The analysis was performed using the open access PROSPECTS + tool, which captures the basic activity and intensity factors driving emissions in the cement sector (ICAT and NewClimate Institute, 2022). This excel-based tool allows building sectoral emissions scenarios by multiplying activity metrics (chiefly cement production) and intensity factors (see Equation 1). The calculation variables are described in Table 3 whereas a schematic view of the links between the variables is shown in Fig. 5. The input data that were altered in the calculation are indicated in the legend. PROSPECTS+ is particularly useful for creating a high-level, long-term vision of how a sector may plausibly evolve under certain assumptions. The tool does not have an optimisation functionality nor does it include cost estimates for different technology options or scenarios.

Equation 1. Calculation of Greenhouse Gas (GHG) emissions in the three scenarios

$$E = \sum_{n=0}^{N} (DEE_n + PE_n + EE_n) \tag{1}$$

Where:

$$DEE = DED \bullet DEEI$$
$$DED = A_{clinker} \bullet DEI$$
$$A_{clinker} = A_{cement} \bullet r$$
$$PE = A_{\ clinker} \bullet (PEI \bullet k)$$
$$EE = ED \bullet EEI$$
$$ED = A_{cement} \bullet EI$$

The following section describes the results of modelling the three scenarios with the above-mentioned assumptions and modelling approach.

4. Results

The scenario calculations are given in Figs. 6 and 7. The Business-as-Usual (BAU) scenario results in a strong increase in emissions from 2015 levels, from 15.2 Mt to 41.6 Mt CO_2e per year in 2050. This represents a 174% growth, driven equally by energy- and process-related emissions. The emissions per ton of cement decrease marginally, from 0.71 tCO_2e/t cement in 2015 to 0.68 tCO_2e/t cement in 2050.

The Ambition scenario sees an increase to 27.9 Mt, or 84% from 2015 levels, with most of the increase driven by process emissions, which grow by 137%. The emission factor decreases from 0.71 in 2015 to 0.46 tCO_2e/t cement in 2050.

Finally, the "Towards Net Zero" scenario reaches a peak of 19.6 Mt in 2038 and decreases slightly to 18.4 b y 2050. This represents only a 21% growth from 2015 levels and puts the sector on the path to deeper emission reductions, including through CCS, which avoid 3.1 Mt up to 2050. The TNZ scenario sees a doubling of process emissions and a 25% decrease in energy-related emissions. The emission factor is halved, reaching 0.34 tCO_2e/t cement in 2050.

The assumptions on demand management measures in the TNZ scenario drive a small proportion of the decrease in emissions. It is important to remember that the scenarios assume that cement demand per capita would only increase to 135–151 kg per capita, which is still significantly lower than other emerging economies.

The following section presents the results in light of existing literature and lays out caveats and critical uncertainties.

5. Discussion

The results share some common points with existing literature on potential pathways for deep decarbonisation in Nigeria's cement sector. The Energy Transition Plan (FGN, 2021b, 2021a) assumes a strong reduction of the clinker-to-cement ratio through the substitution of 50% clinker with calcined clay. This is broadly in line with the assumption of the Towards Net Zero scenario in the present study, which assumes a 60% ratio is achieved by 2050. The report states this would reduce

Table 3
List of variables.

Variable	Description	Unit
E	Total Emissions	$MtCO_2e$
N	Number of historical years in estimation	years
DEE	Direct Energy Emissions	$MtCO_2e$
PE	Process-related Emissions	$MtCO_2e$
EE	Electricity-related Emissions	$MtCO_2e$
DED	Direct Energy Demand	PJ
DEEI	Direct Energy Emissions Intensity	$MtCO_2e$/PJ
$\mathbf{A_{clinker}}$	Activity (Clinker Production)	Mt clinker
$\mathbf{A_{cement}}$	Activity (Cement Production)	Mt cement
r	Clinker-to-cement ratio	t clinker/t cement
DEI	Direct Energy Intensity	MJ/t clinker
PEI	Process-emissions Intensity	$MtCO_2e$/Mt clinker
k	% of process emissions captured by CCS	%
ED	Electricity Demand	TWh
EEI	Electricity Emissions Intensity	tCO_2/TWh
EI	Electricity Intensity of cement production	kWh/t cement

Table 4
Key assumptions of scenarios.

Parameter	Unit	Starting point (2015)	Scenarios (2050)			Affects which strategy?
			BAU	Ambition	Towards Net-Zero	
Direct energy intensity	MJ/t clinker	3.81[a]	Stays constant	Linear decrease to 3.3[b]	Linear decrease to 3.2[b]	Energy efficiency (primarily)
Direct energy emissions intensity	$MtCO_2e/PJ$	0.09[c] (fuel mix 100% coal)	Stays constant	0.06 (Coal 35%, Gas 50%, Biofuels and waste 15%)	0.04 (Coal phased out, Gas 75%, Biofuels and waste 25%)	Fuel mix
Clinker-to-cement ratio	%	77.23%	Stays constant	65%[d]	60%[d]	Clinker-to-cement ratio
Electricity intensity	kWh/t cement	98[e]	Stays constant	86[f]	83[f]	Energy efficiency
Electricity emissions intensity	tCO_2/TWh	0.42 [g] (fuel mix 82% gas, 17% RES)	Stays constant	0.23 (65% gas, 35% RES)	0.32 (45% gas, 55% RES)	Fuel mix
CCS	% share of direct emissions avoided/ year	0%	0%	5% (starting in 2040)	15% (starting in 2035)	CCS
Demand	Mt/year	21.5	60.5 (3% yearly growth rate until 2050)	60.5 (3% yearly growth rate until 2050)	54.3 (3% yearly growth until 2035, then linear decrease to 1.5%)	Demand management

[a] 2015 value for Africa from GNR database, indicator 93AG (GCCA, 2022).
[b] Based on expert interview and 2040 values from IEA 2DS scenario (IEA, 2018).
[c] Nigeria's IEA balances state that coal represents 100% of the direct energy input in the cement industry (IEA, 2020b). These national statistics stand in contrast with company reports that indicate a mix of fuels.
[d] 2015 value for Africa from GNR database, indicator 92AGWce (GCCA, 2022). Decrease to 70%/68% by 2030, 67%/63% by 2040, based on RTS and 2DS scenarios, respectively (IEA, 2018). Extrapolate to 2050.
[e] 2017 value for Africa from GNR database, indicator 93AGW (GCCA, 2022) (2015 value not available).
[f] Based on 2040 RTS and 2DS scenarios, respectively (IEA, 2018).
[g] 2015 value from Nigeria IEA energy balances (IEA, 2020b).

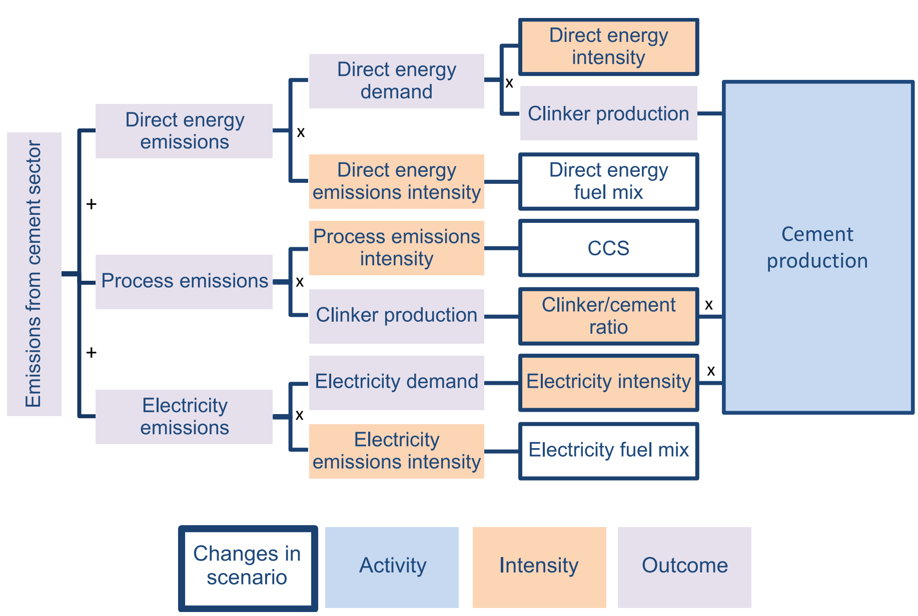

Fig. 5. Depiction of calculation variables and links in PROSPECTS + tool (ICAT and NewClimate Institute, 2022). Activity variables are centered around cement and clinker production, whereas intensity variables refer to energy consumed or emissions produced per unit of activity. Those variables with a thick outline are modified in the scenarios (as described in Table 4), whereas those with no outline remain unchanged.

cement emissions by 8 Mt by 2050, a 30% reduction from the base year levels.

The ETP also identifies BECCS as an option for the cement sector post-2030, and estimates that applying BECCS to half of Nigeria's cement production could abate 62% of cement emissions. This is a much higher value than that considered in the current study and is not in line with the likely timeline of CCS commercialisation in Nigeria, given that the world's first commercial applications in the cement sector are not expected until 2024–2026 (IEA, 2020a). Further comparisons are limited as the study gives no consideration to demand-side measures and no details are provided regarding the assumptions on demand growth. In its Africa-wide scenario for the cement sector, McKinsey (2021) does consider a strong decrease in demand in the long term due to the uptake of cross-laminated timber as an alternative material. However, this does

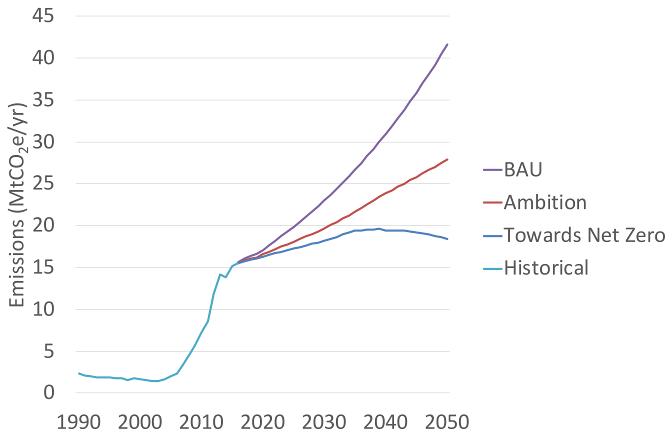

Fig. 6. Emissions from cement sector in Nigeria, 2015–2050, under the different scenarios.

not seem in line with current market and policy trends in Nigeria.

The scenarios by CAT (2017) find that emissions in 2040 would be in the range of 110–200 $MtCO_2$, depending on the scenario. Their scenarios are driven by an assumption of there being 60 Mt of cement produced in Nigeria in 2015 but this figure was obtained from a media report and does not align with current government data. The scenarios in the present study foresee a slower growth in production and emissions. However, the evolution of emission intensity of cement production in the moderate and business-as-usual scenarios is comparable across both studies (in the range of 0.60–0.45 tCO_2/t of cement).

This study's findings are broadly aligned with studies in comparable contexts. For example, Dhar et al. (2020) find no absolute decrease in emissions from the base year in any of the scenarios for the Indian cement sector. Even the most ambitious scenario results in a 30% increase in emissions by 2050, compared to the base year. This is due to a highly certain increase in cement demand.

It is important to remember that the Ambition and Towards Net Zero scenarios rely on substantial investments, improvement in finance, policy, and enabling environment measures. However, Nigeria's industry faces significant barriers to investments: inadequate power and infrastructure (including high cost of transportation of cement), and limited access to finance are key barriers for all industry sectors in Nigeria, including cement. The incentives for the cement industry to transition towards net-zero are an immediate need to reduce its energy costs, and, in the future, compliance with more stringent regulation to avoid competitive disadvantage in international markets.

The Nigerian market and policy environment for industrial energy efficiency is still in its infancy. However, in the last ten years, there have been significant developments. In particular, the development and formal adoption of the NEEAP (National Energy Efficiency Action Plan) which sets energy efficiency targets for industry, and makes energy audits compulsory in all energy-intensive sectors (FGN, 2016). The ISO 50001 standard has been adopted in Nigeria, industrial energy efficiency networks have been set up and a series of capacity-building programmes and energy audits are underway (GIZ, 2020). As a result of recent efforts, awareness on energy efficiency in industry has risen among policy makers and industry. A survey of energy consumption

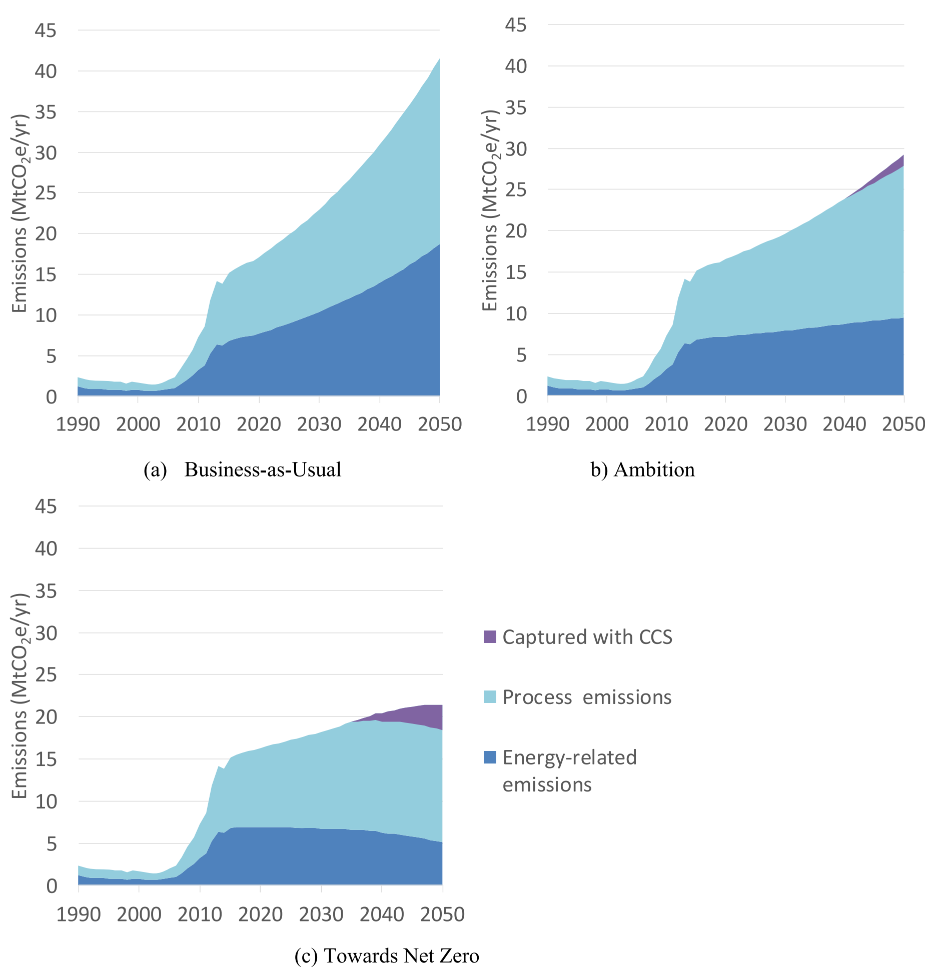

Fig. 7. Emissions by type, under the Business-as-Usual (a), Ambition (b), and Towards Net Zero (c) scenarios.

across multiple large-scale cement plants is however still lacking.

The results indicate a strong potential for policy that could drive improvements in the clinker-to-cement ratio. The uptake of blended cements in national cement standards is an area of high potential, but it is highly uncertain how fast it could happen. Moreover, the value chains for alternative materials for clinker are still to be developed.

Finally, literature on the potential of material efficiency and circularity in the cement sector in Nigeria and comparable economies is extremely scarce. Incentives to material efficiency are likely to act indirectly – for example, requirements for industry to reduce emissions lead to somewhat higher prices, which provide an incentive for construction companies and other industries to use materials more efficiently. Policy-driven changes occurring in other sectors also contribute to lower material demand, for example by encouraging the renovation rather than the replacement of old buildings.

5.1. Key caveats

The key caveats of the present study are of two types: those related to the availability or reliability of published data that informs the assumptions, and those related to the approach chosen for the development and analysis of scenarios. Furthermore, there are limitations related to the applicability of the findings in other contexts in the African region.

With regards to the data availability, the first major area of uncertainty is the assumption for current electricity mix and thermal energy mix. As stated in section 2, Nigeria's IEA balances are in contrast with company reports regarding the use of coal in the sector for heat generation. Moreover, Nigeria's manufacturing sector relies heavily on self-generation of electricity. Using the electricity mix of grid-based electricity (such as the one provided for the International Energy Agency (IEA)) is therefore not a suitable proxy. The coverage of the GCCA database on energy intensity and clinker-to-cement ratio is also rather low for Africa (29% coverage in 2017, cf. 86% for the European Union (EU)) and this diminishes the reliability of the data used.

The second key area of uncertainty concerns the energy efficiency potentials. A public survey of energy consumption and saving potentials across multiple large-scale cement plants is still lacking in Nigeria. The present study makes use of international literature and expert opinion, but future scenario studies should seek to enhance the database on energy and emissions saving potentials in Nigeria, through the use of on-site energy audits.

The third critical source of uncertainty are the assumptions for growth in demand and the potential for demand-side measures. The BAU and Ambition scenarios follow a 3% growth rate consistently until 2050, in line with GDP projections, rate of urbanisation, and findings of integrated models (van Ruijven et al., 2016). The Net Zero scenario assumes that cement production starts to slow down from 2035 onwards due to demand-side management, and settles at a 1.5% growth rate. These growth rates assume that production will mainly meet domestic demand and that demand per capita stays at relatively low levels (up to 135–151 kg per capita by 2050, which is still significantly lower than emerging economies where per capita cement consumption stands at around 200 kg). However, it is important to remember that several Nigerian cement manufacturers have plans to develop a strong export market. For example, several companies have built port facilities for exports (World Cement, 2018). In 2020 Dangote Cement exported 27,800 tonnes of clinker to Senegal and Lafarge Holcim began exports to Ghana in 2017 (OBG, 2018a; Olowookere, 2021).

Growth in production and in exports remains very difficult to forecast based on past trends and published literature and would merit further research through stakeholder engagement and the creation of a detailed dataset for planned production capacity in the next decades, which reflects expected stock turnover and investments. The present study indicates that Nigeria's cement plant fleet stock today is very young but, at the same time, that much of the 2050 stock is yet to be built. As of today, 44% of installed capacity is less than 5 years old, and 83% is less than 15 years old. The average age of the fleet is thus lower than the Chinese and Indian average of 12–13 years (IEA, 2020a; Tong et al., 2019). Despite slight overcapacity at the moment, the sector is likely to need new capacity from 2025 onwards.

A number of limitations emerge from the scope of the study and the approach chosen. Most importantly, the present study does not analyse the economic costs and benefits of the transition, nor its effect on cement pricing and the related distributional impacts. Future studies should use data on upcoming investments in plant capacity for an analysis of the cost and emission implications of different technology choices. For example, calculating the overall costs of delivering certain emission goals, a comparison on the cost of new plant investment vs. retrofits of existing plants, analysing the savings that can accrue from investing in the most efficient kilns available (rather than in outdated technology) or examining the effect of different scenarios on the price of cement products, and the impacts that this would have on consumers (construction sector and cement end-users). An interesting avenue for further research would be the study of the effects of carbon prices on the economic feasibility of different transition scenarios. Finally, a study of the economic externalities of the scenarios is warranted. For example, in terms of the co-benefits that could result from pursuing deep decarbonisation: health, productivity or employment creation (in the cement sector or in alternative value chains).

The scenarios analysed in this study are based on qualitative assumptions about near-term developments in finance, policy, and enabling environment that would drive each scenario. Future studies should seek to build on these underlying storylines and elaborate them further, ideally with the input from key industry stakeholders and relevant institutions. Examples of near-term developments which could be analysed in greater detail are the barriers to investment (such as the risk of further devaluations of the local currency), or the greater availability of finance for energy efficiency investments. A stronger set of qualitative assumptions regarding demand-side measures would also require a study of supply chains for alternative materials, and the policy needs to incentivise uptake Finally, understanding the potential of technologies that are currently not commercial, such as CCS, requires a more detailed analysis of global technological trends and the likely time ranges in which the use of the technology could be tested in Nigeria.

Finally, there are limitations related to the applicability of the findings in other contexts. This study sheds light into the prospects for growth in cement demand and decarbonisation pathways for the sector in other major cement-producing countries in Africa, especially in those characterised by oligopolistic markets with large-scale cement production facilities. However, it is important to keep in mind that macroeconomic factors such as population and GDP growth can significantly differ in other contexts and this may affect the potential of different approaches to decarbonisation.

6. Conclusions

In conclusion, this study finds that an ambitious yet feasible scenario could put Nigeria's rapidly growing cement sector on a path towards net zero emissions. The results indicate that, under a best-case scenario, emissions from the sector can plateau during the 2030s and grow by 21% by 2050 (compared to 2015 levels). This is despite an almost tripling of demand for cement, due to a doubling of the population and an increase in cement demand per capita to the levels of other comparable economies. Achieving this scenario involves action across all three key levers for decarbonisation of the cement sector: demand management, energy efficiency (including reducing the clinker-to-cement ratio), use of cleaner fuels, and carbon capture and storage. Realising each decarbonisation measure will require substantial investments, improvement in finance, policy, and enabling environment.

The findings also shed light into alternative scenarios where not all decarbonisation levers are implemented: a moderately ambitious scenario that relies mostly on savings on energy-related emissions results in an 84% increase in emissions by 2050, far from the path towards net zero emissions. Finally, a Business-as-Usual scenario results in an almost tripling of emissions by 2050.

The cement sector is characterised by long investment cycles and slow stock turnover. Most of Nigeria's cement production capacity has been installed in the last decades, and full refurbishments of relatively young kilns are unlikely. However, there is a large potential to improve energy efficiency of existing kilns via partial retrofits. Moreover, new kilns constructed in the next major investment cycle can incorporate best-available technology. This will likely take place in the mid 2020s and represents a window of opportunity which can either lock in outdated technology or put the sector on track for deep decarbonisation.

The findings of the present study provide an evidence base that can guide the development of a roadmap for the decarbonisation of the sector that seizes this upcoming investment window. The results also demonstrate the strong potential for policies to drive improvements in energy efficiency and clinker-to-cement ratio. Furthermore, Nigeria provides a suitable case study for understanding the potential for decarbonisation in similar contexts, as demand for cement and capacity to produce locally continues to rise in SSA in the mid-term.

Literature around decarbonisation of the cement sector in Nigeria and comparable economies is extremely scarce. The scarcity of published data on the sector limits the applicability of the findings. Some of the central assumptions in the present study are also some of the major sources of uncertainty. Critical areas of uncertainty include:

- The assumptions on production growth rates (including the potential of demand reduction, and the evolution of the export market), and
- The assumptions on energy efficiency potentials and fuel mix, with national statistics standing in contrast with company reports regarding the use of coal in the sector for heat generation.

Conducting on-site energy audits and the creation of a detailed dataset for planned capacity investments would help overcome this limitation. Moreover, updated and industry-validated historical data regarding cement production is required.

Furthermore, a detailed study into the cost implications of different scenarios, which quantifies the investment needs and key investment windows, is warranted. Future studies should also look into the impacts of the scenarios on the price of cement and any related equity implications. Finally, future research on the long-term prospects for decarbonisation of the Nigerian cement sector should seek broad stakeholder engagement and input, including from the cement producing firms, institutional actors, financing bodies, consumers and other affected parties.

Credit author statement

María Yetano Roche: Conceptualisation, Methodology, Formal analysis, Investigation, Data curation, Writing – review & editing, Visualization.

Declaration of competing interest

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

Data availability

The data that support the findings of this study are available on https://doi.org/10.5281/zenodo.7403393.

Acknowledgements

This research was supported by the Nigerian Energy Support Programme - a technical assistance programme co-funded by the European Union and the German Federal Ministry for Economic Cooperation and Development (BMZ) and implemented by Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ) GmbH in collaboration with the Federal Ministry of Power (FMP)-, by the Friends of the Wuppertal Institute association, and by the Promotions programme funding programme of the Wuppertal Institute for Climate, Environment and Energy. The author gratefully acknowledges the contribution of Ene Macharm and Joshua Garba (Nigeria Energy Support Programme) for their support in engaging stakeholders and accessing data. Also, I thank Georg Holtz, Stefan Lechtenböhmer and Prof. Manfred Fischedick (Wuppertal Institute) for their helpful advice.

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Energy Strategy Reviews 53 (2024) 101366

Contents lists available at ScienceDirect

Energy Strategy Reviews

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

Towards clean cooking energy for all in Nigeria: Pathways and impacts

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ARTICLE INFO

Handling Editor: Dr. Mark Howells

Original content: Dataset for Nigeria clean cooking scenarios and impacts study (associated article under review) (Original data)

Keywords:
Clean cooking
Climate change
Health
Long-term scenarios
Net-zero
Nigeria

ABSTRACT

Over 175 million Nigerians rely on the use of traditional biomass for cooking, and it is estimated that more than 128,000 people died in Nigeria in 2019 from household air pollution related to these fuels. There is currently a gap in the study of possible pathways to meet Nigeria's goals in clean cooking and in understanding the health and climate impacts that different pathways can bring about. We explore clean cooking access scenarios for Nigeria until 2060 under a business-as-usual scenario, a moderate climate mitigation scenario, and an ambitious transformative scenario. We carry out a disaggregation at the state level for the period up to 2030 to better guide shorter-term policy development. Our analysis shows that under an ambitious scenario where 85 million households achieve access to clean cooking by 2060, annual premature deaths due to exposure to household air pollution would decrease by 7 % compared to 2018 levels. A baseline scenario, on the other hand, sees a dramatic 77 % increase, resulting in 209,000 people dying prematurely, of which 94,000 children under 5. Furthermore, we find that woodfuel removals from forestland would lead to a tripling of carbon dioxide emissions from land use change, reaching 602 Mt CO_2 by 2060. Our findings stress the vital importance of a clean cooking transition in Nigeria and underline the urgent need for immediate acceleration in national efforts regarding access to clean cooking for all.

1. Introduction

In 2021, over 83 % of Nigerians lacked access to clean cooking technologies and fuels [1]. This rate is just above the regional average for Sub-Saharan Africa (SSA), which is 81.5 % [2]. On a global scale, Nigeria comes only behind China and India regarding the total number of people living without access to clean cooking. The situation is particularly acute in rural areas, where only 4.6 % of the population had access to clean cooking in 2021, as opposed to 32.8 % in urban areas [1,3].

The lack of access to clean cooking energy has implications for achieving Nigeria's health, air quality, climate, gender, and equity goals. The Global Burden of Disease study estimates that more than 128,000 people died in Nigeria in 2019 from household air pollution from the use of solid fuels [4]. Of these, 84,000 were children under 5. Nationally, over one in ten deaths of children under the age of 5 is caused by household air pollution. Next to India, Nigeria has the highest number of overall air pollution-related deaths globally.

While estimates vary, a significant share of Nigeria's current greenhouse gas (GHG) emissions arises from the use of energy for cooking. Nigeria's Nationally Determined Contribution (NDC) indicates that direct emissions from the household sector in 2015 were 31 $MtCO_2e$ [5], or roughly 10 % of the country's total annual emissions (though this does not consider emissions from land use change). The Energy Transition Plan (ETP) - an ambitious programme aimed at eliminating emissions from five sectors, including cooking - estimates that direct emissions from cooking energy stood at 40 $MtCO_2e$ in 2020 [6]. There is great uncertainty over the contribution to GHG from land use change resulting from the demand for fuelwood for cooking energy and the effect of fuelwood removal on deforestation and forest degradation.

Cooking energy is also a source of short-lived climate pollutants such as black carbon (BC), which impacts both air pollution and climate change. Biomass burning in traditional cookstoves represents 57 % of the national BC emissions [7].

Between 2020 and 2060, Nigeria's population is expected to double

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https://doi.org/10.1016/j.esr.2024.101366
Received 27 August 2023; Received in revised form 4 March 2024; Accepted 26 March 2024
Available online 8 May 2024
2211-467X/

Abbreviations

ALRI	Acute Lower Respiratory Infections
BC	Black Carbon
BMR	Baseline Mortality Rate
ETP	Energy Transition Plan
FOLU	Forestry and Other Land Use
GHG	Greenhouse Gases
HH	Households
ICS	Improved Biomass Cookstoves
LPG	Liquid Petroleum Gas
LUC	Land Use Change
NDC	Nationally Determined Contribution
SDG	Sustainable Development Goal
SSA	Sub-Saharan Africa

in size, reaching 375 million in 2050 and making it the world's third most populous country [8]. Achieving universal access to clean cooking is, therefore, vital to delivering Nigeria's development and climate goals.

Efforts are currently underway to develop a comprehensive clean cooking policy in Nigeria, based on existing evidence and best practice. A considerable body of literature exists regarding the dynamics of current household cooking energy patterns, predicting factors for behavioural choices and demand for clean cooking services in Nigeria [9–12]. Similarly, the impacts of current household cooking energy patterns have been assessed across a range of dimensions, such as health and food security [13–15]. A few recent studies explore possible pathways to meet Nigeria's goals in clean cooking, focusing on the long-term dynamics of adopting clean cooking technologies [16,17].

There is an urgent need to bring these strands of literature together and analyse the future transition in terms of potential pathways as well as health and climate impacts.

The goal of this study is to bridge this gap and provide transparency into what Nigeria's clean cooking energy transition entails. Specifically, what would be the impacts of meeting the current national goals, and what would be the cost of inaction. To do so, the study identifies and critically examines possible pathways available to Nigeria to achieve universal access to clean cooking in the context of the country's net zero targets [6,18]. Drawing from socio-technical transition studies, and using the method of scenario analysis, the study identifies plausible future changes in technology adoption. It then tests how these changes lead to outcomes in terms of health and GHG emissions. The assumptions take into consideration critical aspects, such as population growth and the potential development of different clean cooking value chains, based on historical data and stakeholder perspectives.

The novelty of the present study against existing studies in the field is that it incorporates the country's latest national net-zero goals as outlined in the ETP. Furthermore, it is the first study to provide a sub-national analysis of the short-term health impacts from different scenarios. In addition, it analyses the emissions from land use change that are linked to the different scenarios. The analysis is more integrated than previous studies because it considers both health and emissions impacts.

The following section reviews Nigeria's clean cooking goals, the current sector context, and relevant literature on cooking energy transitions in SSA and comparable economies. Section 3 presents the methodology, including the scenarios, key assumptions, and approach to impact assessment. Sections 4 and 5 present the results and discussion, respectively.

2. Literature review

2.1. Nigeria's clean cooking goals

The vision and strategy of the Federal Government of Nigeria for the clean cooking sector are enshrined in its National Climate Change Policy, the ETP, the revised NDC, and other related energy policies [5,6,18,19]. Recently, the National Clean Cooking Policy has been drafted with the goal of aligning the various policies pertinent to the sector [20,21]. This policy focuses on qualitative goals, but two recent policy commitments contain quantitative goals for cooking energy: the revised NDC and the ETP.

In the revised NDC, Nigeria committed to reducing its total emissions by 20 % by 2030 compared with business-*as*-usual levels, and by 47 % conditional on international financial support [5]. This commitment included quantitative goals for cooking energy: in the conditional scenario, 65 % of the population would be using clean fuels for cooking in 2030, up from 17 % in 2019. Specifically, the NDC goals aim at increasing the share of Liquid Petroleum Gas (LPG) users significantly, with almost half (48 %) of households using it by 2030. Improved biomass cookstoves would also increase significantly and displace traditional biomass stoves, becoming the primary technology in 13 % of households. Kerosene stoves would be fully phased out. The NDC does not state the emissions savings that this would lead to but it does state that achieving the NDC goals would mean that 30,000 premature deaths could be avoided by 2030.

In the ETP, the Nigerian government aspires to reach net zero emissions by 2060 and foresees that over 80 % of the population will achieve access to clean cooking by then [6,18]. The strategy is centred around two key steps:

- In the mid-term, the goal is to shift from traditional firewood, charcoal, and kerosene to LPG and electric stoves. Specifically, around 75 % of traditional biomass woodstoves would be replaced by 2030, chiefly LPG stoves. At the same time, the ETP also envisages a strong increase in the number of electric stoves, especially in urban dwellings.
- In the long-term, the goals envisage the achievement of universal access to clean cooking by 2060, as well as a full phase-out of traditional biomass stoves and LPG, replaced by a mix of efficient firewood stoves, electric stoves, and biogas. The potential of efficient firewood and biogas is seen as particularly strong in rural areas, while in urban areas, the strategy foresees renewables-based electricity to cover almost all cooking energy needs.

A third important commitment for Nigeria is the Long-term Low Emissions Development Strategy (LT-LEDS), which was recently unveiled [22,23]. The Nigerian government is in the process of aligning the goals of the NDC, ETP and the long-term strategy, which are currently different in terms of their 2030 ambitions.

Key government goals in the oil and gas sector are also relevant to Nigeria's clean cooking sector. The National LPG Expansion Plan aims to increase national demand for LPG to 5 million tonnes by 2027, of which 2 million tonnes are expected to come from demand for cooking energy. The immediate target in the first phase of the expansion program is to convert 10 million households to LPG as cooking fuel. For this, the programme focuses its efforts on 12 pilot states, two in each geopolitical zone of the country [24,25]. See Table 1 for the list of pilot states. There are currently no similar national policy programmes for other modern cooking energy forms such as biogas or electricity.

Nigeria's national goals and policies influence the choice of assumptions in this study, both in terms of long-term ambition and critical elements of the clean cooking transition (e.g., technology options, time frames, key market segments: urban vs. rural).

Table 1
Pilot states of National LPG Expansion Plan.

Geo-political Zone	Pilot state 1	Pilot state 2
South West	Lagos	Ogun
North East	Bauchi	Gombe
North Central	FCT (Federal Capital Territory)	Niger
North West	Katsina	Sokoto
South East	Ebonyi	Enugu
South South	Delta	Bayelsa

2.2. Cooking energy in Nigeria today

The wood, charcoal and traditional-stoves value chains dominate the cooking energy market in Nigeria. Solid biomass is the primary fuel in two-thirds of Nigerian households, mainly in rural areas. The primary cookstove in most households (51 %) is a 3-stone open biomass fire, whereas 9 % use self-built biomass stoves and 5 % use manufactured biomass stoves. Households predominantly use fuelwood, but charcoal makes up 4–6 % of the biomass used. The use of biomass fuel is particularly prevalent in rural Nigeria, where it is used by over 85 % of households - much of it outside of the commercial fuel market. Kerosene remains an important cooking fuel (17 % of Nigerian households in 2019) despite a rapid decrease in recent years due in part to the removal of a longstanding government subsidy. It is prevalent in urban households (28 %) but also in rural (9 %) [3,26,27].

Despite the central role of fuelwood as an energy source in the country, there are significant knowledge gaps as to the structure of biomass fuel value chains and their socio-economic impacts (e.g., impacts on climate and biodiversity, employment created). The difficulty of capturing data on local biomass use may have to do with the reality that much of it exists on a subsistence, informal, or even illegal (as is sometimes the case for charcoal) basis [28,29]. A map of woodfuel demand and supply areas is currently lacking at the national level, though global studies have attempted this based on geospatial data [30,31].

Within this context, clean cooking value chains (LPG, improved biomass cookstoves (ICS), and other renewable fuels) are emerging nationwide. With a current penetration of over 35 % in urban households [3] (up from just 7 % a decade ago), the LPG value chain is quickly becoming firmly rooted in the Nigerian market. The policy and enabling environment for LPG has recently improved, and a drive to attract large-scale private sector investments. The market has grown rapidly in particular areas, such as Lagos state, the country's commercial capital. Part of this growth has been enabled by innovative private-sector practices such as retailing LPG in smaller quantities to increase affordability for poorer households [32]. However, some of the earlier gains recorded have been undone by recent fluctuations in international LPG prices [33,34]. In any case, a policy focus on enabling access by poorer households is still lacking. LPG is the primary fuel of only 5 % of rural households. The penetration of LPG as a cooking fuel in urban poor and rural households is influenced by infrastructure limitations, income levels, and the availability of distribution networks [35,36]. Specific government interventions and support will be needed to increase market penetration in these segments [34].

Some of the key barriers to LPG expansion lie in supply and distribution, in what is currently a customer-owned LPG cylinder market. In other words, customers own most LPG cylinders currently in circulation in Nigeria, and there is a significant number of small firms in the segment, including informal last-mile distributors. This is characteristic of an early-stage LPG market, showing the signs of a transition to a fully mature retailer-centred cylinder market [37]. A credit facility proposed in 2020 as part of the National Gas Expansion Programme aims to promote this by facilitating access to finance for larger retailers [38]. Waivers of VAT on the domestic production of LPG and import duty on LPG equipment and accessories are in place. Another critical element to expanding cylinder numbers is regulation and standards for LPG distribution and dispensing that will support the market [39].

The ICS sector, though still strongly reliant on carbon finance, public funds, or donor grants, has made important progress. While LPG is generally perceived to have the greatest potential for growth in urban and peri-urban areas, ICSs are seen to have particular potential in rural areas, where fuelwood has greater affordability and accessibility. There is, however, no national-level data regarding the level of penetration of improved wood and charcoal stoves in Nigeria [38]. In contrast to the LPG sector, the enabling environment for ICS firms remains poor, and there is currently no overarching national government programme for their promotion. One further policy-related barrier in the ICS value chain is the lack of standards. It is often unknown how well the stoves perform as no quality assurance programme is in place. A quality standard was approved in 2017 but is yet to be enforced [39].

Electricity is the primary cooking solution in only 1 % of Nigerian households. However, recent price drops are opening the door for the use of solar PV-powered pressure cookers [40]. Key barriers to market penetration of solar electric pressure cookers in Nigeria include cost, consumer awareness, and social norms. It is important to remember that as of 2020, just 55 % of Nigerians had access to electricity, which is concentrated among urban populations [41].

Finally, it is important to note that several firms have emerged in the renewable ethanol and methanol value chains, though this field remains small. Equally, a few firms are pioneering in the supply of biogas for cooking.

Economic factors affecting all manufacturers in Nigeria hinder the growth of the Nigerian clean cooking value chains. These include high costs of electricity self-generation, high transport costs, high investment risks, etc., and are compounded by industry-specific challenges such as the low price of fuelwood, limited awareness among consumers and social norms [38].

There is a substantial body of microeconomics literature regarding demand and preferences for cooking energy services in Nigeria. These studies provide comprehensive insights into the complex dynamics of household energy decisions, shedding light on factors influencing fuel choice and its broader socio-economic implications. Income, fuel accessibility, type of dwelling, household size, level of education (especially of the head of the household), belonging to a cooperative, having access to electricity, and having access to the Internet have been found by various authors to be significant determinants of household cooking fuel choice in Nigeria [9,10,12,42,43]. Emodi et al. [43] find that fuel price elasticity is stronger in rural households, meaning changes in fuel prices are more likely to make them move up or down the 'energy ladder' (i.e., towards cleaner fuels or away from them) than in the case of urban households. Importantly, they find a significant number of Nigerian households 'backsliding' towards lower-quality fuels between 2010 and 2018. Jewitt et al. [11] use qualitative data to show the widespread use of fuel 'stacking' (use of multiple fuels) to shield against variations in fuel prices, access, and reliability of supply. They also note the limited awareness or concern about household air pollution and health risks.

The above snapshot of Nigeria's cooking energy sector, including demand drivers and behavioural patterns, informs the approach and assumptions of this study and provides a framework for interpreting the results. This is particularly important in the case of LPG, which plays a crucial role in the transition.

2.3. Literature on cooking energy transitions and impacts

The number of people without access to clean cooking worldwide declined in the last decade thanks to the progress in Latin America and Asia. However, the number has continued to grow in sub-Saharan Africa. The International Energy Agency estimates that 150 million people in SSA would need to gain access to cleaner cooking each year to ensure universal access by 2030 [2]. Several scenario studies investigate the pathways required to deliver this fast transition, aiming at informing policy. Moreover, they estimate the costs and benefits of the transition and the costs of inaction in terms of premature deaths, deforestation, and GHG.

Scenario studies in the field analyse how future demand for different cooking energy solutions is influenced by key variables such as population growth, urbanisation, shifts in fuel prices, and policies such as subsidies, awareness, and behaviour change [44–46]. Multiple optimisation and simulation models are able to model clean cooking transitions quantitatively based on these variables, whether they are treated as underlying drivers or constraints. A number of recent approaches are able to analyse transitions to a great level of technical detail (different fuels and stoves, e.g. Refs. [44,47], capture spatial aspects [48], and integrate cooking choice and demand models).

A key factor to consider in analysing clean cooking transitions are demographic changes. In their scenario modelling, Pachauri et al. [44] find that access to clean cooking rises under all scenarios until 2050. Still, no scenario achieves full access, and even in the most optimistic scenario, close to 60 % of the population in SSA could continue to lack access. This is due to population growth in the region outpacing the rate of transition to clean cooking systems. Another critical factor is the assumptions on plausible policies and finance. The same study also finds a clear difference in the future transition in urban vs. rural segments. Despite the strong effect of income on fuel choice, even richer households in rural areas are likely to continue relying on solid fuels under certain scenarios, because of the poor accessibility to cleaner alternatives.

Dagnachew et al. [49] find that only with highly ambitious cookstove subsidies and enhanced access to clean fuels can targets be met in SSA by 2050. These subsidies may come at a considerable economic cost but bring about great benefits. They find that by phasing out the use of traditional biomass stoves, child mortality attributable to household air pollution is reduced by around 50 % by 2030. Furthermore, phasing out biomass use in combination with improved and advanced cookstoves reduces attributable child mortality by 95–99 %. Fuelwood demand could be reduced by 70 % compared to the baseline by 2030, and GHG emissions would drop by between 42 and 64 %.

There is a wealth of studies on the health impacts of cooking energy in SSA, especially where it relates to solid biomass fuels. According to a review by Sola et al. [50], most studies related to illness (acute respiratory infection, chronic bronchitis, etc.), but other impacts included low birth weight and low foetal growth. Some studies show how the health impacts are related to factors such as household ventilation, education levels, or women's empowerment.

Many recent scenario studies indeed analyse the synergies and tradeoffs between the achievement of clean cooking access targets and various Sustainable Development Goals (SDGs), including SDG 1 on poverty reduction, SDG 3 on good health and well-being, SDG 5 on gender equality and SDG 13 on climate action. As an example of a synergy, increased access to modern energy, including cooking, has been shown to increase women's autonomy through time savings [51] and to negatively affect women's fertility [52]. On the other hand, Cameron et al. [53] find a trade-off between achieving clean cooking access targets and climate targets in South Asia: imposing climate goal constraints on the clean cooking sector increases the costs of policies to achieve full access to clean cooking by up to 44 %.

The balance of cost and co-benefits in the transition was evaluated by the World Bank, which concluded that the cost of achieving universal access to clean cooking (approximately USD 1.5 trillion over 10 years, or USD 148–USD 156 billion a year) is smaller than the costs of inaction. If universal access is not achieved, negative externalities would cost USD 2.4 trillion a year (including health -USD 1.4 trillion-, gender -USD 0.8 trillion-, and climate - USD 0.2 trillion) [46].

A small number of recent studies analyse the dynamics of the transition and its impacts in Nigeria specifically. Dioha and Kumar [16] use a bottom-up, cost-optimisation model to represent Nigeria's transition to full access to clean cooking and assume a full transition to LPG by 2030. They find this leads to a reduction of indoor air pollutants but significantly increased GHG emissions. This, however, does not take into account the GHG emissions arising from unsustainable wood removal. They also indicate that electricity and biogas are the most economically viable options once external costs are modelled.

Shari et al. [17] use a systems dynamics modelling framework to simulate how different strategies can affect the adoption of clean cooking systems in Nigeria over time. Their model indicates that adoption of clean cooking solutions would occur faster in urban and smaller households than in rural and larger households. It also sheds light on the role of LPG prices and policies on adoption. Furthermore, a study of the impacts of the LPG Expansion plan [13] finds that delivering on the plan's goals would lead to a 25 % reduction in GHG emissions by 2030, compared to the NDC target.

Finally, a study into the employment impacts of Nigeria's NDC targets for clean cooking finds that they have a strong impact on emission reductions but a small negative effect on employment [54]. This is driven by job losses in the informal firewood and charcoal industry, estimated to provide 530,000 full-time equivalent direct jobs. This finding contrasts with the ETP's net zero scenario, where clean cookstove distribution is foreseen to be a major driver of job creation [6]. It is worth noting that women are highly represented in the informal and retail aspects of biomass value chains [55,56] and may, therefore, be disproportionately disadvantaged by a shift to LPG, for which retailers are usually male.

Clean cooking energy transitions have been studied under different frameworks and scales: local, national and global. Scenario studies contribute to the understanding of Nigeria's clean cooking transition by pointing out key drivers (e.g., demographic, economic), trends (e.g., LPG in urban segments), and impacts (e.g., health, gender, deforestation, climate). The approaches and findings vary across SSA countries (e.g., Stoner for SSA and Ghana [57], Yusuf for Liberia [58] and Kypridemos for Cameroon [59]), showing the importance of national and sub-national assessments that capture the peculiarities of each local context.

In sum, a review of existing knowledge points to the variety of approaches available for assessing clean cooking transitions and reveals a gap in the understanding of how Nigeria can meet its long-term goals for the cooking sector. Among other things, Nigeria lacks an integrated and detailed assessment of the potential health and climate impacts that can inform policy and help move the sector higher in the political agenda.

Based on the trends and literature reviewed in this section, the next section describes the approach to developing the scenarios, accompanying assumptions and impact calculations.

3. Methods

3.1. Scenario analysis

This study draws from socio-technical transition studies and other theoretical frameworks that delve into the management and governance of complex transitions toward sustainability [60,61]. Nigeria's cooking energy sector is a socio-technical system that consists of different elements: infrastructure, knowledge, markets, regulation, etc. Scenarios are a tool used within transition studies to improve the understanding of the complex interactions within socio-technical systems and the dynamics of the transition from one system state to a future one. The long-term, system-level foresight provided by scenarios can anticipate key features of transitions, as well as key risks and uncertainties. A scenario is a coherent and plausible description of a possible future state of a socio-technical system. It incorporates internally consistent assumptions about the drivers, relationships, and constraints in the system [62]. Scenario analysis in climate change mitigation research in general, and in this study in particular, helps to evaluate the implications of different approaches to mitigation as well as critical areas of uncertainty [63].

The scenarios analysed in this study are designed to test the feasibility and impacts of Nigeria's clean cooking policy targets. The scenario analysis also quantifies the health and climate impacts of each scenario based on a calculation of both air pollutants and GHG emissions. The focus of this study lies in target-oriented scenarios ("if we reach this target, this happens"). We provide transparency into what the impacts of meeting the current national goals would be and what the cost of inaction would be.

For this purpose, we analyse three possible transition scenarios with varying ambition levels. The most ambitious level is guided by current Nigerian targets within the ETP. This allows us to assess the feasibility of this scenario and compare the effects, synergies, and trade-offs against alternative pathways that the sector could follow.

The analysis was performed using a spreadsheet-based tool, which allows building state-level and national-level scenarios and captures the calculation variables. A schematic view of the key variables considered when building the scenarios and the interactions between them is shown in Fig. 1. This tool allows quantitative simulation of how the sector may plausibly evolve under certain assumptions. It is important to acknowledge that this approach is a simplification of the complex interactions that take place in Nigeria's cooking energy socio-technical system. Key system drivers such as income or education level are not within the scope of the study, nor is a distinction made between urban and rural households. Furthermore, the tool does not have an optimisation functionality, nor does it include cost estimates for different technology options or scenarios. More details on the tool are available under the Methodological Supplementary Material and in Slater et al. [64], and the dataset and tool are publicly available (see Data Availability Statement).

Part of the scenario narratives and a number of scenario assumptions are based on stakeholder interviews and workshops conducted in late 2020 [65]. The stakeholder engagement process brought together key actors in the LPG, improved biomass cookstove and other cooking energy value chains over three virtual discussions and eight 1-to-1 interviews during 2021. The stakeholders included representatives of the Federal Government (LPG Expansion Plan, Ministry of Environment), four private clean cooking firms, a civil society organisation, an international cooperation body active in the field of clean cooking, and two researchers.

The following sections delve into key assumptions of the scenarios and the rationale behind them.

3.2. Base year assumptions

There exist several sources of data on household cooking fuel and cookstove use in Nigeria [3,26,27,66]. The present study uses the Living Standards Survey [3] as the core source of base year data. This 2018/2019 survey provides one of the most comprehensive and diverse sets of socio-economic and demographic data for Nigeria. It included questions on the household's primary cookstove used, time spent collecting woodfuel, and cookstove location, and was disaggregated according to state and rural/urban segments. The key reason why it is selected for this study is that it provides state-level data, a feature that is not available in other surveys. The survey was the source of the study's base year assumptions regarding the type of primary cookstove used in the household (in terms of % of the total number of households). A shortcoming of this choice is that the use of multiple cookstoves within one single household is not captured.

State-disaggregated data reveals key differences in cookstove use across regions: for example, in a number of states, almost 100 % of households cook using traditional biomass, and all states apart from Lagos have at least 25 % of households cooking with biomass stoves. As of 2018, only eight states had over 20 % of households using LPG. A key outlier is Lagos state, where over 57 % of households were using LPG in 2018.

It is important to note that there is no national-level survey regarding the use of improved wood and charcoal stoves in Nigeria, so their share is assumed to be zero in 2018.

3.3. The scenarios

The three scenarios are modelled over two different time horizons: mid-term (2018–2030) and long-term (2030–2060). For the mid-term horizon, scenarios are modelled both at the national and state level. For the long-term horizon, scenarios are modelled only at the national

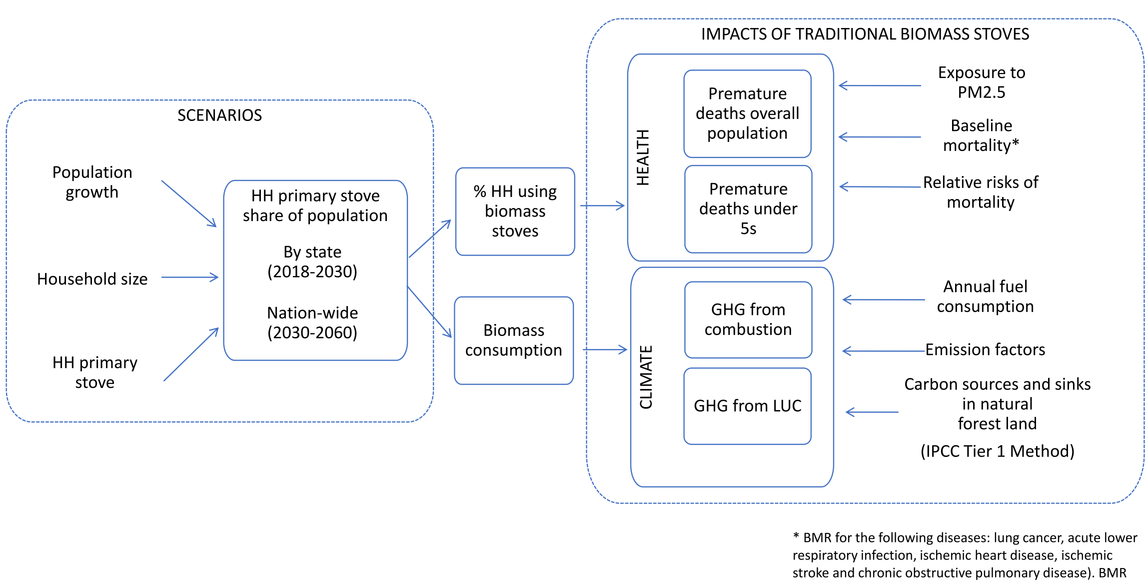


Fig. 1. Schematic of method showing transition scenarios (left) and their key assumptions (population growth, household size and primary stove), the two key inputs to the impact calculations (share of households using biomass and biomass fuel consumption, centre), and the calculation of health and climate impacts (right) with key input assumptions (exposure, baseline mortality, relative risk, emissions factors and carbon stocks calculation based on IPCC Tier 1 Method).

level. This two-step approach allows a greater level of depth in the analysis of near-term impacts at the state level (e.g., impacts of the LPG Expansion Plan) versus longer-term visions at the national scale (e.g., the ETP) that are inherently more uncertain. This approach also better captures the government's current vision of the ETP, where there is a shift from traditional biomass to LPG and electricity in the mid-term and a full phase-out of traditional biomass and LPG in the long-term (replaced by mix of efficient firewood stoves, electric stoves, and biogas). It is important to remember that the scenarios do not make a distinction between the transitions taking place in different populations (urban, rural, peri-urban) or income segments.

Underlying the three scenarios are the following narratives (see Table 2 for a summary):

- **Baseline**: a pessimistic scenario that assumes no specific policies to increase access to clean cooking technologies and continues the historical trend in terms of demographic growth and share of primary cooking technology in households. Other scenarios can be interpreted relative to baseline developments.
- **Moderate**: a scenario that sees significant improvements but does not put the sector on the path toward universal access to clean cooking:
  - o **In the mid-term** (by 2030): each state sees between 10 and 15 % of households using traditional biomass shift to either LPG, ICS or electricity. Moreover, the number of households using kerosene is halved. The majority of the traditional biomass stoves that are displaced are replaced by LPG, particularly in the 12 pilot states of the LPG Expansion Programme. The number of households using electricity doubles.
  - o **In the long-term** (between 2030 and 2060): LPG continues to increase into the 2050s, becoming the primary technology of 50 % of households in 2050. The transition away from traditional biomass stoves continues but 40 % of households still use them in 2040. This shift accelerates in the 2040s, and by 2050, traditional stoves are only used by a quarter of households. The share of other technologies (ICS, electricity, biogas) increases steadily, each reaching around a tenth of households by 2060. Kerosene is completely phased out by 2060.
- **Ambition**: a best-case scenario that sees a large shift from traditional biomass to clean cooking technologies, leading to a substantial transformation of the sector. This scenario relies on significant investments, improvement in finance, policy, and enabling environment measures. The scenario is guided by the ETP's ultimate goals as described in Table 3, particularly regarding its long-term goals and main inflection points. Two different steps are distinguished in the Ambition scenario:
  - o **In the mid-term** (by 2030): each state sees between 30 and 45 % of households using traditional biomass shift to either LPG, ICS, or electricity. This is a strong assumption, which is nevertheless lower than that of the ETP (75 % displacement of traditional biomass by 2030). LPG fully displaces kerosene use, and the number of households using electricity quadruples. LPG replaces the majority of traditional biomass stoves, particularly in the 12 pilot states of the LPG Expansion Programme. Moreover, it is important to remember that the ETP makes no state-level assumptions.
  - o **In the long-term** (2030–2060): The transition away from traditional biomass continues, and they are fully displaced by 2060. This is in line with the ETP's goals. LPG continues to expand between 2030 and 2050, but given demographic growth, its share remains stable. There is a strong shift to biogas and electricity, which starts in the 2030s and continues up to 2060, at which point both technologies completely displace LPG and become the sole technologies in the market (as per ETP goals), each with a 50 % share.

All scenarios integrate the same population growth and household size assumptions (both at the state and national level). These assumptions are derived from the Living Standards Survey [3] and the United Nations projections [8].

The resulting mix of cooking technologies for each scenario is depicted in Figs. 2 and 3. The detailed figures can be found in the Supplementary Information Table S1.

3.4. Calculation of impacts

The scenario analysis quantifies the health and climate impacts of each scenario based on a calculation of both air pollutants and GHG emissions. The chosen variables and their interactions are depicted in Fig. 1 above. The calculation of emissions centres on estimates of biomass consumption for each scenario. To calculate this, we used estimates on the amount of fuel consumed for cooking by each individual household annually and multiplied this by the total number of households cooking with each fuel in each scenario. The annual consumption estimates are outlined in Table 4. Total fuel consumption by households was then multiplied by fuel-specific emission factors detailed in Table 5.

3.4.1. Health impacts

The health impacts of each scenario are expressed in terms of change in mortality, which can be understood as the difference in deaths that would occur with exposure to emissions from cooking with traditional biomass compared to cooking with clean technologies. Change in mortality is calculated based on the method by Burnett et al. [71], which estimates mortality as a function of risk of mortality from five disease categories (lung cancer, acute lower respiratory infection, ischemic heart disease, ischemic stroke, and chronic obstructive pulmonary disease) in each population group (males and females, disaggregated for five age groups). The number of premature deaths due to cooking with

Table 2
Summary of narratives and assumptions on displacements from traditional biomass and kerosene to clean cooking technologies for each scenario.

Scenario	Traditional biomass	Kerosene	LPG	Improved biomass	Electricity	Biogas
Baseline 2018–2060	2018 shares remain constant					
Moderate 2018–2030	10–15 % of HHs shift away from traditional biomass	50 % of HHs shift to LPG	Displaces 9 out of 10 traditional biomass and all kerosene	Displaces 1 out of 10 traditional biomass	Displaces 1 out of 10 traditional biomass and all kerosene	No penetration
Moderate 2030–2060	40 % of HH still use them in 2040, down to 25 % by 2060	100 % displaced by LPG	Increase up to 50 % of HHs	Increase up to 10 % of HHs	Increase up to 10 % of HHs	Increase up to 10 % of HHs
Ambition 2018–2030	30–45 % of HHs shift away from traditional biomass	100 % displaced by LPG	Displaces 9 out of 10 traditional biomass and 100 % of the kerosene	Displaces 1 out of 10 traditional biomass	Displaces 1 out of 10 traditional biomass	No penetration
Ambition 2030–2060	Fully displaced by 2050	n/a	Fully displaced by electricity and biogas	Slight increase up to 2050 but then phased out	Gradual increase up to 2050, reaching 50 % of HHs	Gradual increase up to 2050, reaching 50 % of HHs

Table 3
Comparison between ETP goals and Ambition scenario, in terms of narrative and key quantitative assumptions.

	2030	2050	2060
Energy Transition Plan	**75 %** of traditional biomass stoves replaced, chiefly by LPG The number of electric stoves increases strongly, especially in urban dwellings	**65 %** of households have electric (urban households) and biogas stoves (rural households) LPG has been fully phased out	**100 %** of the population has access to clean cooking Traditional biomass has been fully displaced by electricity (50 %) and biogas (50 %)
Ambition Scenario	Between **30** and **45 %** of traditional stoves replaced, chiefly by LPG. The rate of replacement is higher in the 12 pilot states of the LPG Expansion programme. LPG has fully displaced kerosene use The number of households using electricity has quadrupled.	**65 %** of households have electric and biogas stoves **28.5 %** of households still have LPG	**100 %** of the population has access to clean cooking Traditional biomass and LPG have been fully displaced by electricity (50 %) and biogas (50 %)

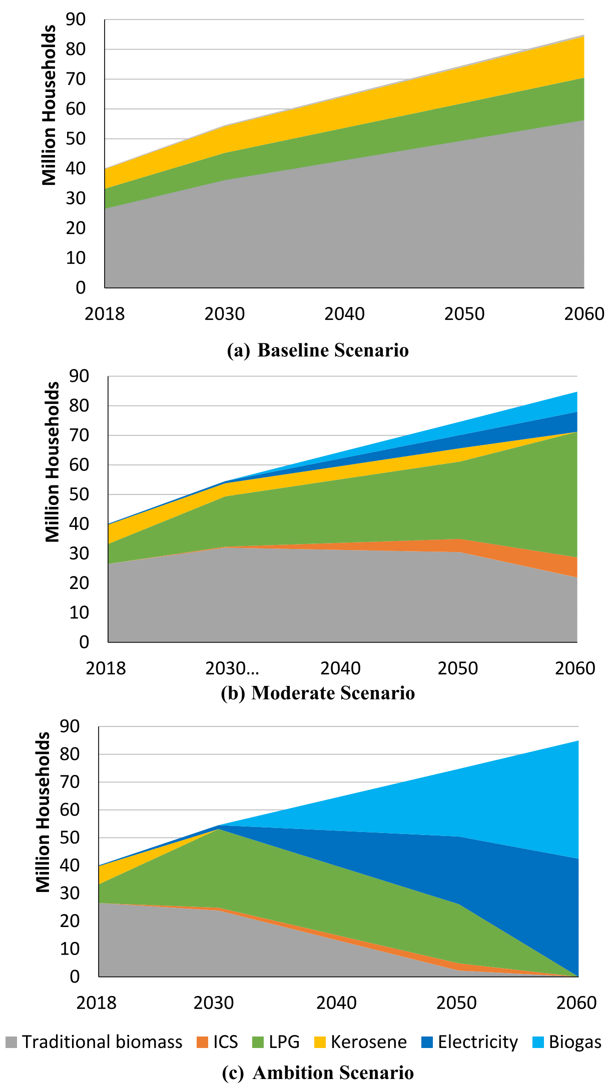


Fig. 2. Primary household cookstove in each scenario: (a) Baseline, (b) Moderate, (c) Ambition.

biomass for each population group and disease category is calculated using Equation (1).

$$\Delta Mort = y_o \left(\frac{RR_{IER} - 1}{RR_{IER}}\right) Pop \quad (1)$$

Where y0 is the baseline mortality rate for a specific population group and disease category, which was taken from the Global Burden of Disease study [3]. RR is the relative risk of mortality from cooking, based on analysis by Shupler et al. [72] and Burnett et al. [71], and Pop is the number of people exposed (in this case, people cooking with a certain type of fuel).

A focus of the health impacts calculation is put on children under 5 due to the high vulnerability of this age group to household air pollution in Nigeria. For this calculation, specific parameters were used, including the baseline mortality (BMR) due to acute lower respiratory Infections (ALRI) for each state in 2018, as described in the Methodological Supplementary Material.

It is important to note that the analysis is centred around the additional risk occurring from cooking with biomass stoves. It was therefore assumed that cooking with LPG, kerosene, electric, or biogas stoves involved zero risk.

3.4.2. GHG emissions

The assessment of climate impacts is made through two complementing approaches: on the one hand, the emissions from combustion of different cooking fuels were calculated for each scenario for two key GHGs (CO_2 and CH_4), using the emission factors and average annual fuel consumption assumptions detailed in Tables 4 and 5 Following IPCC guidelines [73], CO_2 emissions from biomass combustion are not included in this calculation, as these emissions are assumed to be biogenic and they are treated as emissions from land use change (see below). Therefore, only the CO_2 emissions of LPG and kerosene combustion are taken into account in this part of the calculation. This calculation provides a detailed insight into the impacts that displacement of fuelwood by other fuels (e.g., LPG) would have on the emissions from the sector.

On the other hand, we quantified the relative change in CO_2 emissions from land use change that could be brought about by the Moderate and Ambition scenario, relative to the Baseline scenario. The approach is based on the method and assumptions detailed in the Methodological Supplementary Material and in Slater et al. [51], which quantifies net CO_2 emissions from the forestry and other land use sector (FOLU) across Nigeria for a 30-year historical period (1990–2020). This historical analysis uses the IPCC's Tier 1 method [60] to quantify losses and sinks of CO_2 from different land use types, based on data from FAO Global Forest Resources Assessment Nigeria [74]. Slater et al. [51] find that while total carbon sinks in the FOLU sector have remained quite constant in Nigeria in recent decades, carbon losses have increased rapidly. It also indicates that the largest proportion of Nigeria's emissions from the FOLU sector comes from fuelwood consumption.

The present study uses the approach described in Supplementary Material and the historical estimates of Slater et al. [51] to forecast CO_2 emissions from land use change in the future. The focus is put on CO_2 sources and sinks from a specific land type: natural forests. The IPCC Tier 1 methods are then used to estimate the annual change in biomass stocks in Nigeria's natural forests by 2030, 2050, and 2060, from which the following can be derived: i) CO_2 sequestered due to biomass growth, ii) net CO_2 emissions due to wood removals and fuel wood use, and iii) net CO_2 emissions due to disturbances (e.g., forest fires). The estimates on how much wood fuel would be consumed in the Moderate and

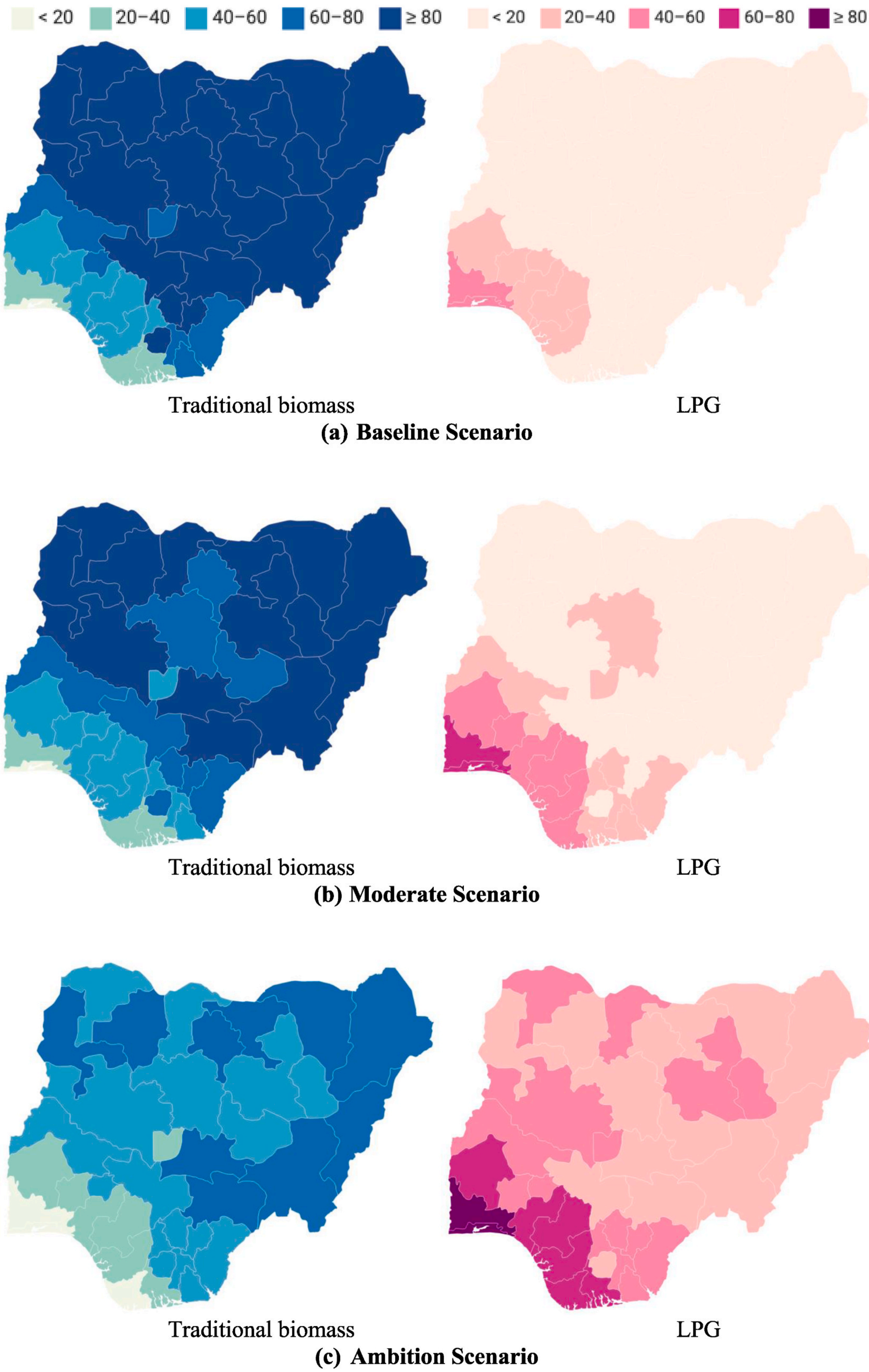


Fig. 3. Share (%) of households cooking with traditional biomass (left) or LPG (right) by 2030, disaggregated by state: (a) Baseline, (b) Moderate, (c) Ambition. Note: Borno state base year figures are not available in the Living Standards Survey [3] and were therefore estimated by averaging the shares in states in the same geo-political zone (North East). All maps created with Datawrapper.

Table 4
Average annual fuel consumption assumptions. Sources: [67,68].

Fuel	Annual fuel consumption (kg/household/year)
Wood	4800
LPG	250.4
Kerosene	257.6
Wood - ICS	1,200

Table 5
Emission factors used to quantify total emissions from cooking with different fuels. Sources: [69,70].

Emission factors (kg/tonne)	Wood	LPG	Kerosene
CO_2	1,548	2,984	3,149
CH_4	4.86	0.236	0.438
N_2O	0.0552	0.15	0.02634
CO	77	14.9	7.39
NMVOC	26.8	18.8	5
NOx	2.18	2.35	1.1
NH_3	0.87	0.0004615	0.0002195
PM10	8.3	0.32	0.134
PM2.5	6.64	0.31	0.129
BC	0.83	0.01	0.017
OC	2.89	0.06	0.013

Ambition scenario are used to calculate the difference in emissions from land use change relative to the Baseline scenario.

4. Results

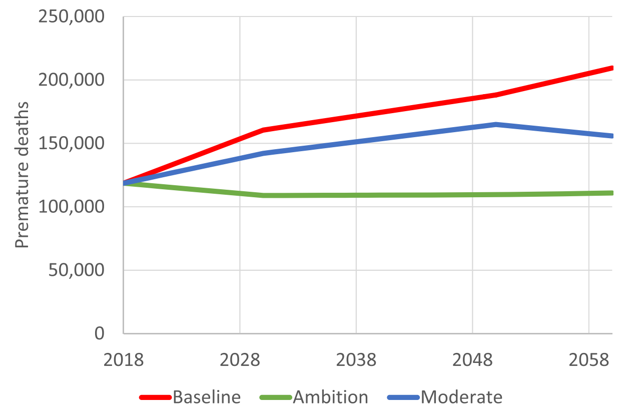
This section lays out the quantitative results for the calculation of health and climate impacts of the cooking energy transitions described above. The three scenarios are modelled over two different time horizons: mid-term (2018–2030) and long-term (2030–2060). For the mid-term horizon, scenarios are modelled both at the national and at state level.

4.1. Health impacts

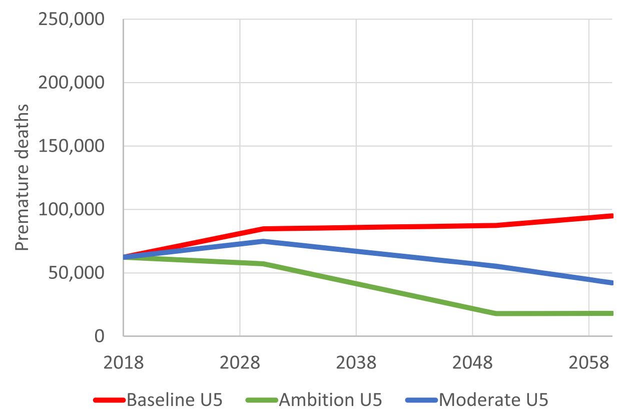
In terms of health impacts, our results indicate that 118,585 premature deaths were caused by indoor air pollution in 2018 (Fig. 4a). The Ambition scenario sees a slight (7 %) decrease in annual premature deaths due to exposure to household air pollution by 2060, compared to 2018 levels. This is despite the population doubling from 2018 levels. The Baseline scenario, on the other hand, sees a dramatic 77 % increase in deaths. This would mean that 209,405 premature deaths would occur annually due to the use of biomass for cooking. The Moderate scenario sees a 31 % increase, to 155,816. The Moderate scenario sees annual premature deaths peak in 2050 and start to decrease slightly. This is due to the embedded assumption that the phase-out of traditional biomass stoves accelerates in the 2040s. In contrast, most gains in health in the Ambition scenario are made very early in the transition, when the bulk of the shift away from traditional biomass takes place before 2040.

With regards to child health (Fig. 4b), the impact of the Ambition scenario is more pronounced than in the overall population: a 71 % decrease in premature deaths of children under 5 is observed. In other words, this scenario would lead to 44,280 premature deaths of under-5s being avoided annually in 2030. The Moderate scenario also sees a decrease in premature deaths, albeit lower (32 %, equivalent to 20,200 deaths being avoided). Finally, the Baseline scenario sees a 52 % increase in premature deaths of under-5s, equivalent to 94,930 annual premature deaths of children under 5 in 2060, or 32,500 more deaths per year than in 2018.

At the state level (Fig. 5), the Ambition scenario has marked impacts in certain states. The results show that the majority of states had less than 4,000 premature deaths in 2018. However, five states had more than 6,000 deaths. Under the Baseline scenario, the number of states with more than 6,000 annual premature deaths by 2030 would increase to eight. Of these, five states would have more than 8,000 deaths annually. In the Ambition scenario, only one state would have more than 6,000 deaths, whereas 27 states would have less than 2,000 deaths per year.



(a) Premature deaths in general population



(b) Premature deaths of children under 5

Fig. 4. Health impacts over time for scenarios: (a) General population, (b) Children under 5.

For children under 5 (Fig. 6), there are 12 states with more than 2,000 premature deaths per year in 2018, with only one state surpassing the level of 6,000 premature deaths. Under the Baseline scenario, a total of 13 states would have more than 2,000 premature deaths in 2030, and among these four would have over 6,000 deaths per year. In the Ambition scenario, 10 states would still see more than 2,000 deaths per year in 2030, but of these, only one state would have more than 6,000 deaths per year.

Fig. 7 shows the trends that are observed in the six geopolitical zones. The biggest impacts of the transition towards clean cooking are found in the North East and North West geopolitical zones. This is not surprising given that they are also the areas with the highest number of premature deaths currently due to high baseline mortality rates and high biomass use. However, it is interesting to note that all geopolitical zones see a similar overall impact: all zones see a percentage decrease in annual premature deaths that ranges between 40 % and 53 %.

4.2. GHG emissions

It is important to remember that the assessment of climate impacts of the scenarios is made through two complementing approaches: on the one hand, the emissions of two key GHGs (CO_2 and CH_4) are calculated for each scenario using the emission factors and average annual fuel

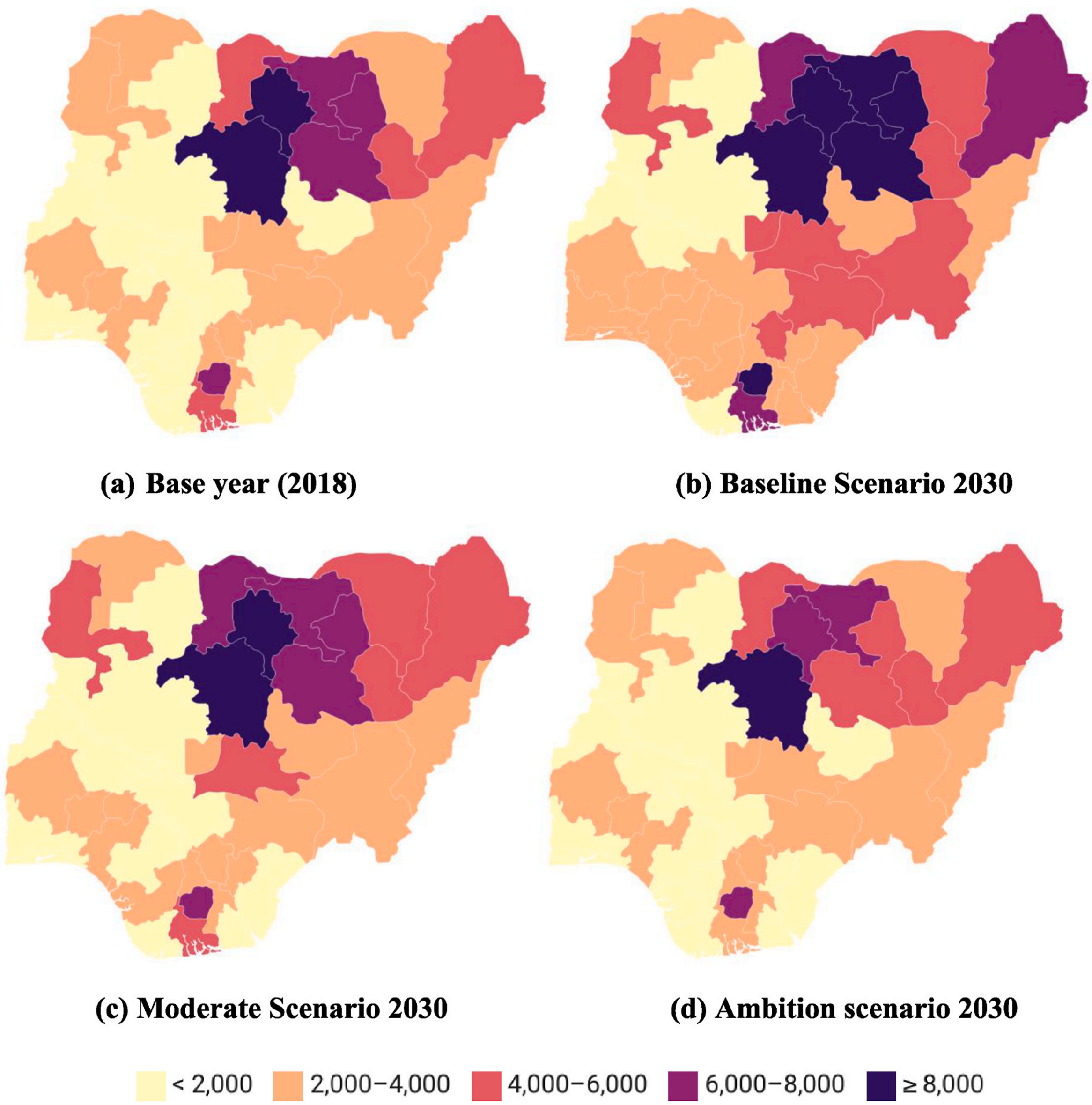


Fig. 5. Total yearly premature deaths in the general population due to household air pollution for each individual state in 2018 and 2030. All maps created with Datawrapper.

consumption assumptions detailed in Tables 4 and 5 On the other hand, we quantified the relative change in CO_2 emissions from land use change that would result from the Moderate and Ambition scenarios relative to the Baseline scenario.

4.2.1. Emissions from combustion

The evolution of CO_2 emissions from combustion of LPG and kerosene is shown in Fig. 8a, whilst Fig. 8b shows how CH_4 emissions would evolve for all cooking fuels (including biomass). The results shed light into the role of LPG and other fuels in displacing GHG emissions from fuel wood combustion. It indicates that from a starting value of 10.2 Mt in 2018, CO_2 emissions would increase in all scenarios, particularly in the Moderate scenario. This is related to the increased share of LPG in the mix. Indeed, the Moderate scenario continues to dominate in terms of CO_2 emissions up to 2060, whereas the Ambition scenario drops sharply to zero after 2050, when LPG is phased out. The baseline scenario shows a steady increase due to the continued use of kerosene as a cooking fuel, and to the relatively stable share of LPG in the mix.

Methane emissions were estimated to be 635 kt in 2018 (Fig. 8b). The Ambition and Moderate scenarios show a similar decrease in methane emissions up to 2030. This is caused by the continued drop in biomass combustion in both scenarios. The Ambition scenario sees a further decrease in methane emissions after 2030 and, ultimately, a drop to zero between 2050 and 2060. This has to do with the phase out of LPG during that final decade and its replacement with emission-free electricity and biogas. The increase in methane emissions in the Moderate scenario after 2030 is caused by the continued use of traditional biomass and kerosene, as well as the increasing share of LPG in the mix.

4.2.2. Emissions from land use change

The second approach to estimating the impact of the scenarios relies on quantifying the amount of woodfuel consumption and, therefore, the wood removals from forested land. We find that total woodfuel consumption in 2018 was 129.9 Mt (Fig. 9). In the Baseline scenario, woodfuel consumption increases by 34 % by 2030 and roughly doubles by 2060, reaching 269 Mt. In the Ambition scenario, it decreases by 11 % by 2030 to 115 Mt and is completely phased out by 2060. The Moderate scenario shows a very stable pattern where it increases by 19 % by 2030 to 153 Mt but then remains largely stable up to 2060 despite population growth.

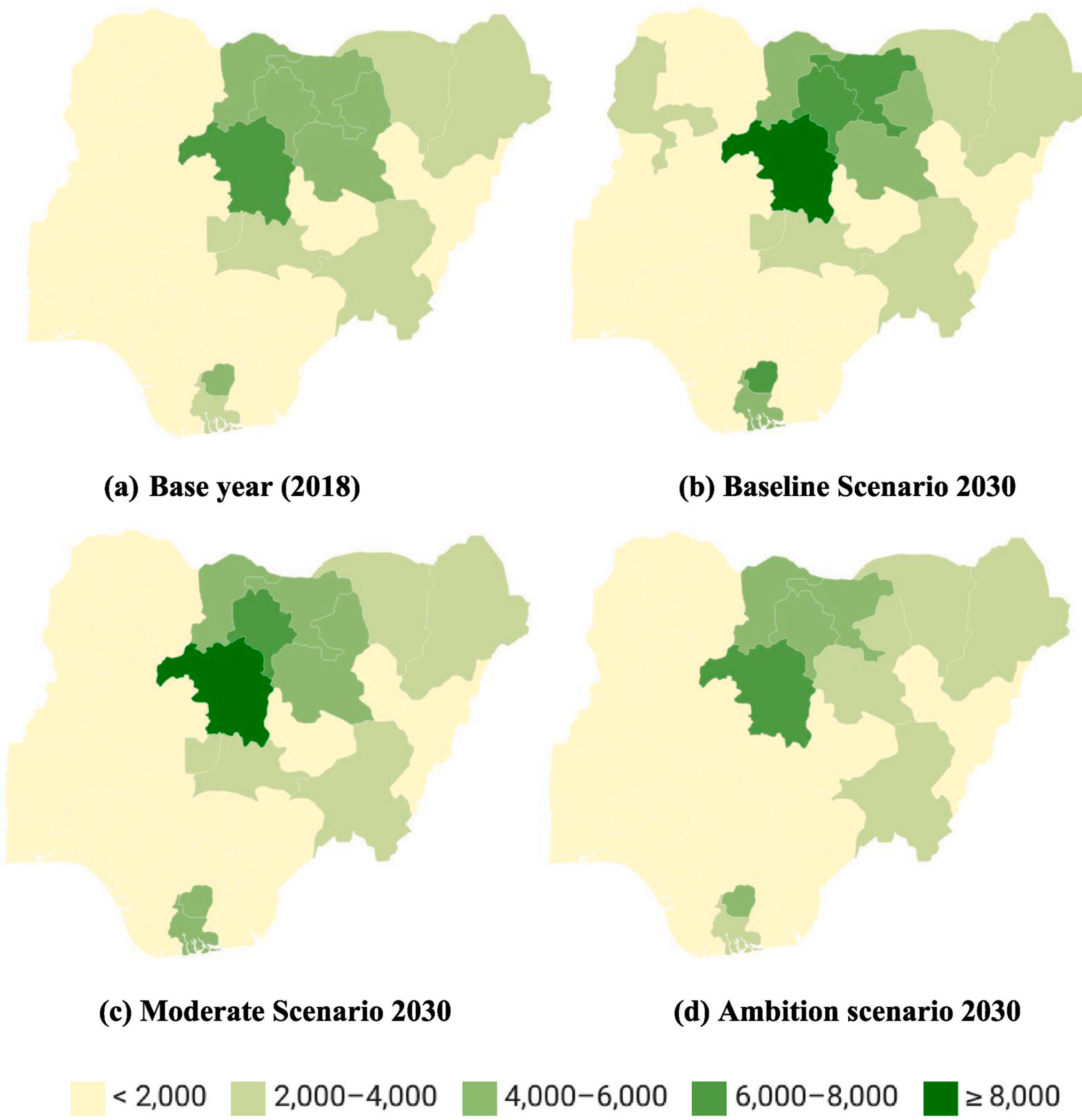


Fig. 6. Total yearly premature deaths of children under 5 due to household air pollution for each individual state in 2018 and 2030. All maps created with Datawrapper.

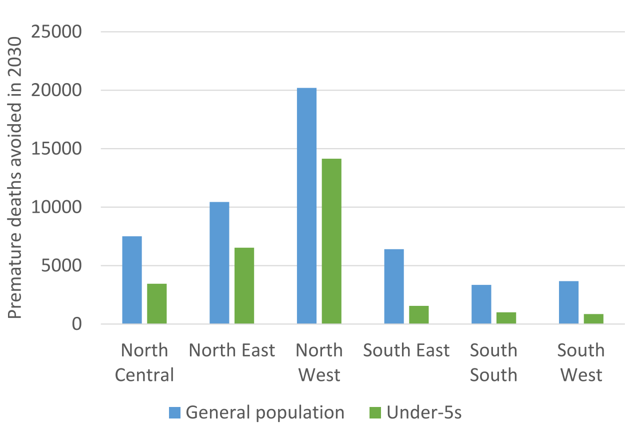
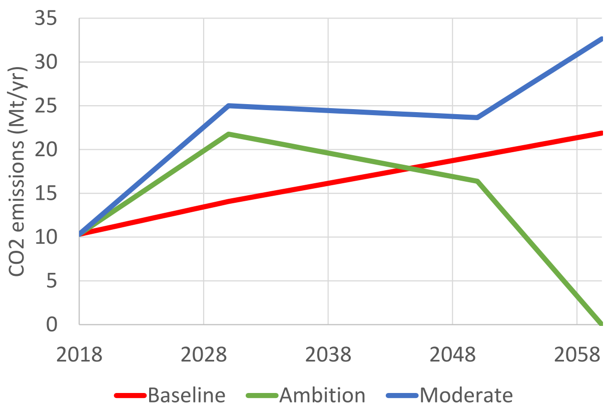


Fig. 7. Premature deaths avoided annually by 2030 in Ambition scenario vs. Baseline, by geopolitical zone.

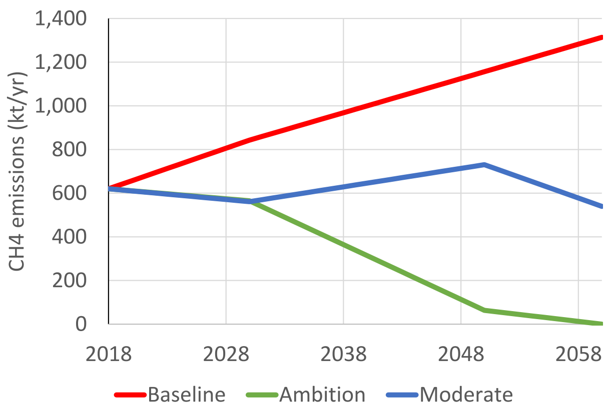
The state-level analysis shows a rather even spread of woodfuel consumption in 2018 across geopolitical zones (Fig. 10a). In the mid-term 2030 timeframe, the majority of states are able to bring yearly woodfuel consumption below the 4 Mt mark. However, six states remain above this mark and one state (Kano) would consume over 8 Mt (Fig. 10b to c).

Based on these estimates, we quantified the relative change in CO_2 emissions from land use change that could be brought about by the Moderate and Ambition scenario relative to the Baseline scenario (Fig. 11). The calculation includes historical data as calculated by Slater et al. [51]. It indicates that the Baseline scenario would lead to a tripling in the net CO_2 emissions from forestland relative to the start year, reaching 602 Mt CO_2 by 2060. The Moderate scenario would lead to a reduction of 44 % in emissions by 2060 compared to the Baseline scenario, and the Ambition scenario would result in close to zero (and occasionally negative) annual emissions from forestland, i.e., this land type could potentially become a carbon sink.

Fig. 12 delves deeper into the dynamics of the change in carbon stock from forestland due to biomass growth vs. removal for 2030, 2050, and



(a) CO_2



(b) CH_4

Fig. 8. Direct GHG emissions from combustion of cooking fuels: (a) CO2 (b) CH4.

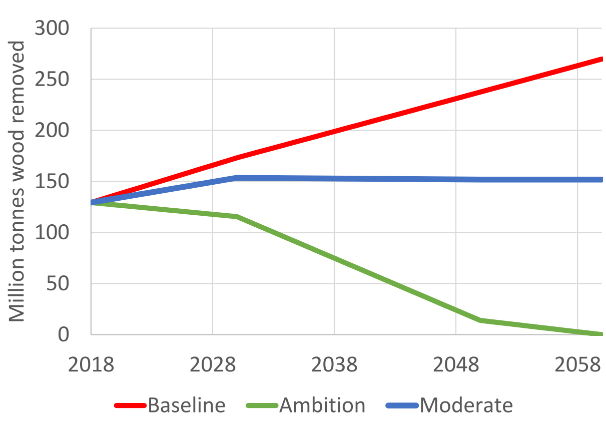


Fig. 9. Fuelwood removed annually for cooking in each scenario (million tonnes).

2060, under each scenario. This sheds light on the key role that woodfuel removal has in the balance, representing between 87 and 90 % of the carbon stock losses in the Baseline scenario, and contributing to over 165 Mt of C lost per year (Fig. 12a). In contrast, the reduced rate of woodfuel removals in the Ambition scenario (Fig. 12c) means that the contribution of woodfuel to biomass removals drops from 75.8 Mt of C in 2018 to 8.5 Mt in 2050 and zero in 2060. In other words, the cooking sector no longer contributes to losses of carbon stock from forestland in 2060.

5. Discussion

The scenarios analysed in this study test the feasibility of Nigeria's current clean cooking policy targets and shed light on the implications of different alternative futures. Moreover, they help to highlight critical areas of uncertainty.

The scenarios assume technology adoption follows a relatively linear trajectory, whereas it is known from cooking energy transitions literature that they can present a non-linear behaviour and that households may fluctuate between fuels as a response to variations in prices and reliability of supply [11,17,43]. This is particularly important in the case of LPG, which plays a crucial role in the mid-term transition, but also in longer-term technologies such as electricity and biogas. Both the ETP and in the Ambition scenario of the current study assume very high rates of penetration and a relatively homogeneous pathway across different demographic segments and geographic areas. While the complexities of clean cooking energy transitions may not be fully captured by the scenarios' high-level assumptions, they provide a picture of how fast the transition would need to be to meet the goals.

Our findings provide a snapshot of the current impacts that the sector has on health and climate mitigation. We find that 118,585 premature deaths were caused by indoor air pollution in 2018, and 62,380 of these were children under 5. The Global Burden of Disease study estimated that more than 128,000 people died in Nigeria in 2019 from household air pollution from the use of solid fuels and that 84,000 of these were children under 5 [4]. This discrepancy may be due to different assumptions on cooking fuel use and a higher level of granularity in the data in our study.

The results also indicate that the impacts of different courses of action have very significant consequences in terms of health and climate change mitigation. In a scenario where households do not transition away from traditional biomass for cooking, and population growth continues as projected, Nigeria would see a dramatic 77 % increase in annual premature deaths in 2060, compared to 2018 levels. This would mean that 209,405 premature deaths would occur annually due to the use of biomass for cooking. A scenario that is aligned with current national goals would result in a slight decrease in annual premature deaths compared to current (2018) levels for the general population, and a strong decrease in the case of children under 5. The latter finding aligns with recent scenario modelling for SSA [2,49] although the degree of impact varies due to the different factors considered in the analysis. No comparable scenario analysis is found in the literature that refers specifically to Nigeria.

The impacts by 2030 would be very marked in certain states, particularly in the North West and North East geopolitical zones. Per capita income in the Northern region is below the national average and this affects the affordability of clean cooking fuels. Our findings show that there is considerable potential in exploring regional and local specificities of cooking energy transitions in Nigeria, taking into account a broader set of known drivers such as income, education, household characteristics, and spatial heterogeneity [9,10,12,42,43], and drawing from existing state-level socio-economic survey data.

There is great uncertainty over the contribution to GHG emissions from cooking energy services in Nigeria. National plans and studies of Nigeria's clean cooking transition have up to date not considered emissions from land use change. By using IPCC methodologies, we find that the impact of a transition to LPG and/or to a fully zerocarbon cooking energy mix would bring about strong emission reductions. Even in a scenario where LPG becomes the main fuel in the long term, carbon dioxide emissions from this fuel in 2060 (approximately 32.6 Mt CO_2 in the Moderate scenario) would be ten times lower than the emissions from land use change in a business-*as*-usual scenario where traditional biomass continues to dominate the mix. This is in line with one scenario study that finds that the LPG expansion plan leads to a reduction in GHG emissions against the baseline projections [25], but sits in contrast to the findings of Dioha and Kumar [6] who find that the LPG transition in

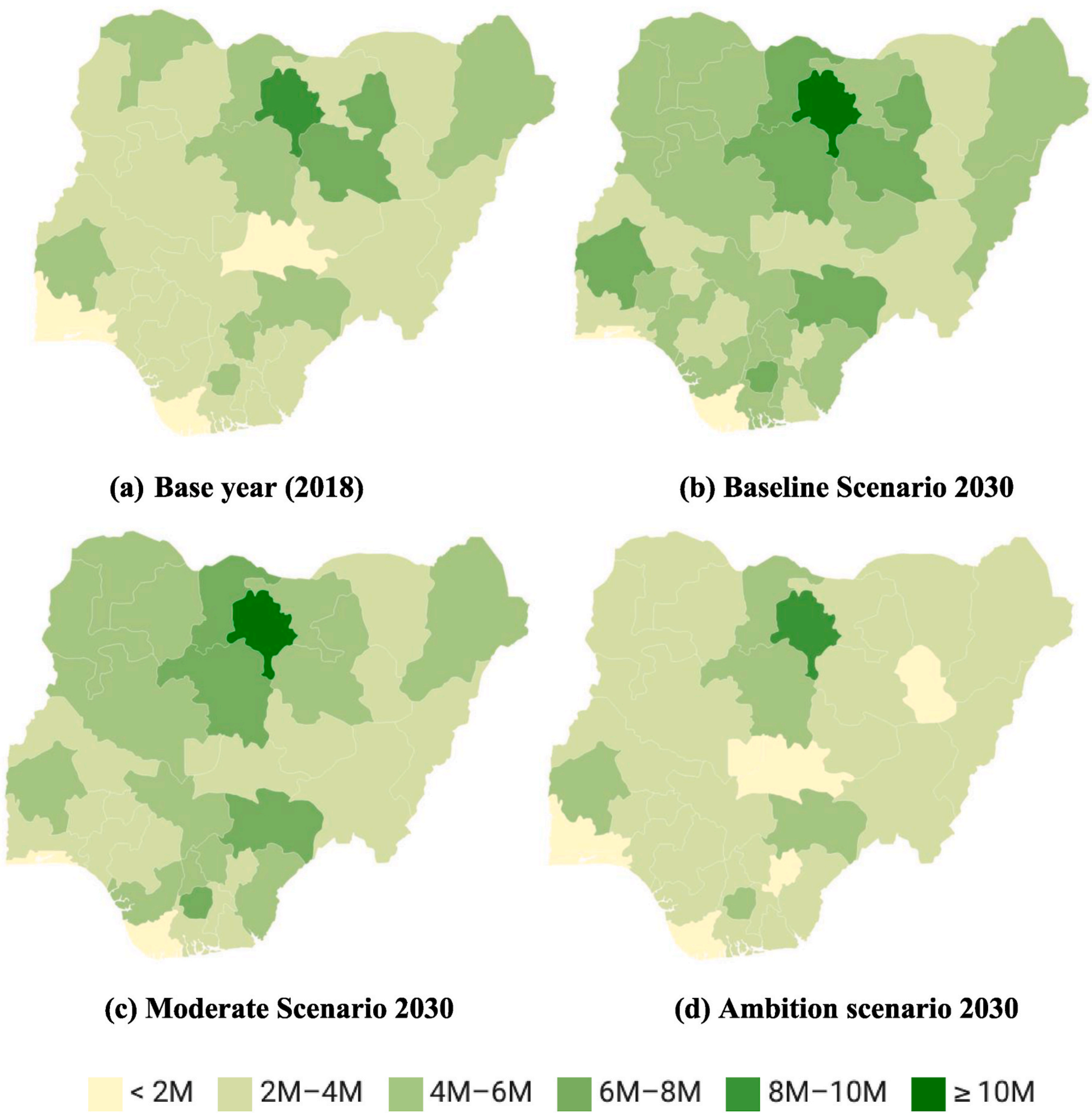


Fig. 10. Fuelwood removed annually in 2030, by state (million tonnes). All maps created with Datawrapper.

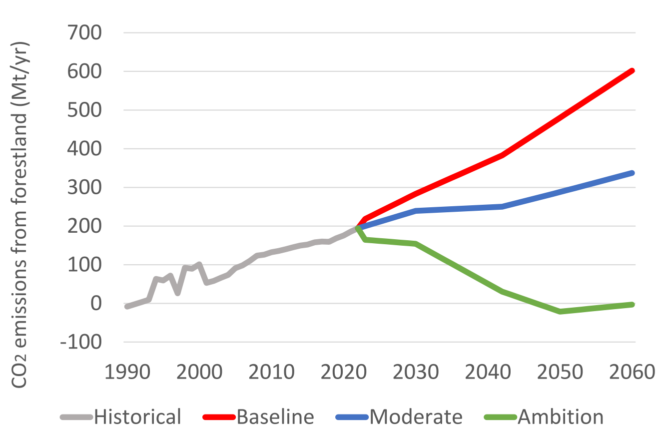


Fig. 11. Forestland biomass change in CO2 emissions due to fuelwood removals (historical and for each scenario).

Nigeria would increase GHG emissions significantly. They did not however take emissions from land use change into account.

The assumptions on short-term developments in the scenarios align with studies in the field. Estimates of future development in access to clean cooking project that around 80 % of the population of Sub-Saharan Africa will still be using polluting fuels for cooking by 2030 [56]. This is in line with our Baseline scenario, which sees no change in the 2018 shares of polluting fuels (used by 82,1 % of the Nigerian population in 2030, with 65.5 % using solid biomass, and 16.6 % using kerosene). In our study, this trend is assumed to continue unchanged up to 2060 in the absence of policies to enable the transition towards clean cooking fuels. This is a key caveat in our study. The Baseline scenario currently assumes that household fuel use shares remain the same over time. This could however change even in the absence of new clean cooking policies, for example, due to changes in household income or GDP per capita, technology innovations, or fuel changes. Moreover, the expansion of LPG use is likely to continue, even if not at the same pace as population growth.

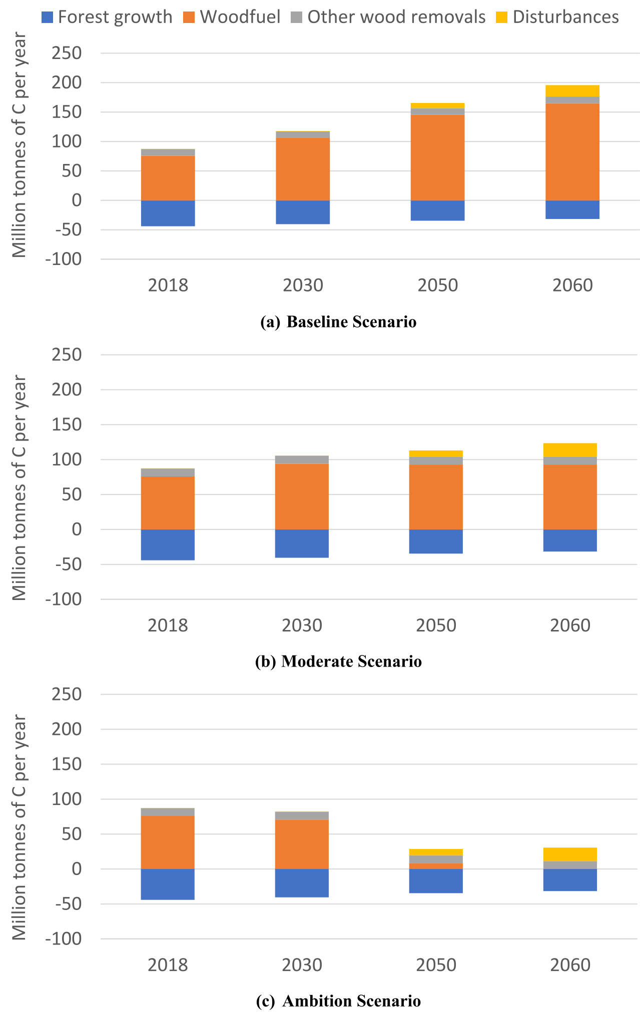


Fig. 12. Forestland carbon sources and sinks for the years 2018, 2030, 2050 and 2060, for all scenarios (million tonnes of carbon per year).

5.1. Policy implications

Our approach and findings provide a basis for some practical recommendations regarding future policy to drive Nigeria's cooking energy transition:

- Plans and scenarios need to be turned into action by way of regulatory and financial instruments that address the key drivers of the transition: affordability, availability, and access to fuels. Policies, plans, and targets for clean cooking should anticipate and mitigate the effects of macroeconomic shocks, such as those witnessed recently in Nigeria.
- It would be important to interrogate the assumptions underlying the key governmental targets, in particular the ETP. This would mean paying greater attention to the drivers of demand for various cooking fuels locally. For example, electricity, which features very prominently in the ETP's long-term vision, is still unreliable and insufficient. Similarly, biogas for cooking is not developed in the Nigerian market and it is highly uncertain that it can take the prominent role envisaged by the ETP. In the short term, the ETP also foresees a very rapid shift to LPG, including in rural areas where its share is still only 5 %.
- Household cooking energy patterns should be measured regularly, at a sub-national level and across different income and demographic segments, as a first step to better monitor the dynamics of the cooking energy transition in Nigeria.
- Given its critical health and emission impacts, detailed and transparent impact evaluations for the cooking sector should be an integral part of Nigeria's energy transition planning.
- National plans should integrate cooking energy health impacts, emissions from combustion, as well as emissions from land use change and forest degradation, in order to inform policies that can support the transition to cleaner fuels.
- While Nigeria develops a single national clean cooking policy, state-level policies are also urgently needed to drive clean cooking transitions, in order to tailor investments and policy instruments to specific contexts.

5.2. Key limitations and caveats

Key caveats in this study include the BMR assumptions, which are a key determinant of the health impact calculations. They are assumed to remain stable at 2018 levels in the future. Factors that could influence this rate are mainly macroeconomic changes. Moreover, it is important to note that the analysis is centred around the additional risk occurring from cooking with biomass stoves. It was therefore assumed that cooking with LPG, kerosene, electric, or biogas stoves involved zero risk.

A further key caveat in our study is the exclusion of certain fuels, especially charcoal, from the scenarios. This is due to it not being covered in the Living Standards Survey [3]. Moreover, our study's assumptions on displacement rates (the rate at which one fuel displaces another) are estimates based only on stakeholder perspectives and do not take into account 'backsliding' from clean to solid biomass fuels, which has been observed in Nigeria [40]. This has been particularly observed after sudden hikes in LPG or electricity prices. This indicates the price-sensitive nature of cooking fuel demand; an important factor that needs to be taken into account in designing policies aimed at increasing the uptake of clean fuels. The LPG market has indeed changed drastically since the publication of the ETP, with rising currency exchange rates and inflation as key contributors to sharp increases in LPG prices during 2023 and 2024 [75].

Moreover, this study assumes a household uses only one type of fuel or stove. This is a simplification, and in reality, the vast majority of households use more than one type of fuel or stove in parallel (also known as 'stove-stacking'). The household survey that is at the core of our assumptions indeed measured the share of primary cookstove use. Further, factors such as price, convenience, and the opportunity cost (especially for women) of using particular fuels all contribute to determining the primary cookstove for different households at various points, further complicating attempts to capture the nuances of household energy use patterns across the population at a given time.

A critical area that remains unexplored in our scenarios is the different dynamics of clean cooking transitions in urban versus rural households. This is an area for further exploration and could aid in further understanding the viability of the ETP goals. The ETP sees different pathways for urban and rural households which we did not address in this study.

Based on our findings, avenues for further research include a better understanding of the transition dynamics at the sub-national level, and across urban and rural segments (as currently rural Nigerians are the most affected by lack of access to clean cooking). Furthermore, a more detailed capture of displacement rates, backsliding, and stove stacking is warranted. The tool used in this study does not have an optimisation functionality but this is an interesting option for future research.

Other impacts including costs of the transition, health impacts of other fuels (e.g., the health impacts of LPG use), and additional benefits such as time saved could be quantified. This is crucial, as a recent study indicates that the benefits to rural populations of a clean energy transition in Nigeria can only be maximised if increases in farm productivity occur in parallel with time savings enabled by the introduction of clean cooking technologies in households [76]. Importantly, a study into the transition of cooking energy in micro, small, and medium enterprises and in industry is urgently needed. There is currently no baseline survey for this important demand sector. Finally, a more detailed look into deforestation and forest degradation impacts of wood removal would bring a better understanding of the hotspots for intervention.

6. Conclusions

Efforts are currently underway to articulate the vision of the Nigerian government for clean cooking into a single clean cooking policy [21]. It is therefore vital to bridge the evidence gap and understand what the transition would entail in different value chains and locations. The focus of this study lies in target-oriented scenarios ("if we reach this target, this happens"). We provide transparency into what would be the impacts of meeting the current national goals and what would be the cost of inaction. We find that if Nigeria does not transition away from traditional biomass for cooking, there could be a dramatic 77 % increase in annual premature deaths in 2060 related to household air pollution, compared to 2018 levels. This would mean that over 209,000 premature deaths would occur annually due to the use of biomass for cooking. A scenario that is aligned with current national goals would result in a slight decrease in annual premature deaths compared to current (2018) levels for the general population, and a strong decrease in the case of children under 5. The results indicate that the different courses of action would also mean a significant reduction in greenhouse gas emissions from fuel combustion and land use change. Key policy implications include the need to interrogate the viability of the ETP's long-term vision, the potential for planning efforts to better capture the dynamics of the transition at the sub-national level, and the opportunity to better account for the impact of biomass use on deforestation and emissions from land use change. Future scenario studies looking at Nigeria's clean cooking energy transition can be strengthened by incorporating socio-economic determinants of fuel adoption as drivers of the transition and capturing some of the complex use patterns of different fuels and interactions among them.

CRediT authorship contribution statement

María Yetano Roche: Conceptualization, Methodology, Formal analysis, Investigation, Data curation, Writing – review & editing, Visualization. **Jessica Slater:** Conceptualization, Methodology, Formal analysis, Investigation, Data curation. **Chris Malley:** Conceptualization, Methodology. **Temilade Sesan:** Writing – review & editing. **Ewah Eleri:** Conceptualization.

Declaration of competing interest

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

Acknowledgements

This research was supported by the Nigeria office of the Heinrich Böll Foundation, the WISIONS of Sustainability Programme, and the Promotionsprogramme of the Wuppertal Institute for Climate, Environment and Energy. The authors gratefully acknowledge the contributions of the experts and stakeholders that took part in the study.

Data availability

The dataset and tool used in this study are openly available on a permanent repository: https://doi.org/10.5281/zenodo.10759649).

Dataset for Nigeria clean cooking scenarios and impacts study (associated article under review) (Original data) (Zenodo)

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.esr.2024.101366.

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