Optimum Predictive Modelling, Holistic Integration and Analysis of Energy Sources Mix for Power Generation and Sustainability in Developing Economies: A Case of the Nigerian Power System

by

Hanif Auwal Ibrahim

UNIVERSITEIT VAN PRETORIA
UNIVERSITY OF PRETORIA
YUNIBESITHI YA PRETORIA

Submitted in partial fulfillment of the requirements for the degree

Doctor of Philosophy, Industrial Systems

Department of Industrial and Systems Engineering
University of Pretoria
South Africa

April, 2023

Abstract

Optimum Predictive Modelling, Holistic Integration and Analysis of Energy Sources Mix for Power Generation and Sustainability in Developing Economies: A Case of the Nigerian Power System

By

Hanif Auwal Ibrahim

Supervisor : Dr Michael K. Ayomoh
Department : Industrial and Systems Engineering
Degree : Doctor of Philosophy (Industrial Systems)

Nigeria being the most populous black nation on earth, with a high birth rate and growing industrial, commercial, transportation, and agricultural activities has been caught up with the dilemma of insufficient power supply which has left the nation lagging in terms of socio-economic development among sister nations. With an aggressive transition to renewables all over the world to meet energy obligations and mitigate greenhouse gas (GHG) emissions, Nigeria is left with no choice but to join the transition in a bid to uphold the Sustainable Development Goals 7 & 13 (clean and affordable energy & climate action). The power generation mix of Nigeria is largely dependent on natural gas hence, largely in conflict with the mentioned SDGs. Despite these sources of electricity being far-fetched from meeting the growing demand for power usage, the non-renewable energy source are noted for creating a significant level of environmental pollution, global warming, and health-related risks. As the need to bring down the rising annual global temperatures to 1.5 degrees in various Conference of Parties (COP) grow in awareness, it's obvious that Nigeria has a significant role to play towards the actualization of this mission.

The ever-increasing demand for electricity, as well as its impact on the environment, necessitates expanding the generation mix by utilizing indigenous sustainable energy sources. Power generation planning that is sustainable and efficient must meet various objectives, many of which conflict with one another in which multi-objective optimization is one of the techniques used for such optimization problems. Using multi-objective optimization, a model for Nigeria's power supply architecture was developed to integrate indigenous energy sources for a sustainable power generation mix. The model

© University of Pretoria

has three competing objectives i.e reducing power generating costs, reducing CO_2 emissions and increasing jobs. To solve the multi-objective optimization problem, the Hybrid Structural Interaction Matrix (HSIM) technique was utilized to compute the weights of the three objectives: minimization of costs, minimization of CO_2 emissions, and maximization of jobs creation. The General Algebraic Modeling System (GAMS) was used to solve the multi-objective optimization problem. According to the simulations, Nigeria could address its power supply shortage and generate up to 2,100 TWh of power by 2050. Over the projected period, large hydropower plants and solar PV will be the leading option for Nigeria's power generation mix. Furthermore, power generation from solar thermal, incinerator, nuclear, gas plants, combined plants, and diesel engine will all be part of the power supply mix by 2050. In terms of jobs expected to be created, about 2.05 million jobs will be added by 2050 from the construction and operation of power generation plants with CO_2 emissions attaining 266 M_tCO_2 by 2050. The cost of power generation is expected to decline from a maximum of 36 billion US$ in 2030 to 27.1 billion US$ in 2050. Findings in this research concludes that Nigeria can meet its power supply obligations by harnessing indigenous energy sources into an optimal power supply mix.

Furthermore, to establish the basis for the power generation mix projection, system drivers responsible for the rising demand of electricity and reduce pace of transition to renewable energy sources were identified from a systems thinking point of view after which they were prioritized using the HSIM concept. Also, the impact of renewable energy on power accessibility, affordability and environmental sustainability was investigated using the system dynamics approach. It was obtained that factors including urbanization, industrialization, agricultural/commercial services growth rates, and pollution are the primary reasons for the rising demand for electricity. The slow transition to renewables in Nigeria is directly linked to the absence of subsidies and government grants, non-existing or few renewable energy financing institutions, scarcity of experienced professionals, barriers to public awareness and information, and ineffective government policies. The outcome from the system dynamics approach on accessibility, affordability, and environmental sustainability of the electricity supply are thought to be enhanced if indeed the country's plan of using 36% renewables in the mix of power sources is to be met.

Keywords: Power generation, sustainability, greenhouse gas, hydropower, solar, bioenergy, wind, geothermal, energy modelling.

© University of Pretoria

Declaration

I, Hanif Auwal Ibrahim, declare that this dissertation/thesis, which I hereby submit for the degree, of Doctor of Philosophy in Industrial Systems at the University of Pretoria, is my own work unless or otherwise explicitly acknowledged by citation of published and unpublished sources and has not previously been submitted by me for a degree at this or any other tertiary institutions. Furthermore, I would like to state that, even though the work presented in various chapters of the thesis have been co-authored with my supervisor, the conceptualization and execution of the research were done by me through the guidance of my supervisor.

Hanif Auwal Ibrahim (17230617)

Signed:

Date: 13th April, 2023

© University of Pretoria

Disclaimer

This thesis has been structured in a publication style of writing, where each chapter is a standalone article that has been published in peer-reviewed journals. The objective of this approach is to disseminate the research findings widely and contribute to the existing body of knowledge in the field.

So far, three articles have been successfully published in peer-reviewed journals, covering objectives 1, 3, and 4 of the thesis. Additionally, one paper has been presented at an IEEE conference, which addresses objective 2. The doctoral researcher's efforts as the principal investigator have resulted in these publications, showcasing their original research findings.

However, due to the unique requirements of different journals, there may be variations or overlaps in the content and style of presentation between chapters in this thesis. Each publication has its own specific formatting, language, and structure that needs to be tailored to meet the requirements of the target journal. This may result in some repetition of the methodology and results sections in the different papers to ensure that each publication is self-contained and follows the guidelines of the respective journals.

It is important to note that the doctoral researcher has taken the lead in initiating and conducting the research presented in these publications. They have put in their individual effort to complete the research for all the stated objectives and are actively working towards addressing the fifth objective, which is currently under review. The aim is to continue contributing to the field through publication of the research findings in reputable journals.

© University of Pretoria

Acknowledgments

The author would like to express his appreciation to the following persons and institutions who have contributed to the success of this research:

- Dr Michael K. Ayomoh (UP) for his continual support, expertise, and leadership throughout the study. Dr. Ayomoh's love and passion for energy accessibility and climate change mitigation by utilizing renewable energy systems in underdeveloped and developing economies is boundless and infectious which provided the foundation for the concepts in this work. Without him, this work would simply not have been possible. The many hours of reading, reviews, and brilliant ideas improved the work substantially. His vast academic and scientific expertise and co-authorship of our publications resulted in this Thesis.

- Energy Commission of Nigeria for the study leave granted me to conduct this PhD research.

- My family to which I owe everything for getting me to this point of my career by continual and unequivocal love and support of everything I do.

- Friends and colleagues for their constant encouragement and scientific mentorship which were instrumental in my scientific development.

© University of Pretoria

Thesis Promoter

Dr Michael K. Ayomoh

Department of Industrial and Systems Engineering, Faculty of Engineering, Built Environment, and Information Technology, University of Pretoria, South Africa.

© University of Pretoria

Research Outputs

The following publications, all of which are derived from the work carried out for this thesis, have been published/accepted for publication with only one currently under review:

Published journal articles

1. **H. A. Ibrahim** and M. K. Ayomoh. Optimum predictive modelling for a sustainable power supply mix: A case of the Nigerian power system. *Energy Strategy Reviews*. 2022;44:100962., doi:10.1016/j.esr.2022.100962 **(Published). Impact Factor 2022 (10.01)**

2. **H. A. Ibrahim** and M. K. Ayomoh. Identification and prioritization of factors affecting the transition to renewables in developing economies. Energy Reports. 2022; 8:94-104, doi.org/10.1016/j.egyr.2022.10.064 **(Published). Impact Factor 2022 (4.937)**

3. **H. A. Ibrahim,** M. K. Ayomoh, R. C. Bansal, M. N. Gitau, V.S.S. Yadavalli and R. Naidoo. Sustainability of Power Generation for Underdeveloped and Developing Economies: A Systematic Review of Pros and Cons of Existing Power Sources Mix. *Energy Strategy Reviews* **(Published). Impact Factor 2022 (10.01)**

4. **H. A. Ibrahim** and M. K. Ayomoh. Renewable energy's impact on power supply accessibility, affordability, and environmental sustainability: A system dynamics approach. *Energy Nexus, Elsevier 2022* **(Under review).**

Conference paper

1. **H. A. Ibrahim** and M. K. Ayomoh, "Identification and Prioritisation of Electricity Driving Factors for Power Supply Sustainability: A Case of Developing and Underdeveloped Nations," 2021 IEEE Asia-Pacific Conference on Computer Science and Data Engineering (CSDE), 2021, pp. 1-6, doi: 10.1109/CSDE53843.2021.9718450 **(Published).**

© University of Pretoria

Table of Contents

© University of Pretoria

© University of Pretoria

© University of Pretoria

© University of Pretoria

List of Figures

© University of Pretoria

List of Tables

© University of Pretoria

Nomenclature

f1	Electricity generation cost objective function, (US$)
f2	CO_2 emissions objective function for energy sources, (Mt)
f3	Jobs objective function, (%)
f4	Multi-objective function with three objectives
w1	Weight of cost objective function
w2	Weight of CO2 emissions objective function
w3	Weight of job creation objective function
G	Power being generated, (MWh)
sLCOE	Simplified Levelized Cost of Electricity, (US$/MWh)
r	Discount rate
C	Capital expenditure of newly installed power plant, (US $/MW)
O	Operating and maintenance costs, (US$/MW, US$/MWh)
F	Fuel cost, (US$/MWh)
ε	Power plant heat rate/thermal to electricity efficiency
CRF	Cost recovery factor
Cf	Capacity factor
$\emptyset$	Learning rate elasticity
N	Cumulative capacity
CO_{2EF}	CO_2 emission factor, (ton CO2/MWh)
D	Electricity demand, MWh
Fs	Fuel supply, (MWh/year)
i	Index for technology type
t	Index for a time horizon
new	Index for new power plant
ext	Index for existing power plant
Fix	Index for a fixed value
Var	Index for variable value
bi	Jobs created in construction phase of the power sector by technology i (GWh)
hi	Jobs created in operation phase of the power sector by technology i (GWh)
X	Net electricity generation (MWh)
ρ	Self-consumption of technology (%)
ωi	Maximum share of technology (%)
CT	Construction time of technology (Year)
INVC	Investment cost of technology ($/MW)
NAC	Newly added capacity of technology (MW)
bgC	Budget required for constructing new capacities ($)

© University of Pretoria

Chapter 1

Introduction

1.1 Background

Nigeria, as one of the most populous countries in Africa and a growing economy, faces significant challenges in meeting its increasing demand for electricity. The stumbling block to Nigeria's economic development is believed to be hinged on poor power generation, inadequate access to electricity, and over-reliance on fossil fuels for power generation. According to the World Bank, as of 2021, only about 57.7% of the Nigerian population has access to electricity, with rural areas facing even lower access rates [1]. The country's installed power generation capacity of around 12,522 MW falls short of the estimated demand of over 25,000 MW, resulting in frequent blackouts, reduced economic productivity, and diminished quality of life for Nigerians [1]. The country's heavy reliance on fossil fuels, particularly gas, for power generation exposes it to price volatility and supply disruptions in the global gas market, affecting the affordability and reliability of electricity for consumers. Moreover, Nigeria has abundant renewable energy resources such as solar, wind, and hydropower, but has been slow in transitioning to renewables, lagging behind in renewable energy utilization.

Meeting today's power requirements without jeopardizing the ability of future generations to do the same is what is meant by a sustainable power supply mix. Sustainable development has been the focus of a wealth of study on numerous issues, levels, and viewpoints ever since it was first introduced and put into practice [2]. To remain competitive and relevant among nations, Nigeria must address its problem of insufficient power supply, particularly now that the COVID-19 pandemic has wreaked havoc on the economy [3]. As such, there is a critical need for research to address Nigeria's power poverty and promote sustainable solutions. This research aims to investigate innovative strategies to enhance power generation by promoting the adoption of renewable energy sources. Thankfully, Nigeria has a wide variety of abundant energy sources from which to draw in order to create a sustainable power supply mix that would meet the rising demand for electricity, protect the environment, and lower greenhouse gas (GHG) emissions [4]. Despite having an abundance of power generation sources, Nigeria struggles to meet its fast-rising electricity demand and is afflicted by rolling blackouts in most of the nation [5, 6]. Sustainable power supply is thought to be impossible without the use of RE (renewable energy) sources [7]. Through industrialization, Nigeria will be able to address its main problems, such as unemployment and security threats, and this can only be done with a reliable, affordable, and environmentally friendly power supply [6].

Energy modeling and optimization techniques must be used by policymakers and researchers who aim to create a power supply system that is ecologically friendly to ensure that several goals, including cost, emissions, jobs, and others, are achieved [8]. Since the 1990s, modelers have been creating energy system optimization models [9–13]. To create the best power supply mixes for regions, cities, and countries, costs or emissions are optimized [14–22].

© University of Pretoria

Due to the connection between energy use, environmental protection, economic growth, and social responsibility, power planning has grown to be a complex subject encompassing many variables [23]. Therefore, methods for energy modeling and optimization that may incorporate a variety of goals into the creation of a power policy are crucial. The primary modeling idea underpinning long-term energy planning is developing the best power generation mix to meet electricity demand while satisfying a number of constraints. The type of power technology employed, the amount of installed power capacity, the time it took to build and operate the technology, and the required fuel sources are a few major outcomes of such procedures. The employment of cost optimization models like MESSAGE, MARKAL, TIMES, etc. has been the focus of numerous studies examining the socio-economic optimality of power planning (see, for example, Refs. [24-33]). On the other hand, the strategic planning of power planning systems invariably considers many conflicting goals [34–36]. Environmental or social goals were previously handled in multi-objective optimization studies by being converted into cost-equivalent objectives [37] or by being seen as constraints having lower and upper bounds [38]. However, due to its ability to directly assign an objective function to each sustainability criterion (cost, emissions, jobs, land, societal opposition, etc.) without the need for intricate calculations, multi-objective optimization is more feasible.

Prior multi-objective studies mostly focused on costs and emissions without considering the social issues. Ren et al [39] investigated the decentralized energy source's operating method while balancing energy cost reduction and environmental effect minimization. An economic and environmental analysis of the Japanese power production system was conducted by Zhang et al. [40]. To lower the cost of electricity generation and CO_2 emissions in Taiwan, Ko et al. [41] employed a multi-objective optimization. Lowest generation costs and lowest CO_2 emissions were two objectives Purwanto et al. [42] put into their conceptual framework for an Indonesian long-term power producing mix. Mahbub et al [43] researched on identification of the best possible scenarios for dealing with Italy's restrictions on reducing energy prices and CO_2 emissions. Based on trade-offs between the economy and the environment, Pratama et al. [44] evaluated alternative future scenarios for Indonesian power generation. While Tekiner et al. [45] looked at three objective functions, both of their non-cost criteria considered air pollutants like CO_2 and NO_x. A multi-objective optimization model still must be created in order to evaluate trade-offs between various sustainability parameters that conflict with one another. In order to incorporate indigenous energy sources while reducing power generation costs, reducing CO_2 emissions, and optimizing the number of employment generated through the building and operation of power plants, multi-objective optimization was employed in this work.

The Nigerian power sector faces significant challenges, including inadequate power generation and distribution infrastructure, poor transmission, and a lack of reliable power supply. Addressing these challenges requires a comprehensive approach that leverages all available energy sources. In this context, the following information is provided:

i. The interventions to address Nigeria's power challenges must be timely, given the urgent need for reliable power supply. These interventions must include short-term and long-term strategies. In the short-term, efforts must focus on improving the existing power infrastructure to increase power generation and distribution capacity. In the long-term, the government must invest in renewable energy sources and other alternative sources of energy to reduce the country's dependence on fossil fuels and improve the sustainability of the power sector.

© University of Pretoria

ii. The need to harness all available energy sources is essential to address Nigeria's power challenges. The country has abundant natural resources that can be used to generate power, including coal, oil, gas, hydropower, solar, wind, and biomass. By tapping into these resources, Nigeria can increase its power generation capacity and reduce its dependence on fossil fuels, which are expensive and have significant environmental impacts.

iii. The resource capacities for each energy source vary, and it is essential to consider each source's potential in the context of Nigeria's power sector. Nigeria has significant coal reserves, estimated at over 2 billion metric tons. The country also has significant oil and gas reserves, with proven reserves of over 37 billion barrels of oil and over 188 trillion cubic feet of gas [6]. Hydropower is another energy source with significant potential, with several dams and reservoirs already in place. Nigeria also has significant potential for solar and wind energy, with an estimated capacity of over 100 GW for solar and over 10 GW for wind [6]. Finally, biomass is another potential energy source, with significant potential for electricity generation from agricultural and forestry waste [10]. Exploiting all energy sources can offer several benefits, including increased power generation capacity, reduced reliance on fossil fuels, and improved sustainability.

1.2 Problem statement

The situation with Nigeria’s power availability is critically dire, with only 57.7% of the population having access to electricity, and a chronic supply deficit of over 25,000 MW. This has resulted in frequent power outages, load shedding, and reliance on expensive alternative energy sources. Despite being endowed with a variety of energy sources, including renewables such as hydro, solar, wind, biomass, tidal, and non-renewables like gas and crude oil, Nigeria's power supply mix is limited to only hydro and natural gas, which is inadequate for a booming population of over 200 million people with a high birth rate and increasing electricity demand due to factors such as industrialization.

Existing studies on Nigeria's power supply mix are scarce and do not comprehensively address economic, environmental, and social objectives. Some studies have focused on specific aspects such as carbon emission pinch analysis, energy system simulations, energy consumption forecasts, and regional power supply scenarios. However, there is a gap in research that develops a holistic power supply mix for Nigeria, considering all available sustainable energy sources to meet the growing power demand while minimizing CO_2 emissions, costs, and maximizing job creation, particularly for the youthful unemployed population.

Given the urgency of the power poverty situation in Nigeria, there is a need for research that addresses the inadequacies in the power supply mix, generation costs, and job creation. This study aims to fill the research gap by developing a comprehensive power supply mix for Nigeria that considers economic, environmental, and social objectives, and proposes strategies to improve the power generation outlook in the country. Considering Nigeria’s power poverty, it is timely and of great importance to come up with a power supply mix that harnesses all the energy sources to address the power supply inadequacies, reduced generation costs, and creation of jobs for the youthful unemployed population.

© University of Pretoria

1.3 Research gap

Despite the growing global interest in renewable energy and sustainable power supply, there remains a significant research gap in understanding the unique challenges and opportunities faced by developing economies, including Nigeria. Existing literature often focuses on developed economies, and there is a lack of comprehensive research that specifically explores the pros and cons of existing power sources mix, identifies and prioritizes factors driving electricity sustainability, and investigates factors influencing the transition to renewables in developing economies, with a specific focus on the Nigerian power system. Additionally, there is a need for the development of predictive models that can optimize power supply mix in the context of developing countries, including Nigeria, taking into account factors such as energy demand, resource availability, and environmental sustainability. Furthermore, the application of system dynamics approaches to analyze the impact of renewable energy on power supply accessibility, affordability, and environmental sustainability in developing economies, including Nigeria, remains understudied.

1.4 Research questions

The research questions formulated for this study are as follows:

1. What are the advantages and disadvantages of the current power sources mix in developing economies, including Nigeria, considering factors such as cost, reliability, environmental impact, and accessibility to electricity, and how can these findings inform policy decisions and strategies for sustainable power supply in these regions?

2. What are the key factors driving electricity sustainability in developing economies, including Nigeria, and how can these factors be identified and prioritized to guide policy interventions and actions towards sustainable power supply in these regions?

3. What are the factors influencing the transition to renewable energy sources in developing economies, including Nigeria, and how can these factors be systematically identified and prioritized to facilitate the adoption and integration of renewables in the power mix of these countries?

4. How can an optimal predictive model be developed to determine a sustainable power supply mix for the Nigerian power system, considering factors such as energy demand, resource availability, and environmental sustainability, and how can this model be used to inform policy and planning decisions for a sustainable energy future in Nigeria?

5. How can a system dynamics approach be applied to model and analyze the impact of renewable energy on power supply accessibility, affordability, and environmental sustainability in Nigeria, and what valuable insights can be gained from such analysis to guide policy formulation and decision-making towards sustainable energy development?

© University of Pretoria

1.5 Scope of study

The scope of this thesis is to develop a multi-objective optimization model for Nigeria's power supply architecture, which integrates indigenous sustainable energy sources for a sustainable power generation mix. The study aims to provide a roadmap for Nigeria's transition to renewables in line with Sustainable Development Goals 7 & 13. The study also seeks to identify the factors responsible for the rising electricity demand and slow transition to renewable energy sources in Nigeria and to investigate the impact of renewable energy on power accessibility, affordability, and environmental sustainability.

The study utilizes the Hybrid Structural Interaction Matrix (HSIM) technique to prioritize the factors responsible for the rising electricity demand and slow transition to renewable energy sources. It also employs the system dynamics approach to investigate the impact of renewable energy on power accessibility, affordability, and environmental sustainability.

The study uses the General Algebraic Modeling System (GAMS) to develop a multi-objective optimization model for Nigeria's power supply architecture. The model aims to minimize power generating costs, reduce CO_2 emissions, and increase jobs. The study projects the power generation mix for Nigeria up to 2050, which includes large hydropower plants, solar PV, solar thermal, incinerator, nuclear, gas plants, combined plants, and diesel engine. The study also projects the jobs expected to be created, CO_2 emissions, and the cost of power generation.

The study is limited to Nigeria's power supply architecture and the factors responsible for the rising electricity demand and slow transition to renewable energy sources. The study does not cover the distribution and transmission of electricity or the political, social, and economic factors that may affect Nigeria's transition to renewables. The study's projections and recommendations are based on the assumptions and data used in the models and may change due to unforeseen circumstances or changes in policy.

1.6 Aim

Given the problem statement in section 1.2, the aim of this study is to develop a sustainable power supply mix model premised on holistic thinking for the Nigerian power supply system that would be able to meet the rising power demand while mitigating CO_2 emissions, reducing power generating costs, and creating job opportunities.

1.7 Objectives

The main objectives of this thesis are as follows:

1. Exploring the pros and cons of existing power sources mix of developing countries.
2. Identification, prioritization and understanding of electricity driving factors for power supply sustainability in developing economies.
3. Identification and prioritization of drivers affecting the transition to renewables in developing economies.

© University of Pretoria

4. Development of an optimum predictive model for a sustainable power supply mix for the Nigerian power system.
5. Modeling and Analysis of the impact of Renewable energy on power supply accessibility, affordability and environmental sustainability using a system dynamics approach.

1.8 Original outcomes

The outcomes of this study were published as part of this thesis in Scopus Indexed Journals. The original contributions and highlights of the articles with relevant chapters are as follows:

Chapter 2. Sustainability of Power Generation for Developing Economies: A Systematic Review of Existing Power Sources Mix

- Expansion of the existing literature of pros and cons of existing power supply mix of developing countries.
- The findings contribute to the existing body of knowledge on the advantages and disadvantages of various energy modelling tools.

Chapter 3. Identification and Prioritization of Electricity Driving Factors for Power Supply Sustainability: A Case of Developing and Underdeveloped Nations [46]

- Expansion of the existing literature of factors responsible for the rising electricity demand.
- The significance in terms of hierarchy of the twenty-two electricity demand drivers.
- Weights of each of the electricity demand drivers which also determines their level of importance in driving the demand for electricity.

Chapter 4. Identification and prioritization of factors affecting the transition to renewables in developing economies [47]

- Expansion of the existing literature of factors responsible for the slow transition to renewables in Nigeria.
- The significance in terms of hierarchy of the eighteen barriers responsible for the slow transition to renewables in Nigeria.
- Weights of each of the barriers affecting the transition to renewables in Nigeria which also determines their level of importance in slowing down the transition to renewables.

Chapter 5. Optimum predictive modelling for a sustainable power supply mix: A case of the Nigerian power system [48]

- The rising power demand for Nigeria can be met by harnessing the available energy sources.
- Power generation capacity from each considered energy source.
- Present and future electricity demand in the agricultural, industrial, transportation, and household sectors.
- Nigeria can mitigate its CO_2 emissions by the development of the sustainable power supply mix.
- Influence of a sustainable power supply mix on costs.
- Jobs created from the construction and operation of power plants as a result of the implementation of the power sources mix.

© University of Pretoria

Chapter 6. Renewable energy impact on power supply accessibility, affordability, and environmental sustainability: A system dynamics approach

- Expansion of the existing literature database on renewable energy's impact on power accessibility.
- Expansion of the existing literature database on renewable energy's impact on power affordability.
- Influence of renewable energy on environmental sustainability of power supply.

1.9 Overview of the Thesis

Chapter 1 covered the introduction and background, problem statement, aim, objectives, original outcomes and the thesis overview. **Chapter 2** detailed the comprehensive literature survey on the potential of energy sources such as hydro, wind, biomass, etc., in developing countries together with the pros and cons of existing power sources mix in developing countries. Also, highlighting the pros and cons of various energy modelling tools utilized for the development of the power sources mix. **Chapter 3** contained the factors that are responsible for the rising demand for electricity in developing countries. The identified factors were prioritized based on hierarchy and their normalized weights. **Chapter 4** focused on the barriers for renewable energy transition in Nigeria. **Chapter 5** contains the projection of the sustainable power supply mix, costs, CO_2 emissions, and jobs. . **Chapter 6** focuses on how renewable energy does affect the accessibility, affordability, and environmental sustainability of power supply. **Chapter 7** provides the summary, conclusions of the thesis and recommendations for future work.

1.10 Chapter References

[1] World Bank, in: Access to electricity (% of the population) - Nigeria | Data, 2022. Available from, https://data.worldbank.org/indicator/EG.ELC.ACCS.ZS?locat ions=NG. (Accessed 28 March 2022).

[2] Ye N, Kueh T, Hou L, Liu Y, Yu H. A bibliometric analysis of corporate social responsibility in sustainable development. *J Clean Prod*. 2020;272:122679. doi:10.1016/j.jclepro.2020.122679.

[3] World Bank. Nigeria's Economy Faces Worst Recession in Four Decades, says New World Bank Report. The World Bank. https://www.worldbank.org/en/news/press-release/2020/06/25/nigerias-economy-faces-worst-recession-in-four-decades-says-new-world-bank-report. Published 2020. Accessed July 29, 2022.

[4] Olujobi O, Ufua D, Olokundun M, Olujobi O. Conversion of organic wastes to electricity in Nigeria: legal perspective on the challenges and prospects. *International Journal of Environmental Science and Technology*. 2021;19(2):939-950. doi:10.1007/s13762-020-03059-3.

[5] Iroh O, Kalu I, Nteegah A. Empirical Cost of Electricity Outage on Labour and Capital Productivity in Nigeria. *Applied Journal of Economics, Management and Social Sciences*. 2022;3(1). doi:10.53790/ajmss.v3i1.23.

[6] World Bank. Access to electricity (% of the population) - Nigeria | Data. Published 2022. Available from: https://data.worldbank.org/indicator/EG.ELC.ACCS.ZS?locations=NG

© University of Pretoria

(accessed Mar. 28, 2022).

[7] Zhao X, Mahendru M, Ma X, Rao A, Shang Y. Impacts of environmental regulations on green economic growth in China: New guidelines regarding renewable energy and energy efficiency. *Renew Energy*. 2022;187:728-742. doi:10.1016/j.renene.2022.01.076.

[8] Walther J, Weigold M. A Systematic Review on Predicting and Forecasting the Electrical Energy Consumption in the Manufacturing Industry. *Energies (Basel)*. 2021;14(4):968. doi:10.3390/en14040968.

[9] C. Berglund and P. Söderholm, "Modeling technical change in energy system analysis: Analyzing the introduction of learning-by-doing in bottom-up energy models," *Energy Policy*, vol. 34, no. 12, pp. 1344–1356, 2006, doi: 10.1016/j.enpol.2004.09.002.

[10] R. G. Cong, "An optimization model for renewable energy generation and its application in China: A perspective of maximum utilization," *Renewable and Sustainable Energy Reviews*, vol. 17. pp. 94–103, Jan. 2013. doi: 10.1016/j.rser.2012.09.005.

[11] K. U. Rao and V. V. N. Kishore, "A review of technology diffusion models with special reference to renewable energy technologies," *Renewable and Sustainable Energy Reviews*, vol. 14, no. 3. pp. 1070–1078, Apr. 2010. doi: 10.1016/j.rser.2009.11.007.

[12] P. D. Lund, "Energy policy planning near grid parity using a price-driven technology penetration model," *Technological Forecasting and Social Change*, vol. 90, no. PB, pp. 389–399, Jan. 2015, doi: 10.1016/j.techfore.2014.05.004.

[13] P. Lund, "Market penetration rates of new energy technologies," *Energy Policy*, vol. 34, no. 17, pp. 3317–3326, Nov. 2006, doi: 10.1016/j.enpol.2005.07.002.

[14] S. Mallah and N. K. Bansal, "Renewable energy for sustainable electrical energy system in India," *Energy Policy*, vol. 38, no. 8, pp. 3933–3942, Aug. 2010, doi: 10.1016/j.enpol.2010.03.017.

[15] N. A. Utama, K. N. Ishihara, T. Tezuka, N. A. Utama, K. N. Ishihara, and T. Tezuka, "Power Generation Optimization in ASEAN by 2030," *Energy and Power Engineering*, vol. 4, no. 4, pp. 226–232, Jun. 2012, doi: 10.4236/EPE.2012.44031.

[16] Q. Zhang, K. N. Ishihara, B. C. Mclellan, and T. Tezuka, "Scenario analysis on future electricity supply and demand in Japan," *Energy*, vol. 38, no. 1, pp. 376–385, 2012, doi: 10.1016/j.energy.2011.11.046.

[17] Z. A. Muis, H. Hashim, Z. A. Manan, F. M. Taha, and P. L. Douglas, "Optimal planning of renewable energy-integrated electricity generation schemes with CO2 reduction target," *Renewable Energy*, vol. 35, no. 11, pp. 2562–2570, Nov. 2010, doi: 10.1016/j.renene.2010.03.032.

[18] Q. Zhang, K. N. Ishihara, B. C. Mclellan, and T. Tezuka, "Scenario analysis on future electricity supply and demand in Japan," *Energy*, vol. 38, no. 1, pp. 376–385, 2012, doi: 10.1016/j.energy.2011.11.046.

[19] Q. Zhang, B. C. Mclellan, T. Tezuka, and K. N. Ishihara, "An integrated model for long-term power generation planning toward future smart electricity systems," *Applied Energy*, vol. 112, pp. 1424–1437, 2013, doi: 10.1016/j.apenergy.2013.03.073.

[20] T. Luz, P. Moura, and A. de Almeida, "Multi-objective power generation expansion planning with high penetration of renewables," Renew Sustain Energy Rev, vol. 81, pp. 2637- 2643, 2018, http://doi.org/10.1016/j.rser.2017.06.069.

[21] A. Poullikkas, G. Kourtis, and I. Hadjipaschalis, "A hybrid model for the optimum integration

© University of Pretoria

of renewable technologies in power generation systems," *Energy Policy*, vol. 39, no. 2, pp. 926–935, Feb. 2011, doi: 10.1016/j.enpol.2010.11.018.

[22] C. Barteczko-Hibbert, I. Bonis, M. Binns, C. Theodoropoulos, and A. Azapagic, "A multi-period mixed-integer linear optimisation of future electricity supply considering life cycle costs and environmental impacts," *Applied Energy*, vol. 133, pp. 317–334, Nov. 2014, doi: 10.1016/j.apenergy.2014.07.066.

[23] Purwanto WW, Pratama YW, Nugroho YS, Hertono GF, Hartono D, Tezuka T. Multi-objective optimization model for sustainable Indonesian electricity system: analysis of economic, environment, and adequacy of energy sources. Renew Energy 2015;81:308e18.

[24] Amorim F, Pina A, Gerbelov a H, da Silva PP, Vasconcelos J, Martins V. Electricity decarbonisation pathways for 2050 in Portugal: a TIMES (The Integrated MARKAL-EFOM System) based approach in closed versus open systems modelling. Energy 2014;69:104e12.

[25] Dountio EG, Meukam P, Tchaptchet DLP, Ango LEO, Simo A. Electricity generation technology options under the greenhouse gases mitigation scenario: case study of Cameroon. Energy Strat Rev 2016;13:191e211.

[26] Hainoun A, Aldin MS, Almoustafa S. Formulating an optimal long-term energy supply strategy for Syria using MESSAGE model. Energy Pol 2010;38(4): 1701e14.

[27] Jaskolski M. Modelling long-term technological transition of Polish power system using MARKAL: emission trade impact. Energy Pol 2016;97:365e77.

[28] Komusanac I, Cosic B, Duic N. Impact of high penetration of wind and solar PV generation on the country power system load: the case study of Croatia. Appl Energy 2016;184:1470e82.

[29] McPherson M, Karney B. Long-term scenario alternatives and their implications: LEAP model application of Panama′ s electricity sector. Energy Pol 2014;68:146e57.

[30] Merkel E, Fehrenbach D, McKenna R, Fichtner W. Modelling decentralised heat supply: an application and methodological extension in TIMES. Energy 2014;73:592e605.

[31] Park NB, Yun S, Eui CJ. An analysis of long-term scenarios for the transition to renewable energy in the Korean electricity sector. Energy Pol 2013;52: 288e96.

[32] Tomaschek J, Kober R, Fahl U, Lozynskyy Y. Energy system modelling and GIS to build an integrated climate protection concept for Gauteng Province, South Africa. Energy Pol 2016;88:445e55.

[33] Welsch M, Deane P, Howells M, Gallachoir BO, Rogan F, Bazilian M, et al. Incorporating flexibility requirements into long-term energy system modelseA case study on high levels of renewable electricity penetration in Ireland. Appl Energy 2014;135:600e15).

[34] Heinricha G, Bassonc L, Cohena B, Howellsd M, Petrie J. Ranking and selection of power expansion alternatives for multiple objectives under uncertainty. Energy 2007;32:2350e69.

[35] Ren HB, Zhou WS, Nakagami K, Gao WJ, Wu Q. Multi-objective optimization for the operation of distributed energy systems considering economic and environmental aspects. Appl Energy 2010;87:3642e51.

[36] Antunes CH, Martins GA, Brito IS. A multiple objective mixed integer linear programming model for power generation expansion planning. Energy 2004;29:613e27.

[37] Aryanpur V, Shafiei E. Optimal deployment of renewable electricity technologies in Iran and implications for emissions reductions. Energy 2015;91: 882e93.

[38] Dhakouani A, Gardumi F, Znouda E, Bouden C, Howells M. Long-term optimisation model of the Tunisian power system. Energy 2017;141:550e62.

© University of Pretoria

[39]Ren et al. Ren HB, Zhou WS, Nakagami K, Gao WJ, Wu Q. Multi-objective optimization for the operation of distributed energy systems considering economic and environmental aspects. Appl Energy 2010;87:3642e51.

[40] Zhang Q, Mclellan BC, Tezuka T, Ishihara KN. Economic and environmental analysis of power generation expansion in Japan considering Fukushima nuclear accident using a multi-objective optimization model. Energy 2012;44(1):986e95.

[41] Ko L, Chen CY, Seow VC. Electrical power planning and scheduling in Taiwan based on the simulation results of multi-objective planning model. Int J Elect prower Energy Syst 2014;55(1):331e40.

[42] Purwanto WW, Pratama YW, Nugroho YS, Hertono GF, Hartono D, Tezuka T. Multi-objective optimization model for sustainable Indonesian electricity system: analysis of economic, environment, and adequacy of energy sources. Renew Energy 2015;81:308e18.

[43]Mahbub MS, Viesi D, Crema L. Designing optimized energy scenarios for an Italian Alpine valley: the case of Giudicarie Esteriori. Energy 2016;116(1): 236e49].

[44]Pratama YW, Purwanto WW, Tezuka T, McLellan BC, Hartono D, Hidayatno A, Daud Y. Multi-objective optimization of a multiregional electricity system in an archipelagic state: the role of renewable energy in energy system sustainability. Renew Sustain Energy Rev 2017;77(1):423e39.

[45]Tekiner H, Coit DW, Felder FA. Multi-period multi-objective electricity generation expansion planning problem with Monte-Carlo simulation. Elec Power Syst Res 2010;80(12):1394e405.

[46]Ibrahim HA, Ayomoh MK. Identification and Prioritisation of Electricity Driving Factors for Power Supply Sustainability: A Case of Developing and Underdeveloped Nations. In2021 IEEE Asia-Pacific Conference on Computer Science and Data Engineering (CSDE) 2021 Dec 8 (pp. 1-6). IEEE.

[47]Ibrahim HA, Ayomoh MK. Identification and prioritization of factors affecting the transition to renewables in developing economies. Energy Reports. 2022 Nov 1;8:94-104.

[48] Ibrahim HA, Ayomoh MK. Optimum predictive modelling for a sustainable power supply mix: A case of the Nigerian power system. Energy Strategy Reviews. 2022 Nov 1;44:100962.

\

© University of Pretoria

Chapter 2

Sustainability of Power Generation for Developing Economies: A Systematic Review of Existing Power Sources Mix

2.0 Chapter Overview

The chapter on "Sustainability of Power Generation for Developing Economies: A Systematic Review of Existing Power Sources Mix" focuses on the current state and future prospects of power generation in developing economies, with a specific emphasis on sustainability. It reviewed and analyzed the existing mix of power sources in developing economies and assess their sustainability from economic, environmental, and social perspectives.

This chapter begins with an introduction to the context of power generation in developing economies, highlighting the challenges and opportunities they face. These economies often have limited access to reliable and affordable electricity, which can hinder economic growth and social development. The chapter then provides a systematic review of the existing power sources mix in developing economies, which may include traditional sources such as fossil fuels (coal, oil, and natural gas), as well as renewable sources such as hydroelectric, solar, wind, biomass, and geothermal energy.

The review evaluates the sustainability of these power sources from different angles. Economic sustainability considers the affordability and accessibility of power for local communities and industries, as well as the potential for economic growth and job creation. Environmental sustainability assesses the impact of power generation on the environment, including greenhouse gas emissions, air pollution, water usage, and land degradation. Social sustainability looks at the social implications of power generation, such as health and safety, social equity, and community engagement.

The chapter discusses the advantages and disadvantages of each power source in terms of sustainability, taking into account the unique characteristics and challenges of developing economies.

The selection of the GAMS modelling tool for multi-objective optimization in Chapter 5 was influenced by this chapter. The increasing demand for electricity in developing economies and the need for sustainable power generation solutions has also been highlighted in this chapter. Additionally, insights into the challenges of transitioning to renewable energy sources in developing economies have been provided. Overall, valuable insights that can guide policymakers and practitioners in developing sustainable power generation strategies for developing economies have been contributed by the chapter.

© University of Pretoria

2.1 Introduction

Power is generated by utilizing primary energy sources such as natural gas, biomass, coal, uranium, sunshine, wind, tidal, etc. In 2013, power constituted 18% of global energy demand, making it crucial to nations' social well-being and economic competitiveness [1]. Recent population boom, industrialization, modernization, and most recently, the arrival of the fourth industrial revolution have made power generation an issue of increasing global concern with a much more devastating effect on developing and underdeveloped economies [2]. Considering electricity's versatility across all endeavors of human activity, including households, agriculture, industry, transportation, and the service sector, the need to objectively analyze various power generation mixes to determine their sustainability has become crucial. To name a few, the depletion of fossil fuel supplies, energy stability, global warming, and the damaging environmental effects of continuous utilization of specific power generation systems brings about a discussion premised on multi-objective optimization. This domain of the problem, which is strongly linked to electricity supply mix, equilibrium, and optimization, is worth investigating for the sustainability of the power sector in developing economies [3]. Coal and gas are still heavily utilized in the generating electricity in developing economies and this trend will continue until 2035, this is because of their vast oil reserves, and disregard for environmental, health, and safety implications [4, 5]. The negative impact of fossil fuels on the environment, health, and energy security are significant. As a result, Presidents from various countries convened for COP26 in the United Kingdom to address these global challenges. The 26th UN Climate Change Conference (COP26) in Glasgow (2021) is committing all nations that rely on carbon-related power generation sources to a sustainable facing out dealing with all the necessary support. These countries span from the developed nations (where carbon-centered power sources are utilized for heavy industrial and agricultural operations) to the developing and underdeveloped economies where (carbon sources are used primarily for power generation) [6].

Assessing the U4RIA criteria against the power sources mix of developing countries considered in this study, accessibility is underpinned in the context of strategic energy planning. These consists of a community of practitioners (Ubuntu), retrievability (i.e., the data can be easily found and accessed), reusability (i.e., licensing practices that may allow reuse), repeatability (i.e., the modelling process can be repeated), reconstructability (i.e., complete meta data to reconstruct the modelling are available), interoperability (i.e., high compatibility of modelling output). and auditability (i.e., the transparency derived by the previous factors allows for peer review of the modeling). Among the attributes retrievability was particularly scarce due to the absence of shared infrastructure where data could be stored. Data used during the capacity development program were stored mostly in folders created ad hoc. From there local versions were created by each participant through time, in non-collaborative ways and with no version control. This resulted in the absence of one common and updated database academia and governmental institutions could source from and could present as the reference. Without a common database, it is more difficult to establish a platform for communication and collaboration between institutions in building science evidence supporting the power source mix to the round table principles may increase the effectiveness and sustainability of the demand led support development partners given to countries engaged in strategic energy.

In the case of the developing economies considered in this study, the expressed need is making the

© University of Pretoria

national energy planning ecosystem more self-standing, efficient and lasting. This is envisaged to become important as the push for decarbonization, green energy and mixed renewable energy sources become fully entrenched as energy policies into the far future in several African countries. Links, websites, journals, conferences, webinars, videos and audio sources of information have been collated and preserved for easy retrivability. Reusability in this research was addressed under two auspices namely: reuseability of resource materials and reuseability of the documentation in the review paper all for future energy policies in underdeveloped economies. Reuseability of the resource materials is enabled by the achieved retrievability while reuseability of the research paper to guide the formulation of sustainable green energy policy across developing economies was facilitated through transparency in documentation. Repeatability herein was facilitated through the adaptable or adoptable nature of the multi-objective optimization energy mix model proposed at the tail-end of this review paper and fully developed and validated in an accompany energy mix optimization paper which technically is an extension and a continuum of this review paper. The adaptable nature of the proposed model entrenches the repeatability component of U4RIA. The term reconstructability was achieved in this research through the principle of systematic traceability for a possible enhancement. This was imbibed in the proposed multi-objective energy mix model. The model can be enhanced in all its sections via extension or reduction to meet a specific need. Interoperability was achieved through systems thinking. Diverse factors interlinked towards energy mix for sustainable power generation were identified from a holistic perspective and built into an integrated model that satisfies interoperability of multiple and diverse level of factors for effective energy policy. Auditability in this research is linked to every aspect of the research from conception to completion. The power generation planning, design, development, deployment, operations and discarding will be monitored by the community that formed part of the entire modeling process from scratch. As the world is transitioning to a sustainable power supply mix, accountability and potentially improved public acceptance (reasons behind U4RIA) as highlighted in this review are of great benefit if targets set at COP26 are to be achieved.

Researchers have conducted studies to forecast the demand and supply of electricity due to the significant increase in demand. The increased interest in power demand and supply forecasts is primarily due to the growing population and the incorporation of new and advanced technology. A few of these technologies revolve around the ever-increasing use of rechargeable and renewable domestic and industrial devices, the growing need for distributed electricity, growing numbers of electric vehicles, and smart metering system. A reliable and workable optimum electricity supply mix can evolve with a sound knowledge of today's electricity demand drivers.

Electricity planning is at the forefront of most research work conducted around the world with 1,250 publications in 2019 but studies carried in relation to the development of clean and affordable power sources mix are less than 300. This highlights the significance of achieving an equilibrium between electricity demand and supply for nations to meet their electricity supply obligations and mitigate GHG emissions.

The significant determinants for a more robust power generation system vary across different societies, from developing to developed economies. Developing economies have a 3% electricity demand growth rate fueled by income levels, industrial output, and service rendering [7]. On the other hand, developed economies have a modest electricity demand growth rate of 0.7%, which is

© University of Pretoria

driven by digitalization and electrification with a gradual migration towards a carbon-free electricity supply mix mostly made up of renewable energy sources [8]. Again, the electricity supply forecast is essential to policymakers, investors, and researchers because it can facilitate matching growing electricity demand with the available supply in the affected.

The studies that have systematically reviewed various studies on power generation mix in developing countries that are in line with SDG7 (affordable and clean energy) are hard to come by or unavailable in the existing literature. This paper examined the pros and cons of various power supply mixes for developing economies in a way to attain a reasonable assessment of how to overcome the complex problem of insufficient power supply while reducing GHG emissions. This was done by summarizing power supply mixes that are in line with SDG 7 in developing economies and the various energy modelling tools that have been used in coming up with these power supply mixes. Thus, this review will contribute to the realistic representation and the accurate planning for an affordable and clean power generation mix. Natural gas, coal, biomass, uranium, wind, solar, tidal, and other energy sources generate electricity. After being harnessed, these primary energy sources are frequently converted into heat energy (steam), which is then used to power a turbine connected to an electric generator to produce power. When it comes to wind, wind's kinetic energy is used to rotate the turbine, whereas hydro uses the kinetic energy of water. Solar photovoltaics converts sunlight into electricity using a solar photovoltaic collector. **Table 2.1** compares the power generation mix of Brazil, Argentina, Chile, Mexico, Nigeria, South Africa, Ghana, China, Egypt, Ethiopia, Cameroon, Malaysia, Pakistan, India, Kenya, Turkey, Thailand, and Iran for 2020. The developing countries chosen for this review were based upon the availability of literature on power generation mixes that are in line with Sustainable Development Goal (SDG) 7 that utilized different energy modelling tools.

Table 2.1: Power generation mix, 2020 [9-26]

Country	Solar (MW)	Hydro (MW)	Biomass (MW)	Nuclear (MW)	Wind (MW)	Thermal (MW)	Geothermal (MW)
Brazil	3,262	102,206	-	1,970	16,813	43,952	-
Argentina	2,501	10,812	-	1,755	402	24,549	-
Chile	5,194	7,280	438	-	3,720	12,773	39
Mexico	5,795	12,612	408	1,608	6,977	55,776	951
Nigeria	7	2,062	-	-	10	11,972	-
South Africa	2,323	3,485	-	1,920	2,323	48,380	-
Ghana	23	1,580	-	-	-	2,796	-
China	253,430	370,160	23,610	49,890	281,530	1,130,870	-
Egypt	190	2,832	-	-	967	51,424	-
Ethiopia	-	3,743	-	-	337	126	-
Cameroon	-	787	-	-	-	614	-
Malaysia	132	4,359	-	-	-	28,301	-
Pakistan	1,304	9,688	373	2,608	559	23,102	-

© University of Pretoria

Kenya	51	826	28	-	331	749	828
India	36,911	50,440	10,146	6,780	38,434	230,811	-
Turkey	8,776	31,531	408	2,041	11,123	46,430	1,735
Thailand	2,023	3,079	3,348	-	244	40,961	-
Iran	450	15,976	234	1,000	300	48,800	-

2.2 Renewable energy potential in developing economies

This section examines the enormous potential of RES such as solar, wind, hydro, distributed renewable energy systems, and bioenergy as well as evaluating them against the U4RIA criteria.

2.2.1 *Solar energy*

The energy generated by nuclear fusion within the sun is referred to as solar energy. The latitude and climate of a certain location on Earth have an impact on how much sun energy is received [27].

Nigeria receives 1.804×10^{15} kWh of incident solar energy yearly with 6.5 hours of sunlight per day based on a surface area of 924,103 km^2 and an average of 5.535 $kWh/m^2/day$ [28]. This study utilized the U4RIA criteria of retrievability in which data is easily accessible and auditability due to the peer review process undergone for transparency. According to Ghana's energy commission, there is a significant solar energy potential throughout the whole nation. With solar irradiation between 4 and 6 kWh/m^2, there is significant grid connection potential [29,30]. The data was collated through the involvement of energy experts both locally and internationally (Ubuntu), the data is easily accessed and critically reviewed (Retrievability and Auditability). Due to its tropical position, Malaysia has the highest chances of utilizing solar energy, according to P.D. Abd. Aziz et al. [31]. With an average daily solar irradiation of 4,500 $kWh/m^2/day$, Malaysia likewise has a naturally tropical climate. Ubuntu criteria of U4RIA was considered in the gathering of data and the study underwent peer review showcasing auditability. Turkey, which has a typical Mediterranean climate and is located between 36° and 42° N latitudes, has a considerable solar-energy potential, claim Kaygusuz and Sar [32]. The yearly radiation exposure is 2,610 hours with an average solar radiation intensity of 3.6 $kW\ h/m^2/day$. The number of solar radiation occurrences on a horizontal surface and the duration of the day are counted by several recording stations in Turkey. Results for India showed that the yearly exposure to solar radiation was between 1,200 and 2,300 kWh / m^2, with an incidence of 4 to 8 kWh / m^2 in a day. There are 250–300 sunny days and 2,300–3,200 hours of sunshine per year. On 3,000 km^2 of land, or 0.1% of India's total land area, the country's power needs may be met. This study involved the input of various energy stakeholders (Ubuntu), it is also easily accessible (Retrievability) and underwent rigorous peer review (Auditability) [33–35]. Bob et al. [36] investigated the potential of solar energy in Ethiopia, where irradiation levels ranged from 180 kWh/m^2 /month (in December) to 15.348 kWh/m^2 /month (in April) and from 207 kWh/m^2 /month (in February) to 25 kWh/m^2 /month (in April) (in May). According to the Laurea University of Applied Sciences [37], the average sun irradiation in Cameroon is 5.8 $kWh/m^2/day$. The U4RIA criteria of retrievability in which data is easily accessible and auditability due to the peer review process undergone for transparency were all considered in this study. As a developing nation, Mexico can generate vast amounts of power from solar energy. 70% of the nation receives more than 4.5 $kWh/m^2/day$ of insolation. Using photovoltaics that is 15%

© University of Pretoria

efficient, 0.01% of Mexico could generate all the country's power. The U4RIA criteria of retrievability and auditability were considered in this study due to data availability and transparency [38]. Thailand has a lot of solar potential, especially in the southern and northern parts of the province of Udon Thani's northeastern region and certain locations in the center. Around 14.3% of the country gets between 19 and 20 kWh/m^2/day of daily sun exposure, while the other half gets between 18 and 19 kWh/m^2/day. Thailand trails the United States in solar potential but surpasses Japan. This study is easily accessible (Retrievability) and transparent (Auditability) [39].

PV technology can be complemented by CSP. High temperature heat is delivered to a typical power cycle using concentrating collectors. In order to produce electricity in accordance with the demand profile, efficient and affordable thermal energy storage technologies may be added into CSP systems. Additionally, CSP systems can minimize the requirement for "shadow plant capacity," which is necessary to ensure the ability to generate power during periods of low sunlight or wind, as well as offer grid services and, if wanted, black start capabilities. In order to avoid a significant share of expensive electric storage technology in the grid systems, it encourages the penetration of a high percentage of intermittent renewable sources, such as wind or solar power. It wasn't until 2007 that CSP technology began to be widely used commercially, mostly in Spain and the US. Nearly 6 GW of capacity is now in use, and 1.5 GW more are being built globally. Recently, markets have begun to develop, particularly in the Middle East and North Africa, but also in South Africa, India, and China [40].

2.2.2 *Hydropower*

Hydropower potential exists in almost all developing and underdeveloped countries. This section examines the hydropower potential of a few emerging countries, focusing on Nigeria, South Africa, Kenya, Argentina, Ethiopia, Turkey, Cameroon, and Mexico.

Nigeria has many rivers, waterfalls, and dams, making hydropower the country's main source of electricity production. The total hydroelectric capacity of Nigeria is thought to be around 14,750 MW. Only 1,930 MW have been used up to this point. This study involved the input of various energy stakeholders (Ubuntu), it is also easily accessible (retrievability) and underwent rigorous peer review (auditability) [41].Despite being currently underutilized, Cameroon's entire hydro potential is now estimated to be 23 GW, with a production capacity of 103 TWh per year. This study utilized the U4RIA criteria of retrievability in which data is easily accessible and auditability due to the peer review process undergone for transparency [42]. Turkey's gross annual hydro potential, which makes up more than 1% of the total worldwide, is 433,000 GWh. This data is readily available and easily accessible (Retrievability) [43]. The National Commission for the Efficient Use of Energy (CONAE) has already identified over 100 excellent locations, even though Mexico's true potential for this energy generation has not yet been determined. For instance, Veracruz and Puebla states are anticipated to produce 3,570 GWh annually, which is equal to an average installed capacity of 400 MW. This study is easily accessible (Retrievability) and transparent (auditability) [44]. In comparison to other countries, South Africa has a low average annual rainfall of 500 mm. This, the seasonal flow of the nation's rivers, and extreme droughts or floods all have an impact on how much hydropower can be generated. The eastern escarpment, which has between 6,000 and 8,000 feasible sites, is where most of the country's hydroelectric potential is concentrated. 8,360 MW of hydropower are available in South Africa. Ubuntu, Retrievability and, Auditability are the U4RIA criteria considered in this country [45]. With

© University of Pretoria

a theoretically feasible capacity of 130,000GWh, only around 23% of Argentina's theoretical total hydropower potential (354,000GWh, 40,400MW) has been utilized. About 9,780MW of the total generating capacity is now deployed (41% of the total capacity). The data was collated through the involvement of energy experts both locally and internationally (Ubuntu), the data is easily accessed and critically reviewed (Retrievability and Auditability) [46]. Ethiopia has a huge hydropower potential with an about 45,000 MW capacity [47]. Retrievability and Auditability are imbibed in this study [48]. About 6,000 MW of electricity are anticipated to be produced by Kenya's hydropower potential, which includes small-scale hydro facilities with a total capacity of more than 3,000 MW. This study is easily accessible (Retrievability) and transparent (auditability) [49].

Many African nations rely largely on hydropower, but during the past few decades, the frequency of droughts has had a significant impact on hydropower output. Installing floating photovoltaics (FPV) in existing hydropower reservoirs will assist offset hydropower output during dry spells, minimize evaporation losses, and sustainably meet the present and future energy demands of the rapidly expanding African population. The installed power capacity of current hydropower facilities may be doubled, and energy output can increase by 58%, producing an additional 46.04 TWh annually, as achieved, with less than 1% complete coverage. In this instance, the water savings might amount to 743 million m3/year, resulting in an increase of 170.64 GWh in the annual hydroelectricity output. The data was compiled with the help of energy specialists from both domestic and foreign sources (Ubuntu), and it is simple to access and evaluate (retrievability and auditability) [50].

2.2.3 *Bioenergy*

Photosynthesis produces biomass, which is a kind of indirect solar energy. The most common biomass energy source is fuelwood. This section will assess the potential of bioenergy in underdeveloped and developing countries, focusing on Nigeria, Mexico, Turkey, South Africa, Egypt, Cameroon, and Ghana.

Nigeria's biomass resources are believed to be 8,102 MJ, according to Garba and Bashir [51]. In autonomous businesses, plant biomass may be used as a fuel source. Anaerobic bacteria might also mature it, producing highly flexible biogas at a low cost. Mexico has a potential for bioenergy that ranges from 2,635 to 3,771 PJ annually. This study involved the input of various energy stakeholders (Ubuntu), it is also easily accessible (retrievability) and underwent rigorous peer review (auditability) [52]. Turkey's yearly biomass potential is 32 million tons of oil equivalent (mtoe). Turkey has a 32 million tons of oil equivalent annual biomass potential (mtoe). There is a total of 16.92 million tons of oil equivalent in recoverable bioenergy (Mtoe). Ubuntu, Retrievability and, Auditability are the U4RIA criteria considered in this study [53]. In South Africa, contemporary and household trash may generate around 11.000 GWh of electricity each year. This study utilized the U4RIA criteria of retrievability in which data is easily accessible and auditability due to the peer review process undergone for transparency [54]. Khalil [55] focused on how Egypt produces over 60 million tons of oil-equivalent annually, mostly from urban garbage, fuel crops, and agricultural products including sugar cane, rice, maize, and wheat, which can be utilized to generate electricity. The primary sources of Cameroon's biomass potential are agriculture and forestry. 66 locations added 2.7 million m^3 of transformation capacity in 2006. The data was collated through the involvement of energy experts both locally and internationally (Ubuntu), the data is easily accessed and critically reviewed (Retrievability and Auditability) [56]. The accumulation of wood will rise to more than 2.5 million tons by 2020 and to

© University of Pretoria

about 3 million tons by 2025 as a result of Ghana's expanding horticulture industry. Alone, the waste from ranches, forestry operations, and sawmills could generate 95 MW of power, enough to handle 600 GWh annually. Ubuntu criteria of U4RIA was considered in the gathering of data and the study underwent peer review showcasing auditability [57].

2.2.4 *Wind energy*

The wind is natural when the earth's surface warms up unevenly. The wind's kinetic energy provides lift, which causes the blade of a turbine to spin. Blades coupled to a driving shaft rotate the electric generator, generating power. Wind power output has expanded significantly over the last 30 years, and governments are giving incentives to encourage the use of wind for power generation. This section will look at the wind potential of developing and underdeveloped nations focusing on Nigeria, Mexico, South Africa, Kenya, Ethiopia, Turkey, India, and Argentina.

Similar to South Africa, wind speeds in Nigeria range from 4.0 to 5.12 m/s in the extreme north to 1.4 to 3.0 m/s in the south. In most coastal locations, wind speeds range between 4.0 and 5.0 m/s, although they may exceed 8.0 m/s in hilly places. Ubuntu criteria of U4RIA was considered in the gathering of data and the study underwent peer review showcasing auditability [58–61]. Mexico has a 71,000 MW [62] wind energy potential, however only 1.7% of that capacity is now being used. This study is easily accessible (Retrievability) and transparent (auditability). There are 500 to 2,000 MW of wind energy in Malaysia. The data was collated through the involvement of energy experts both locally and internationally (Ubuntu), the data is easily accessed and critically reviewed (Retrievability and Auditability) [63]. Around Lake Turkana and the Ngong Hills, Kenya offers wind resource potential that might be used to produce power. In the northwest of Kenya, the average wind speed is around 9 m/s at 50 m, but it is about 5-7 m/s at 50 m closer to the shore. This study utilized the U4RIA criteria of retrievability in which data is easily accessible and auditability due to the peer review process undergone for transparency [64]. Ethiopia's overall wind energy potential is more than 10,000 MW, claim Gaddadal and Kodicherla [65]. The U4RIA criteria of retrievability in which data is easily accessible and auditability due to the peer review process undergone for transparency were all considered in this study. The coast of South Africa has strong wind potential overall, with typical wind speeds of 4 to 5 m/s at 10 m altitude and 8 m/s in certain hilly areas. This study is easily accessible (Retrievability) and transparent (auditability) [66]. According to estimates, South Africa has a wind potential of 500 to 56,000 MW. Ubuntu, Retrievability and, Auditability are the U4RIA criteria considered in this country [67]. Turkey has an estimated 48,000 MW of wind energy capacity. However, there are only 7,012.75 MW of installed electricity capacity in the entire nation. This study utilized the U4RIA criteria of retrievability in which data is easily accessible and auditability due to the peer review process undergone for transparency [68]. The Centre for Wind Energy Technology (C-WET) first pegged India's entire wind power capacity at about 45 GW; however, it recently increased that figure to 48.5 GW. This number is now considered to be the official estimate by the administration. Ubuntu, Retrievability and, Auditability are the U4RIA criteria considered in this study [69]. Furthermore, despite Argentina having a 2.5 TW projected offshore wind potential, no offshore wind turbines have yet been built. This study is easily accessible (Retrievability) and transparent (auditability) [70].

2.2.5 *Geothermal energy*

© University of Pretoria

The Greek words "geo" (for earth) and "thermos" combine to get the word "geothermal" (heat). Geothermal energy is produced by the radioactive disintegration of minerals in the Earth's core, which results in the generation of radiant heat (alpha, beta, and gamma). This section examines the geothermal potential of several underdeveloped and developing countries, focusing on Mexico, Turkey, Ethiopia, Kenya, Cameroon, Argentina, and China.

According to recent estimations, Mexico's geothermal power potential ranges from 2,310 MW to 5,250 MW [71]. Turkey has significant geothermal potential, contributing to one-eighth of the global total. Turkey has a total geothermal potential of 38,000 megawatts (MW) (electric and thermal) [72]. Ethiopia is one of Africa's geothermal energy potential nations, with 5,000 megawatts (MW) [73]. By 2018, Kenya has 653 MW of installed geothermal capacity, and further projects are being planned to enhance its proportion of the power generating mix [74]. The potential for geothermal energy in Cameroon has yet to be fulfilled. There are hot water locations. However, there have been no feasibility studies. To assess their genuine potential, tests have been carried out. They claim that the report on Cameroon is inaccurate [75]. According to Laura et al. [76], Argentina's geothermal potential is 490-2010 MWe. However, this resource is now only used for direct purposes, such as balneology (52.7%), household usage (24.6%), home heating (4.6%), greenhouses (4.5%), aquaculture (1.5%), industrial applications (6.7%), and snowmelt (5.4%). Hui et al[77] .'s analysis revealed that China has considerable geothermal resources, making up around 8% of the world's geothermal energy reserves [78].

2.2.6 *Distributed renewable energy systems*

The use of distributed energy resource (DER) projects is expanding in industrialized nations, particularly in Europe. This has made it possible to reduce CO2 emissions, utilize fewer primary energy sources (PES), and employ more renewable technologies [79]. However, low levels of economic growth and poor indices of human development are characteristics of undeveloped nations (HDI). Low income, unstable economic and governmental situations, historical barriers to technology transfer, high costs of technical innovation, and a lack of effective environmental and technological policies are the causes of these issues [80]. Nevertheless, recent decades of industrial development and educational advancements have sparked changes in several economic sectors, including the adoption of new laws and policies governing the energy markets [81]. The adoption of technology that might lessen environmental effect and promote social and economic growth in local communities has been encouraged by these changes [82]. As a result, the application of mathematical modeling tools has been provided, taking into consideration the unique characteristics of developing nations, for detecting trends, impediments, problems, possibilities, and benefits in the startup of distributed energy resources [83]. The greatest obstacle to expanding the contribution of renewable resources to energy generation in developing nations is the economic situation [84]. Therefore, employing more efficient technology is a means of encouraging the implementation of distributed energy systems as opposed to centralized ones. Based on unique criteria and the relative low reliance and operability with regard to the technologies that use fossil fuels and biofuels, there is a significant preference for renewable sources employed as the core of energy systems, especially in off-grid systems. Renewable energy use has grown in developing nations; for example, India has seen a 20% growth in generation from renewable sources. Brazil has created major economic mechanisms to promote the use of renewable energy sources in the energy sector's technological transformation [85]. However, the reliance on environmental factors forces the employment of conventional technologies as a fallback and the

© University of Pretoria

incorporation of new technologies as storage units. As a result, capital costs rise and lead to a dependency on subsidies and outside strategies. Around 15% of the world's population lacks access to energy facilities, the World Bank reports. This group is primarily found in rural, low-income areas of emerging nations [86]. Therefore, it is crucial to take into account a variety of technical options when defining the design and configuration of the system rather of focusing on a single energy source and taking the availability of nearby energy resources into account. In this view, hybrid systems are viable substitutes for enhancing the systems' economic performance and quality of energy, notwithstanding the complexity involved in modeling and operating the units. Determining taxes and rates, however, is a significant issue. Despite the potential dual involvement of consumers and producers in the creation of DG projects, the primary actors in the deployment of DG systems at this time are external carriers, the government, and private companies. Therefore, a pressing problem for developing technologies is the establishment of appropriate tariff and pricing regulations for local manufacturing considering the needs of the end user [87]. The economic benefit for the end users must also be considered as a specific concern in this examination. Due to the establishment of a micro-grid and the existence of several linked players, this problem becomes more difficult.

2.3 Power supply mix for developing economies

Even among industry experts and veterans, the terms "renewable power supply" and "sustainable power supply" are frequently interchanged. Many sustainable energy sources are also renewable, so there is some overlap between the two. These two terms, however, are not synonymous.
Renewable energy sources replenish themselves at a pace that enables us to meet our power needs. The sustainable power supply is from sources that can meet our current power needs without putting future generations at risk [88].

Energy efficiency (EE) is frequently promoted as a way to conserve both money and energy. By shifting the emphasis from saving to purchasing more goods and services, emerging nations will be able to expand more quickly while simultaneously fostering a more sustainable future for everybody. To support this development, developing nations are attempting to obtain more energy. The developing world's predicted increase in energy consumption spans South Africa, Indonesia, India, and South America. Between 2015 and 2030, it is anticipated that the overall energy consumption of emerging nations would increase by around 30%, nearly double that of industrialized nations. Developing nations' reliance on rising energy consumption to fuel economic growth (as opposed to mature economies, where energy demand has often already peaked) is somewhat a reflection of their stage of development. The argument that developing nations have more urgent objectives, such as the eradication of poverty, access to essential services, economic development, severe inequality, and public safety, is sometimes used to explain why these nations lack ambition in the area of energy efficiency [89].

IEAs analysis [90] predicted that electricity demand would increase faster in the long run than any other energy source. Electricity is expected to supersede oil products as the principal ultimate energy carrier in the IEAs main scenario. Electricity has many advantages, including being generated exclusively by sustainable sources and emitting no carbon at the point of use. It is the most adaptable, effective, and controllable source of energy. This makes it likely that the transition to a clean energy economy would need a renewable power system with a diverse range of renewable energy sources. At

© University of Pretoria

the same time, the growing need to increase power accessibility, combat climate change, and the local environment and health consequences of power generation emissions necessitate changing an energy system's environmental footprint. These ongoing worries have encouraged several policymakers and academics to develop tsustainable power source mix for developing nations. This study summarized the pros and cons of each power source mix and compared them with the U4RIA criteria as shown in **Table 2.2**. The countries shown in **Table 2.2** were selected based on the rigorous evaluation of available literature on power generation mixes that are in line with Sustainable Development Goal (SDG) 7, (affordable and clean energy) spanning from 2014-2021.

Table 1.2: Overview of studies on sustainable power supply mix

Country	Objective of study	Significant findings of the study	Pros	Cons	U4RIA criteria employed	References
Brazil	To assess the environmental impact of hydropower generation in Brazil.	The most significant contributor to air emissions from power generation is carbon dioxide.	1. Lower pollution levels, as measured by carbon footprints. 2. Cleaner and healthier environment .	1. Aside from hydro and bioenergy, other renewable energy sources appear to be non-existent due to a lack of funding.	- Retrievability - Reusability - Reconstructability - Auditability	[91]
	Five scenarios for the Brazilian power industry until 2050 were developed and evaluated.	Scenarios with a more significant proportion of fossil fuels are the least desired, whereas wind and biomass-based scenarios are the ideal alternatives through 2050.	1. Positive impact on the environment. 2. Job creation	1. Policy constraint.	- Retrievability - Reconstructability - Auditability	[92]
	The study examined emissions in the Brazilian power production industry.	According to Brazilian power generation estimates, CO2eq and NOx emissions per MWh are growing.	1. Negative environmental impact. 2. The electricity mix is affordable in terms of emissions.	1. Large hydropower plants are not considered sustainable. 2. Electricity supply is dependent on rainfall. 3. Lack of energy efficiency and	- Ubuntu - Retrievability - Reusability - Auditability	[93]

© University of Pretoria

				conservation guidelines.		
Argentina	To investigate the complementary functioning of a hydro station and wind farm.	The Hydro Power Plant (HPP) may be coupled with the new Wind Farm (WF) to reduce future active power leakage.	1. Energy security. 2. Reduction in carbon emissions.	1. Financially challenging.	• Ubuntu • Retrievability • Reusability • Auditability	[94]
	Energy conversion towards cleaner and explicit systems was investigated, and energy data for hydrogen storage of changeable renewable energy.	Fossil fuels should be phased out in favor of a system that can store vast amounts of power and fuels.	1. Hydrogen for sea transportation can be feasible	1. Transition to renewables is slow.	• Ubuntu • Retrievability • Reusability • Auditability	[95]
Chile	Employment of bioenergy for electricity generation was studied.	Biomass and biogas are typically employed for small capacity power generation, with biofuel used for transportation.	1. Saves the environment. 2. Employment opportunities.	1. Unavailability of skilled workforce.	• Retrievability • Reusability • Auditability	[96]
	A complete assessment of Chile's electrical generation's environmental sustainability across its entire life cycle.	For six effects, it was 13%, 98% better than solar PV, and for four categories, it was 17%, 66% better than wind.	1. Hydropower provides a cleaner and healthier environment, followed by wind and biogas.	1. To reduce human toxicity, global warming, and ecotoxicities, fossil fuels must be phased out of the current power supply mix.	• Ubuntu • Retrievability • Reusability • Interoperability • Auditability	[97]

© University of Pretoria

	The environmental influence of electricity generated from solar energy was investigated.	PV systems will still contribute their quota to environmental degradation up until 2050, according to the findings.	1. Environment friendly.	1. Until 2050, solar panels will have a substantial environmental impact.	• Reusability • Reconstructability • Auditability	[98]
Mexico	The research investigated the present state of electricity generation in Mexico, with the social and environmental issues.	Renewable energy has great potential for power generation, but a lot still needs to be done by the government to ensure its integration target of 35% by 2025.	1. Renewable energy systems (RES) have the potential to address. environmental and social issues. 2. Job creation.	1. There is a cultural impact in places where RES are deployed. 2. Because most technology is imported, there is a lack of long-term development.	• Retrievability • Reusability • Auditability	[99]
	This study generates and evaluates scenarios for achieving 75 percent integration of renewables to have a 100 percent renewable power system.	To transition to a 100% renewable power supply system by 2050, electricity demand must be drastically reduced.	1. The full potential of renewable energy can be realized. As a result, the harmful effects of fossil fuels will be eliminated.	—	• Retrievability • Reusability • Reconstructability • Interoperability • Auditability	[100]
	A sustainability impact assessment for electricity generation for solar thermal technology using the “Framework for Integrated Sustainability Evaluation”	The findings highlight that solar thermal electricity plants (STE) plants will stimulate the economy and decarbonize the electricity supply mix, which will lead to a massive reduction of fossil fuels’ effect on the environment.	1. The power suppl y mix will help to boost the economy and create jobs.	1. Social effects.	• Retrievability • Reusability • Reconstructability • Auditability	[101]

© University of Pretoria

	was performed.					
Nigeria	Review of developments in the utilization of concentrated solar power (CSP) and other solar energy technologies.	The parabolic CSP is the cheapest with minor water usage. Still, it requires an adequate feasible application when minors to price per unit of energy and water utilization capacity.	1. Less land requirement. 2. Technical maturity.	1. High capital cost. 2. Water consumption is high.	• Retrievability • Reusability • Auditability	[102]
	A thorough examination of Nigeria's readiness to clean and modern energy was conducted.	In Nigeria, decentralized energy systems have been found to have significant advantages over traditional power generation. This holds in various areas, such as the environment, economics, efficiency, security, and dependability.	1. Environmentally friendly, efficient, cost-effective, secure, and dependable.	1. The scale of decentralized electricity projects is minimal. 2. Only decentralized energy systems that involve users in planning, development, building, operation, and maintenance are long-term viable. 3. The federal government cannot provide the necessary funding.	• Ubuntu • Retrievability • Reusability • Reconstructability • Auditability	[103]
	The paper looks at how a sustainable power supply system will evolve until 2050.	The findings show that integrating renewables with various energy storage technologies will be a competitive alternative.	1. In the medium term, incorporating RE into the existing power supply mix is the most cost-effective solution.	1. It is necessary to have a policy that is both steady and supportive.	• Ubuntu • Retrievability • Reusability • Auditability	[104]

© University of Pretoria

			2. Local and international investors will find it quite appealing.			
South Africa	The study evaluated different renewable energy technologies (RETs).	According to the findings, solar PV and wind were preferred over CSP.	1. RE sources further enhance South Africa's social and environmental benefits.	1. Inadequate knowledge and maintenance abilities 2. Site suitability.	• Ubuntu • Retrievability • Reusability • Reconstructability • Auditability	[105]
	This study proposes an IEEM for South Africa that combines demand-side and supply-side management (DSM).	The study improves traditional grid expansion planning by providing practical policy advice on using IEEM to reduce related network losses, increase local energy resource use, and reduce construction and plant running costs.	1. Beyond normal demand growth development and generation capacity estimation, conventional generation expansion planning (GEP) is advanced.	1. Including industrial and commercial users in the analysis of flexible industrial loads (HVAC), revenue generation, and energy cost reduction is critical. 2. The significance of social institutional processes in promoting a wise and equitable power growth has not been taken into account.	• Retrievability • Reusability • Auditability	[106]
Ghana	The report examines Ghana's Renewable Energy Act's regulatory	The performance of Ghana's renewable energy strategy on-grid-linked power has been determined to be inadequate compared to	1. Will address environmental and social issues.	1. Slow in addressing the rising power demand. 2. Rules are	• Ubuntu • Retrievability • Reusability • Reconstructability • Auditability	[107]

© University of Pretoria

	structure, funding incentives, and other elements.	its aim.		partially implemented. 3. Network grid is poor. 4. Financing is difficult to obtain. 5. Disparities in renewable energy policies.		
	This paper examines the Renewable Energy Act and the regulatory structure.	The policy's performance on grid-connected electricity was judged to be below target.	1. RE to be exploited to meet the growing electricity demand. 2. Great for GHG reduction and ensuring sustainable development.	1. Non-implementation of policies.	• Ubuntu • Retrievability • Reusability • Reconstructability • Auditability	[108]
	Building Ghana’s power system model using OSeMOSYS and OnSSET, we termed it "business as usual" (BAU).	BAU might be a realistic alternative for lowering fossil fuel usage and CO2 emissions, but it comes with the risk of an unstable electricity supply.	1. Good for the environment.	______	• Retrievability • Reusability • Auditability	[109]
Egypt	This study evaluates Egypt's energy policy and identifies the potential to fulfill rising electricity demand.	A balance of renewable and conventional energy sources is essential, the model's quantitative results suggest.	1. Improves energy security. 2. Reduction in emissions. 3. Reduction in reliance on fossil fuels.	1. Cost constraint.	• Ubuntu • Reusability • Reconstructability • Auditability	[110]
	To shed light on utilizing Egypt's enormous	Gasification for ammonia and diesel fuel production is the preferred energy	1. Reduces carbon dioxide emissions.	1. No policy 2. Unavailability of incentives	• Retrievability • Reusability • Auditability	[111]

© University of Pretoria

	agricultural residual resources optimally and identifying enablers for promoting long-term biomass energy generation.	generation pathway for the implementation horizons. Even though no targets for biomass energy have been specified in Egypt's RE generation targets for 2022, a target proportion of 3% should be set for biomass energy.	2. It is possible to create fertilizer and diesel fuel.			
	To predict the evolution of Egypt's electricity industry through 2040 is assessed in terms of its economic and environmental effects.	Egypt's projected renewable penetration objective is primarily met by wind power technology. It may be an alternative to balance the country's vast renewable resource endowments.	1. Wind, PV, and combined cycle are suitable technologies used in Egypt's power generation mix.	1. Change in carbon emissions is moderate.	- Ubuntu - Retrievability - Reusability - Auditability	[112]
Cameroon	The electricity challenges in Cameroon and the potential and practical contributions of renewables to energy difficulties were studied.	Cameroon will achieve future power objectives and ensure considerable growth in the country with appropriate laws, guidelines, policies, information, capacity building, and off-grid RE investment projects.	1. Solves the problem of insufficient power supply. 2. Energy security. 3. Addresses environmental and health challenges.	1. Depends on rainfall. 2. Inadequate financing. 3. Non-availability of funding.	- Ubuntu - Retrievability - Auditability	[113]
	Decentralized PV/wind/diesel hybrid power generating long-term system viability and techno-economic feasibility.	A standard diesel-producing system was hybridized to improve reliability and cost-effectiveness.	1. Achieving a sustainable power supply system. 2. Reduction of emissions. 3. Reduction of costs.	_____________ _	- Ubuntu - Retrievability - Reusability - Reconstructability - Interoperability - Auditability	[114]
	The potential of geothermal energy for power	There is unexplored geothermal potential in Cameroon. Consequently, renewable	1. Energy security 2. Power supply sustainability.	1. No enthusiasm from the government	- Ubuntu - Retrievability - Reusability - Auditability	[115]

© University of Pretoria

	generation in the Cameroon Volcanic Line is assessed by geological research.	energy may reduce energy consumption, particularly in rural regions.		to exploit the vast geothermal potential of Cameroon.		
Malaysia	This paper suggests policy and industry roadmaps for the long-term viability of Malaysia's grid-connected oil palm biomass renewable energy sector.	According to the paper, synchronizing upstream and downstream palm oil agricultural activities is required to make the waste to energy industry viable.	1. Job creation in the agricultural sector. 2. Saving the environment.	1. Translating an excellent idea into reality.	• Ubuntu • Retrievability • Auditability	[116]
	This article examines Malaysia's long-term power generating alternatives using the integrated MARKAL-EFOM system (TIMES) model.	According to the report, big hydropower and other indigenous sustainable energy sources can completely replace fossil fuels by 2050.	1. Diversification of the energy mix. 2. Improvement of the economy and wellbeing of the population. 3. A 100% sustainable power generation by 2050. 4. No need to embrace nuclear energy technology.	____________ _	• Ubuntu • Retrievability • Auditability	[117]
Pakistan	To make long-term electrical supply suggestions to close the demand-supply gap.	The study said that energy efficiency and conservation initiatives would help Pakistan close the supply-demand imbalance and finally balance its energy mix for power generation.	1. Will solve the problem of insufficient power supply. 2. Ensuring energy security. 3. Combatting climate change.	1. Financial constraint. 2. Lack of commitment from policymakers. 3. Need for energy efficiency	• Retrievability • Auditability	[118]

© University of Pretoria

				and conservation measures.		
	This study aimed to see if chicken manure could be used to generate electricity in Pakistan.	Biogas from chicken manure may be used to generate power, and it is both practical and ecologically sound.	1. Saving the environment.	1. Unavailability of infrastructure.	• Retrievability • Reusability • Reconstructability • Auditability	[119]
	Wind energy is being harnessed for a long-term power source.	Wind energy has the potential to be Pakistan's answer to the country's energy problems.	1. Energy security. 2. Economical 3. Environment friendly. 4. Conservation of conventional energy resources.	1. Financial constraint. 2. Suitable site location. 3. Low-frequency noise. 4. Poor wind output.	• Retrievability • Reusability • Auditability	[120]
India	Examine multiple power demand scenarios for 2015 through 2030, based on publicly accessible data and trends.	Both scenarios highlight the importance of fossils, renewables, and nuclear generation. For such a situation, both energy and environmental policies should be developed.	1. Reduction of high carbon emissions.	1. High cost of maintenance.	• Ubuntu • Retrievability • Reusability • Auditability	[121]
	An hourly resolved model is used to predict a 100% renewable energy transition pathway for India until 2050.	According to the findings, a decarbonized power system will be achieved by 2050.	1. Cost savings. 2. Net zero-emission option. 3. Competitive.	1. Disposal of nuclear waste. 2. Health risks. 3. Constraint of funds for research and development.	• Retrievability • Reusability • Interoperability • Auditability	[122]
	An in-depth look at India's solar energy potential, current	Various devices can be powered by solar energy, with coal plants providing 70% electricity.	1. Emissions reduction.	1. Lack of knowledge of renewable energy	• Ubuntu • Retrievability • Auditability	[123]

© University of Pretoria

	development status, and future possibilities.			technologies. 2. Market barrier. 3. Policy barrier.		
Iran	The study examines Iran's bio-power generating capability.	The report estimates Iran's annual bio-power potential at 62,808,106 kWh or 27% of total energy consumption. Bio-based power generation reduces CO_2 emissions by 4,096 kt/yr or 0.6 % of Iran's annual GHG emissions.	1. Practical way of recycling biowaste. 2. Potentials of GHG emissions reduction.	1. Animal waste management challenge.	- Ubuntu - Retrievability - Reusability - Reconstructability - Interoperability - Auditability	[124]
	From 2015 to 2050, the report presents a power planning method for evaluating the long-term feasibility of future energy scenarios.	The results suggest that the most significant scenario is Cl 32, in which non-hydro renewable energy contributes 32% of total power output.	1. Reduction in GHG emissions.	1. Policy barrier.	- Auditability	[125]
Turkey	The effects of nuclear and renewable energy on Turkey's economic development will be examined.	Turkey's dependency on energy generation would be considerably reduced if nuclear power were produced. As a result, renewable and nonrenewable energy sources and nuclear energy must be employed to keep Turkey's development and power consumption in check.	1. Will solve the problem of growing electricity demand. 2. Energy security.	1. Turkey is an earthquake zone, which might be disastrous if a nuclear disaster occurs.	- Ubuntu - Retrievability - Auditability	[126]
	To make sustainable energy decisions, energy generation systems must	Solar PV and wind power, for example, have high ratings and are increasing their generation share. From a sustainability aspect, renewable energy	1. Good for the environment. 2. Energy security.	1. Coal is still the primary energy source.	- Retrievability - Reusability - Auditability	[127]

© University of Pretoria

	be compared. Consequently, Turkey's primary seven power-producing methods were given an output score.	sources should be utilized entirely.				
Thailand	This paper investigates the viability of boosting sun photovoltaic (PV) energy in current diesel-based power production systems.	The optimal scenario would reduce COE to $0.374/kWh, CO2 (796.61 tons/yr), and other gas emissions (21.47 tons/yr).	1. Reduction of electricity cost. 2. Reduced emissions 3. Reduction in fuel consumption.	1. Increase in capital cost of the system.	• Ubuntu • Retrievability • Reusability • Auditability	[128]
	This research looked into the advantages of community renewable energy (CRE) programs supported by Thailand's Ministry of Energy.	CRE initiatives may assist communities in various ways, including coexisting with human agricultural operations and forest conservation.	1. Environmental protection. 2. Contribution to the sustainable development of communities.	1. Policy constraint.	• Ubuntu • Retrievability • Reusability • Reconstructability • Auditability	[129]
Mexico	Investigate an alternate scenario for a Mexican Low Carbon Electric Power System from an environmental and economic angle.	By 2020, GHG emissions would have decreased by 33%, and by 2035, they would have reduced by 79%.	1. Positive about the environment. 2. Good for the economy.	1. Cost constraint. 2. Policy barrier.	• Ubuntu • Retrievability • Auditability	[130]
	The temporal energy	Mexico has various areas with high energetic	1. Sustainable power supply.	1. Policy constraint.	• Ubuntu • Retrievability	[131]

© University of Pretoria

	complementarity of solar and wind energy is illustrated in Mexico.	complementarity, some presently being used. However, according to the research, there are still places in the country's center, and north that have not been explored and where renewable energy generating systems may be created.	2. Positive about the environment.		• Reusability • Interoperability • Auditability	

2.4 Power generation models

Developing and analyzing computer models of power systems is known as power generation modelling. In these models, scenario analysis is widely applied. The system under consideration's viability, greenhouse gas emissions, total cost of ownership, resource use, and energy efficiency might all be outputs. There are many different strategies applied, from generally economic to broadly engineering [132]. Power generation models are instruments for analyzing energy policy and making medium- and long-term plans, according to the literature. They aid in establishing how energy technologies' technical and economic components interact and how choosing a particular technology affects energy security, accessibility, cost, and the environment.

The significance of power modeling has grown along with the urgency of addressing climate change. The largest contributor to global greenhouse gas emissions is the energy supply sector [133]. The IPCC asserts that combating climate change would need a thorough overhaul of the energy system, including the substitution of unrestricted (non-CCS) fossil fuel production methods with low-GHG substitutes [134]. In models, mathematical optimization is widely employed to handle redundant system requirements. Operations research is the foundation for several of the methodologies. While nonlinear programming is sometimes used, linear programming is the most common (including mixed-integer programming). The strategies used by solvers might be conventional or genetic. Recursive-dynamic models have the potential to solve each time interval in turn while evolving over time. Additionally, hourly transient responses are necessary for models to fully reflect the real-time dynamics of renewable energy and energy demand management as their importance rises.

In order to create pathways for the energy transition, particularly their ambitious decarbonization, policymakers and academics may simulate and assess energy systems using a variety of computer tools that cover a wide geographic range from towns to countries. Given that these models typically differ greatly from one another, these decision-makers and academics must select the most suitable power system modeling tool depending on the goal and particular objectives of their investigation [135]. **Table 2.3** summarizes modelling tools, such as TIMES, EnergyPLAN, NECAL2050, LEAP, SWITCH, GAMS, Network Planner, ARDL, PLEXOS, GAMS, and MATLAB & MOSE were used for countries covered by this review. We came up with the modelling tools in **Table 2.3** from the studies that were reviewed on power generation mixes that employed the models in **Table 2.2**.

© University of Pretoria

The significance of power system modelling for energy planning cannot be overstated. This has prompted policymakers and academics to use various energy modelling tools to determine the best power generation mix for Nigeria, South Africa, Ghana, Kenya, Ethiopia, Egypt, China, and India. As a result, **Table 2.4** provides an overview of modelling tools used by some underdeveloped and developing countries, including the application, the model used, study description, strengths and weaknesses of the models, and relevant references of each publication. The frequency of use of models in **Fig. 2.1** is the number of studies from the total number of studies reviewed that employed each model. At 28% of policymakers and researchers adopting it, the LEAP model is the most used, followed by TIMES, GAMS, and SWITCH with 11% each. PLEXOS follows them, Network Planner, ARDL at 6%, MATLAB & MOSE, Network Planner, Portfolio approach, NECAL2050, and EnergyPLAN at 5%.

Table 2.3: Summary of power modelling software [135-152]

Name	Type (open source or Propriety licenses)	Developer	About	Uses	Shortcoming
The TIMES energy model	Free and open-source software.	IEA’s (ETSAP)	TIMES utilizes a bottom-up multi-period optimization model for the most cost-effective energy system.	To assess a country's energy system includes primary energy supply, secondary energy conversion, energy service needs across multiple end-use industries, and the associated infrastructure and technology.	Low resolution.
The EnergyPLAN simulation program.	Freeware	Aalborg University's Sustainable Energy Planning Research Group	It is designed to examine energy systems using various technical and economic methodologies.	It's utilized for RE integration, studying combined heat and power (CHP) production, market exchange analysis, technical analysis, and feasibility assessments, among other things.	Not efficient when modelling non-future energy systems.
Nigerian Energy Calculator 2050-NECAL2050.	Open-source	UK-DECC and Nigerian Energy Commission (ECN).	NECAL2050 uses an accounting system to match supply and demand continually. It combines a mix of present and future technologies to fulfill shifting demand.	Evaluating various low-carbon scenarios' energy balance and GHG reduction potential.	Lacks the capability to be utilized for modelling of different countries or regions.
LEAP model	Free use for academic purposes.	Stockholm Environment Institute.	It's a tool for assessing energy strategy and reducing	It generates different scenarios for projected energy usage and	Absence of optimization capabilities.

© University of Pretoria

			climate change.	environmental effect depending on residential or industrial unit counts.	
MATLAB & MOSEK	The free version is available for students.	Cleve Moler	The energy system model is a linear optimization tool.	The optimal investment and generating technology combination to fulfill demand.	Open-source available for students only.
PLEXOS	Commercially available.	Energy Exemplar	A modelling tool for the electricity, gas, and water market.	Iterative planning procedures for lower costs and higher returns.	Functions on a static database and doesn't allow the inclusion of new generators.
SWITCH model	Commercial	Fripp, Johnston & Maluenda	An aggressive expansion model focuses on new generation and transmission assets and end-use and demand-side planning and management to explore system performance under different scenarios.	Examines the most cost-effective energy systems that fulfill particular reliability, performance, and environmental quality requirements.	Versatility is low.
Portfolio approach.	Free	US Department of Energy CCS R & D management.	A model that correctly depicts the decision problem's key characteristics.	Provides a structure for the many forms of data that must be included in resource allocation choices and a systematic and repeatable procedure for assessing options against goals.	Outcome is under-calculated compared to the actual simulation.
GAMS (General Algebraic Modelling System).	Free for students.	Alexander Meeraus , Richard C. Price, and Gary Kutcher.	A mathematical optimization system with a high-level modelling system.	Mixed-integer, linear, and nonlinear optimization problems may all be modeled and analyzed with this tool.	Commercial software is expensive for young researchers.
Network planner	Free	Modi research group, earth institute, Columbia University.	Examining the cost of various electrification methods.	Cost analysis	RE systems such as small hydro, bioenergy plants, tiny wind turbines,

					solar household systems, and so on are not considered.

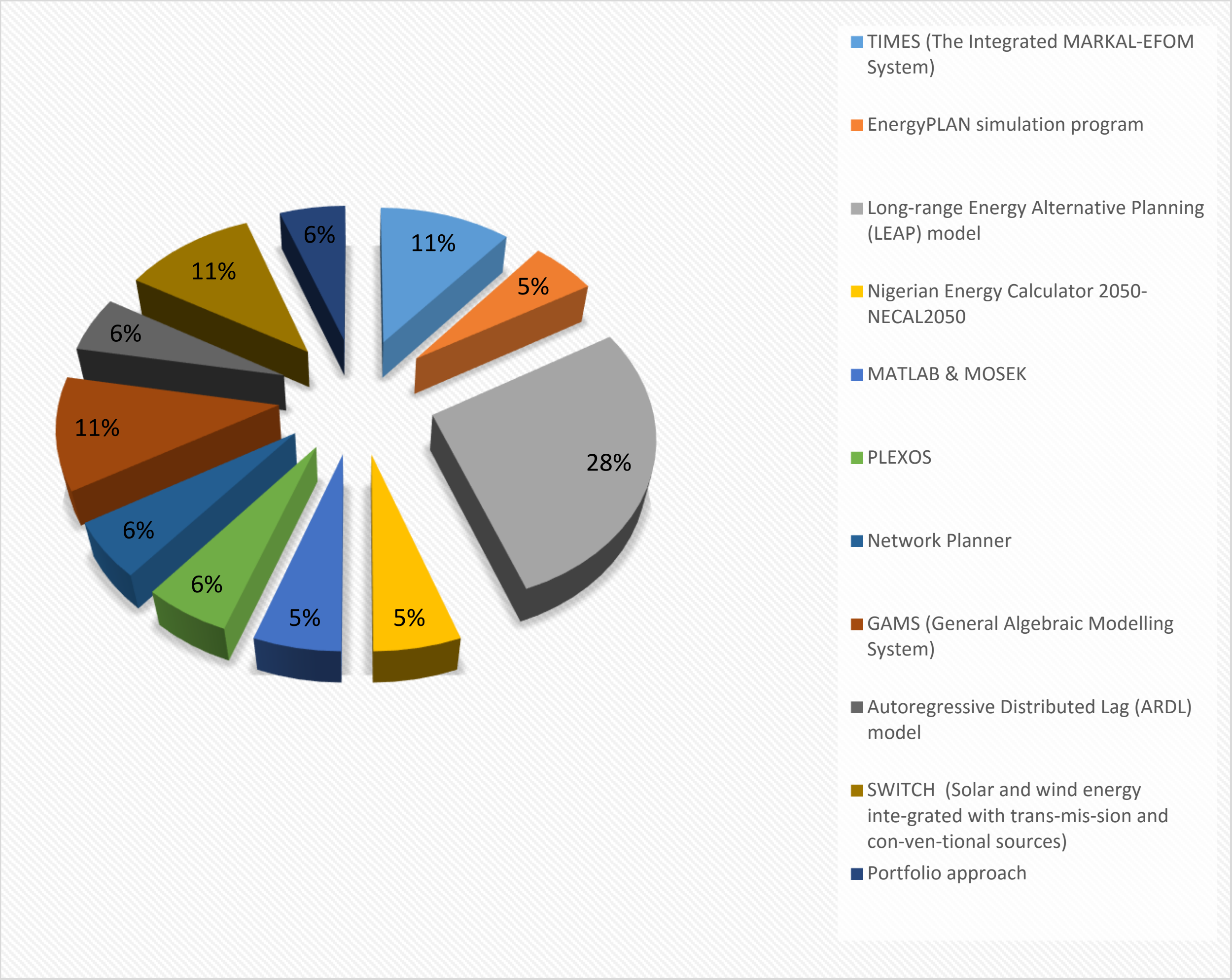

Fig. 2.1. Models used for power generation

Table 2.4: Overview of energy modelling tools used in the selected developing countries

Country	Model	Area of Application	Description of study	Strength	Weakness	References
Brazil	The EnergyPLAN simulation program.	1. Energy Planning	100% RE system was researched.	1. Renewable scenarios were able to be compared for technical, cost, emissions, and risk	1. Not efficient when modelling non-future energy systems.	[153]

© University of Pretoria

				parameters.		
	LEAP model	1. Analyse Energy Policy	100% RE system was researched.	1. Highlights how systematically accounting for health and climate costs in energy planning would economically justify the decarbonization of energy systems.	-	[154]
Argentina	LEAP model	1. Emissions mitigation	Evaluated the impact of a variety of climate change control policies.	1. Based on scenarios and an energy-environment modeling tool, it tracks both energy demand and environmental impacts on the same platform. 2. It contains a TED talk (Technology and Environment Database). 3. It is adaptable in terms of data availability, with a modest initial data need that may be increased if comprehensive data for the study area becomes available.	-	[155]
	LEAP model	1. GHG mitigation	Explored deep decarbonization pathways for the country until 2050 which break with existing more conservative national scenarios.	-	-	[156]
Chile	LEAP model	1. Energy planning and analysis	Generated an energy and environmental model	-	-	[157]
	LEAP model	1. Energy modelling	Examined different CO_2 emission baseline	1. It's simple to use and ideal for measuring energy demand and	-	[158]

© University of Pretoria

			scenarios	transformation in underdeveloped nations.		
Mexico	The EnergyPLAN simulation program.	1. Energy planning	Evaluates several scenarios of renewables incorporation into the Mexican electricity system.	1. It allows for applying various energy methods in energy system analysis.	1. Not efficient when modelling non-future energy systems.	[159]
	LEAP model	1. Environmental analysis	Presented three scenarios relating to the environmental futures of Mexico	-	-	[160]
	LEAP model	1. GHG mitigation	Analyzed the potential contributions of Carbon Capture and Storage (CCS) systems on the electrical sector, as well as the participation of the cement, metal and chemical industries.	--	- -	[161]
Nigeria	The TIMES energy model	1. Energy planning	100% RE system was researched.	1. Over the whole modelling horizon, simultaneous operation and investment optimization across the entire energy system. 2. Explicit portrayal of the economy's most important sectors. 3. Modular framework with the option of connecting to a quantifiable equilibrium model for an extra model to get insight into.	1. Low resolution	[135]
	The EnergyPLAN simulation program.	1. Energy system analysis 2. Analyzing CHP production.	This report proposes how electricity will be 100% available in all parts of the	1. It's a deterministic model that can do RES calculations using data that's both stochastic and	2. Not efficient when modelling non-future energy systems.	[136]

© University of Pretoria

			country.	intermittent. 2. Different systems are optimized in different ways. 3. With an hourly time-step, it may undertake an annual study of an entire innovative system. 4. It models a RE system by taking losses and other technical factors into account. 5. It may analyze district cooling and heating, electric car integration, RE integration, electricity import/export, etc. 6. It allows for applying various energy methods in energy system analysis. 7. Analytic programming, rather than dynamic, sophisticated mathematical tools, or iterative programming, is used for analysis.		
	Nigerian Energy Calculator 2050-NECAL2050.	1. Energy modelling 2. GHG emissions 3. Land use	Using the Nigerian Energy Calculator 2050, the researcher developed four scenarios; their energy balances and emissions were compared.	1. The model's paths were created utilizing Nigerian data and economic and technological options.	1. Under the heading "emissions from fuel burning," a more detailed examination of methods for reducing emissions from power generation, gas flaring, and transportation is gathered. As a result, it is impossible to achieve.	[137]

© University of Pretoria

	LEAP model .	1 Analyse Energy Policy 2. Mitigation of climate change	Leap compared predicted emissions, demand, and supply from 2010-to 2040.	1. It's simple to use and ideal for measuring energy demand and transformation in underdeveloped nations. 2. Based on scenarios and an energy-environment modeling tool, it tracks both energy demand and environmental impacts on the same platform. 3. It contains a TED talk (Technology and Environment Database). 4. It is adaptable in terms of data availability, with a modest initial data need that may be increased if comprehensive data for the study area becomes available. 5. It is free to use for researchers in underdeveloped countries.	1. Lacks optimization capability.	[138]
South Africa	MATLAB & MOSEK	1. Engineering 2. Finance 3. Computer science	South Africa's pathways to a completely decarbonized and low-cost power grid are studied.	1. Conic, conic-integer, and convex nonlinear problems.	1. Free for students only.	[139]
	PLEXOS	1.Energy planning	For South Africa, this report advises boosting energy sector capacity to discover the best	1. Simple computation	1. Functions on a static database and does not allow the inclusion of	[140]

© University of Pretoria

			cost-effective and decarbonized energy mix.		new generators.	
Ghana	LEAP model	—	The level to which Ghana might rely on biomass was studied.	—	—	[141]
	Network Planner	1. Investigating the costs of various electrification alternatives in un-electrified communities.	Costs for providing electricity were evaluated using Network Planner.	1. The model generates precise demand estimations. 2. Produces cost forecasts. 3. Suggests the most cost-effective method of powering communities.	1. RE systems such as small hydro, bioenergy plants, tiny wind turbines, solar household systems, and so on are not considered.	[142]
	LEAP model .	—	The research evaluates Ghana's existing electricity generating growth plan and compares it to potential development paths with increased Renewable Energy Technology adoption.	—	—	[143]
Egypt	The TIMES energy model.	—	This article establishes a local TIMES modelling basis for the energy industry.	—	—	[144]
Ethiopia	GAMS	—	Investigated the most cost-effective investment choices for Ethiopia's various integrated	—	—	[145]

© University of Pretoria

			Energy sources.			
	ARDL model .	1. Economic scenario 2. Energy planning 3. Emissions assessment and so on.	Under an improved EKC framework, the research emphasizes the influence of renewables and conventional energy sources in impacting emissions.	1. Adaptable	1. Performs better for a small amount of data.	[146]
Kenya	SWITCH model	1. Planning transitions to low-emission electric power systems. 2.	The research looked at low-carbon growth routes for Kenya's power industry.	1. It allows users to compose customized models.	1. Less versatile	[147]
	LEAP model	—	Three pathways were analyzed based on emissions and costs.	—	—	[148]
China	SWITCH model	—	The financial and technical costs of a decarbonization scenario, from medium to long term, were examined considering extremely short-term renewable variability.	—	—	[149]
	LEAP model	—	Investigations on how to reduce emissions were carried out.	—	—	[150]
	Portfolio approach.	1. Energy planning	The article compared costs, efficient frontiers,	1. haracterized by having a more	1. Outcome is under-calculated compared to the	[151]

© University of Pretoria

			diversification, and risk levels under various instances and scenarios.	comprehensive capacity and conceptual richness.	actual situation.	
Cameroon	MESSAGE modelling tool	1. GHG mitigation	Identified the energy electricity demand, proposes solutions, and calculates the greenhouse gases emitted in each of the interconnected networks available in Cameroon.	1. Most basic data is only required. 2. Models can be formulated using concise algebraic statements.	1. Commercial software is expensive for young researchers.	[162]
Malaysia	ARIMA	1. Energy forecasting	Fitted the 40 years forecast up to 2053 by assessing 40 years of past data from 1973 until 2013	1. Simple to implement. 2. No parameter tuning.	1. Difficult to predict turning points.	[163]
	LEAP model	1. Energy planning	Developed a few power generation scenarios with various fossil and renewable resource shares for Malaysia.	1. Low data requirements.	-	[164]
Pakistan	LEAP model	1. Energy planning	Four supply side scenarios for the study period (2013–2035) have been developed for power generation.	1. Flexibility	-	[165]
	LEAP model	1. Cost analysis 2. Energy plannin	Compared five supply side scenarios to find the best competitor of Business as Usual scenario and technically tries to increase the share of RE in electricity generation.	1. It is free to use for researchers in underdeveloped countries.	-	[166]
India	GAMS (General	1. Energy optimization	This report examines the	1. Models can be formulated using	1. Commercial software is	[152]

© University of Pretoria

	Algebraic Modelling System).	2. Environment assessment. 3. Transportation and so on.	region's power supply status for the year 2018.	concise algebraic statements. 2. Most basic data is only required. 3. Data can be entered into the model without changing the algebra. 4. Formulate linear, non-linear, and integer problems.	expensive for young researchers.	
Turkey	ARDL model	1. GHG mitigation	Examined the potential of renewable energy sources in reducing the impact of GHG emissions in Turkey.	1. Adaptability	1. Performs better for a small amount of data.	[167]
	LEAP model	1. Environmental analysis	Presented the outcomes of the environmental impact assessment of renewable energy scenarios relevant with the sustainable perception in Turkey using energy modelling for the period 2014–2050.	-	-	[168]
Thailand	LEAP model	1. Energy security analysis 2. GHG mitigation	Estimated and analyzes the renewable energy potential in the energy mix in Thailand.	-	-	[169]
Iran	MESSAGE modelling tool	1. Long-term energy planning	Focus was paid to the long-term adoption of renewable electricity technologies and their implications for emissions reductions in Iran.	1. Helps design long term strategies by analysing cost optimal energy mixes, investment needs and other costs for new infrastructure, energy supply security, energy resource utilization, rate of introduction of new technologies (technology learning),	-	[170]

© University of Pretoria

				environmental constraints.		

2.5 Comparison of power modelling tools used in developing countries

This section compares power modelling tools used in underdeveloped and developing countries summarized in **Table 2.4**. The power models reviewed in this study are either scenario analysis-based or optimization models. These models have been utilized to improve power access by looking to renewable energy and mitigating GHG emissions to achieve a sustainable power supply mix. A sustainable power supply mix among underdeveloped and developing economies will strengthen their economies, create jobs, improve the decaying infrastructure, security, etc. Such an electricity supply mix will address the significant issue of power accessibility, environmental and health risks, and global warming, which affects the entire world. The magnitude of the problem of global warming prompted nations to come together, as they have done in the past, to come up with significant outcomes that will significantly reduce rising temperatures to 1.5 degrees. The 26th UN Climate Change Conference (COP26) at Glasgow has several nations in attendance. The conference is keenly focused on addressing the issue of global warming, which is responsible for difficult situations of heavy rains leading to floods, excessive heat, and drought. The conference's primary goal is to convince governments to agree to keep global warming below 2%. The developed economies have pledged over 100 billion dollars annually to support developing countries in preserving their forest habitats and enhancing renewable energy investments. Furthermore, various developing countries have made pledges toward zero emissions. For instance, Nigeria, a powerhouse in fossil fuel exploration, has set a decarbonization target for 2060. Others include India with a target of 2070, Saudi Arabia with 2060, Israel 2050, Denmark 2050, etc. Several other nations, including South Africa, South Korea, Russia, China, Canada, the USA, etc., have also committed themselves via pledges towards achieving zero carbon-based energy system emissions. Therefore, it's fascinating to look at these countries' modelling tools to plan their electricity supply from literature. Comparing and contrasting each other in terms of application, strengths, and weaknesses.

These power planning models have been utilized for energy system analysis and analyzing CHP production for the Nigerian power system in the case of EnergyPLAN. The ECN's NECAL2050 was used in energy modelling, GHG emissions, and land use. Policymakers and researchers used LEAP for GHG emissions, energy planning, and cost analysis for Kenya, Nigeria, China, and Ghana. The TIMES energy model has been used for energy planning studies in Nigeria and Egypt. GAMS, SWITCH, ARDL, Network Planner, MATLAB & MOSEK, and PLEXOS were adopted for cost planning, energy planning, economic scenario analysis, emissions assessment, and energy optimization in other developing and underdeveloped nations, including India, China, Ethiopia, South Africa, and Egypt. This clearly shows the diversity in which these models have been utilized.

These power models have benefits and drawbacks, but none can be classified as the greatest or worst. Every approach has strengths and weaknesses based on its use in all planning implications and goals. Compared to other models, the NECAL2050 being a country-specific model using Nigeria's data and economic and technical alternatives makes projections much more accurate and closer to reality. The

© University of Pretoria

TIMES energy model has an advantage over models because of its simultaneous operation and investment optimization and explicit portrayal of the power system. Another model, LEAP is simple for energy planning, comes with a TED database, and is very adaptable to available data. These advantages have made LEAP the preferred modelling tool for developing and underdeveloped nations, mainly because of its low data requirements, adaptability, and ease of usage. LEAP is adaptable to a wide variety of users, from top global experts who want to devise policies and explain their advantages to decision-makers for trainers who wish to build capacity among new analysts who are taking on the challenge of comprehending the complexities of energy systems. NECAL2050 lists GHG emission sources as fuel combustion, industrial operations, solvent, and other product usages, agricultural, LULUCF, waste, bioenergy credit, and carbon capture and storage [138]. PLEXOS is simple for computation. MATLAB & MOSEK solves non-linear, quadratic, mixed-integer quadratically constrained, conic and convex problems. The network planner generates precise demand estimates compared to the other modelling tools in the literature. Finally, GAMS has the capability of entering data without changing the algebra.

The challenges being confronted with by utilizing these modelling tools include low resolution as noticed when using TIMES, LEAP does not have optimization capabilities, Network Planner does not consider small hydro, bioenergy plants, small wind turbines, solar household systems, etc., and the remaining modelling tools such as GAMS, PLEXOS, MATLAB, SWITCH and so on. are free for students only. However, critical sub-sectors, including power generation, gas flaring, and transportation, are included under fuel combustion emissions. As a result, NECAL2050 cannot be utilized to do a more in-depth study of the options for lowering emissions from these primary sources. The GAMS, PLEXOS, and MATLAB have optimization capabilities. At various phases of the policy and modeling cycles, the limits of these energy modeling techniques do influence policy decisions. Models' effect on policymaking depends on both how successfully a country has used energy models and the procedures it uses to apply them. Additionally, it appears that variations in the use of models are depending on broader policy choices. Modeling is more frequently employed as an exploratory, auxiliary tool for goal-setting and effect evaluation. Models are often used more frequently as exploratory tools for aim formulation and instrument evaluation in policy processes with lower levels of internal disagreement. It was noted that models were more frequently employed to defend established ideas than to consider other perspectives. It is anticipated that model-based climate and energy policy advice will become more significant over time as policymaking becomes more complicated. Due to the case study nature and complexity of policy making processes, it is impossible to determine the extent to which models affected final policy decisions or to make firm generalizations about the circumstances in which models had a disproportionately positive impact.

The study considered attributes such as low input data requirements, user support, user friendly interface, data set availability, ability to export results, adaptability, distribution capability, optimization capability, power system tracking, fuel availability, cost availability, etc., as shown in **Table 2.5** to compare the various energy modelling tools considered in this study. This would help researchers and policy makers on choosing the best modelling tool based on the criteria.

© University of Pretoria

Table 2.5: Evaluation of energy modelling tools

Ranking Criteria	Energy Modelling Tool													
	TIMES	**Energy PLAN**	**NECAL 2050**	**LEAP**	**MATLAB & MOSEK**	**SWITCH**	**PORTFOLIO**	**GAMS**	**MESSAGE**	**ARIMA**	**ARDL**	**Network Planner**	**ARDL**	**PLEXOS**
Low input data requirements				✓										
User support				✓	✓	✓		✓	✓			✓		✓
User-friendly interface	✓		✓	✓	✓	✓		✓	✓			✓		
Data set availability			✓	✓				✓	✓					
Ability to export results			✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Adaptability	✓			✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Integration with other software				✓					✓					✓
Online training	✓				✓							✓		
Simulation	✓		✓	✓	✓	✓		✓	✓			✓		✓
Unit set points	✓		✓	✓	✓		✓	✓	✓			✓		✓
Total emission intensity	✓			✓	✓		✓	✓	✓			✓		
Climate modelling						✓		✓				✓		
Transmission capability			✓	✓	✓		✓	✓	✓			✓		✓
Distribution capability			✓	✓	✓		✓	✓	✓			✓		✓
Optimization capability	✓		✓		✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Power system tracking	✓		✓	✓	✓		✓	✓	✓			✓		✓
Fuel availability			✓	✓	✓		✓	✓	✓			✓		✓
Cost availability	✓		✓	✓	✓	✓	✓	✓	✓			✓		✓

2.6 Existing renewable projects for power generation in developing economies

Power consumption per capita is frequently used to assess a country's technical, social, and economic development [171,172]. In comparison to developing economies, electricity consumption in industrialized economies is relatively high across all sectors of the economy. Electric cars and trains are now the norm, compressors, electric heaters, boilers, refrigerators, and air conditioners are all

© University of Pretoria

powered by electricity. These countries' electrical supply mix includes conventional and renewable energy sources [173].

Power outages are a significant issue in underdeveloped and developing countries, which rely heavily on diesel and gasoline-powered generators, polluting the environment and producing a lot of noise. RE sources should be adopted for power generation to meet this enormous power supply burden while also ensuring environmental safety, as supported by the literature used for this study [174–178]. An electricity supply mix that includes renewable energy sources and existing energy sources is required to ensure a sufficient, cost-effective, and environmentally friendly power supply system.

This section reviews several studies on renewable energy systems, microgrids, and smart grids for developing economies. This would be highly beneficial because it would allow such countries to design policies that would encourage the deployment of renewable energy sources. At the same time, investors would be able to look into renewable energy investment opportunities.

According to international standards, South Africa has not paid much attention to the extensive deployment of hydropower generation. Except for a new small-scale plant with a capacity of 7 MW that was just commissioned in the Sol Plaatjie municipality Free State area, there has been no significant hydropower development in the last three decades. Hydropower electricity accounts for only 5% of the total installed capacity of 45,500 MW [179]. Only around 1,930 MW (14%) is generated in Nigeria's three most extensive hydroelectric power facilities, which are located in Shiroro, Kainji, and Jebba [180]. Small hydropower plants (SHPs) were built before Nigeria's independence. Currently, Kano, Sokoto, the plateau, and Ogun have eight SHPs totaling 37 MW. Egypt's hydropower capacity is 3,664 MW, with a 15,300 GWh yearly production. Currently, there are five significant hydropower plants [181]. With 280 MW, 85.68 MW, 270 MW, 64 MW, and 2100 MW, Aswan I is the largest hydroelectric facility in Egypt. Egypt has mini/small hydropower potential. Table 6 shows the small/mini hydropower potential location, head (m), flow (m^3/sec), and power (MW) [182]. Almost 80% of Brazil's electrical energy consumption (currently 60%) was generated by hydroelectric power facilities [183]. Following Russia and China, Brazil has the third-highest hydroelectricity potential. In terms of installed hydroelectric power by the end of 2021, Brazil was the second-place nation globally (109.4 GW). [184]. According to the Energy Ministry, 17 additional hydroelectric power facilities with a combined capacity of 3,517 MW are also being built around the nation. The capacity of Iran's current electricity production is 81 GW, with hydroelectric power accounting for around 16% of that total [185]. About 80% of Mexico's renewable energy supply still comes from hydropower, making it the greatest renewable energy source in the nation. By the end of 2017, hydropower accounted for 10% of all forms of energy generation in the nation, or around 17% of the total installed capacity. The nation's installed hydropower capacity is 12,125 MW, while its potential hydropower output is predicted to be 27,000 MW [186]. With a total installed capacity of over 7000 megawatts (MW) of hydropower producing capacity in 26 hydroelectric dams around the nation, hydropower in Thailand is the largest renewable energy source in the country, surpassing both solar energy and wind energy. The Bhumibol Dam, which has eight turbines and a combined capacity of 749 MW, is Thailand's largest hydroelectric dam [187]. Sarawak Hidro's 2,400 MW Bakun project, which became Malaysia's largest hydropower plant when it was opened in 2011, and Sarawak Energy's 944 MW Murum facility, which started full operations in 2015, are current examples of hydropower plants in Malaysia. Additionally, Sarawak Energy's 1,285 MW Baleh

© University of Pretoria

project obtained state government clearance in 2016, and there are a number of other hydro projects in the works that may provide an additional 4 GW of capacity [188]. 197 hydropower facilities exist in India. The rise of authority in India began around the end of the 19th century. The Sidrapong Hydropower Facility, a hydroelectricity project in Darjeeling, was inaugurated in 1897. And a hydroelectric power plant was inaugurated in Sivasamudram, Karnataka, in 1902 [189]. The domestic hydropower potential of Cameroon is projected to be 23,000 MW, with 75% of this capacity concentrated in the Sanaga River basin, which lies in the country's north. But today, barely 3% of Cameroon's hydropower potential is being used. The building of the 200 MW Memve'ele hydroelectric project was finished in 2017. The Cameroonian government, the International Finance Corporation, and the EDF Group created the 420 MW Nachtigal hydropower project, the biggest independent hydroelectric project in Sub-Saharan Africa. The 1,800 MW Grand Eweng project, which will be finished in 2024 and rank as Africa's fourth-largest hydropower plant, is another significant project now under development [190]. In the Ethiopian state of Beneshangul Gumuz, the Blue Nile River is being developed for the Grand Renaissance Hydroelectric Project (GRHEP), formerly known as the Millennium Project of Ethiopia. With an installed capacity of 6,450MW [191], it will be the greatest hydroelectric project in Africa and one of the largest power plants still under development worldwide.

Photovoltaic (PV) is extensively used in rural South Africa for lighting, household appliances, telecommunications, and water pumps. PV technology will be used up to 14% of the time. Supply will double by 2050 [192]. A French oil company developed one of Nigeria's most significant PV projects to produce 1,000 MW of solar electricity. The location is ideal for the project since it gets a lot of solar radiation and has numerous dispersed inhabitants [193]. Private companies from Egypt and abroad have offered to build 20 solar energy projects for $30 billion with a capacity of 20,000 megawatts (MW) in only two years [194]. Brazil installed 17 GW of solar energy in August 2022. Brazil was the 11th greatest producer of solar energy in the world in 2021 (16.8 TWh), and it ranked 14th globally in terms of installed solar power (13 GW) [195]. Ituverava and the Nova Olinda plants are the two biggest solar power facilities in Brazil. Both the Nova Olinda and Ituverava solar plants have outputs of 254 MW and 292 MW, respectively [196]. Bhumibol Dam Solar PV Park, with a capacity of 778 MW, is being built near Tak by the Electricity Generating Authority of Thailand. The primary project is anticipated to start in 2024 and go into operation commercially in 2026 [197]. In India, one of the most popular and quickly growing industries is solar power. The largest solar parks and electricity producing facilities in India are located in Tamil Nadu, Gujarat, Rajasthan, Telangana, Maharashtra, and Madhya Pradesh. One of the largest solar farms in the world, Shakti Sthala Pavagada Solar Park in Karnataka spans 13,000 acres and has a 2,000 MW power producing capacity. Kadaladi Solar Park, located in the Ramanathapuram district, is a projected 4,000 MW power station and 500 MW solar park constructed by Tangedco near Naripaiyur Village [198].

Although South Africa's wind energy potential is between 500 and 56,000 megawatts, the ESKOM Klipheuwel demonstration plant and the Darling wind farm have only produced 0.05%. There are many small wind turbines. However, they are not linked to the national grid [199,200]. The 10 MW wind farm near Rimi village, 25 km south of Katsina, is Nigeria's first. The average annual mean monthly wind speed in Katsina is 6.044 m/s. The wind farm has 37.55 m tall wind turbines with a 275 kW rated output. The project is sponsored solely by the Federal Ministry of Power and is 98%

© University of Pretoria

complete as of May 2015. The average annual mean monthly wind speed in Katsina is 6.044 m/s [201]. Egypt's Supreme Council of Energy authorized a proposal to use renewable energy sources to generate 20% of power by 2020. Wind energy may make up to 12% of overall energy usage. Wind farms at Zafarana and the Gulf of El-zeyt can produce 545 MW and 200 MW, respectively [202]. Brazil installed 22 GW of wind energy as of July 2022. Brazil was the fourth-largest producer of wind energy in the world in 2021 (72 TWh), after only China, the United States, and Germany [203]. In terms of installed wind power, Brazil ranked seventh in the world in 2021 (21 GW). Argentina offers a perfect environment for the generation of wind energy, with strong winds covering around 75% of the country's surface. The Argentinian government authorized 6.5 GW of renewable energy projects between 2016 and 2019, bringing in investments totaling about $7.5 billion. Of this capacity, 5GW are currently in use [204]. The amount of wind energy produced in Mexico is increasing quickly. Its installed capacity was 3,527 MW in 2016 and will reach 8,128 MW in 2020 [205].

The estimated biomass contribution to Nigeria's power sector is negligible and unavailable [206]. Egypt's biomass resources offer tremendous potential for energy production, despite minimal development. The most prevalent agricultural waste is wheat, maize, rice, and sugar cane. For Suzan Abdelhady and co. (ICAE2014), a year's worth of rice straw may provide 2,477 GWh of electricity. According to the FOA, Egypt is Africa's largest rice producer (Food and Agriculture Organization). In South Africa, specific paper and sugar mills burn bagasse to create steam, yielding over 210 GWh of energy each year. The streams in Kwazulu-Natal and Mpumalanga have the most biomass energy. It contains around 4,300 km2 of sugar cane plantations and 13,000 km2 of forestry farms. A sugar mill annually uses 210 GWh of paper and bagasse [207]. With 15,2 GW installed, Brazil ranked second globally in the production of energy from biomass (electricity from solid biofuels and renewable waste) in 2020 [208].

The South African National Energy Development Institute (SANEDI) says smart grid technologies would help South Africa achieve its desired energy mix. Without smart grids, large-scale renewable energy integration is impossible. In terms of service delivery, smart grid technology enables municipalities to use integrated systems and procedures, resulting in unprecedented efficiency and effectiveness. The South African National Energy Development Institute (SANEDI) says smart grid technologies would help South Africa achieve its desired energy mix. Without smart grids, large-scale renewable energy integration is impossible. In terms of service delivery, smart grid technology enables municipalities to use integrated systems and procedures, resulting in unprecedented efficiency and effectiveness [209]. Johannesburg, the Municipality of Tshwane, and the Nelson Mandela Bay Municipality have all undertaken smart metering programs. The EThekwini Municipality is trialing smart meters for customers who are small-scale energy generators (SSEG), such as those with rooftop solar panels [210]. Smart grid technology paves the path for greater use of green energy from renewable sources. Nigeria's electricity industry has yet to progress to the point where it can accommodate smart grid technology [211]. Egypt's state-owned Egyptian Energy Holding Company (EEHC) will upgrade its electrical system with Schneider Electric's help. Schneider Electric will build four control centers to monitor and improve the electrical network in 18 months. It will also deploy over 12,000 smart ring central units nationwide. They aim to upgrade 1,000 distribution points and substations. Hardware-based cybersecurity software will protect the network [212].

© University of Pretoria

In Africa, where the power grid has failed, microgrids and off-grid household solar systems are rapidly adopted. A gas-diesel hybrid microgrid powers the Zwartkop Chrome Mine and the Thabazimbi Chrome Mine in South Africa. ABB is also "drinking their own kool-aid" with a microgrid with a big solar footprint at the ABB Longmeadow Facility in South Africa [213]. Six new microgrids have been built in Nigeria at the same time as part of a World Bank-backed rural electrification scheme. The examples demonstrate the vast potential that can be realized by scaling up microgrid rollout efforts. The solar hybrid microgrid projects in Nasarawa State will supply clean, reliable, and inexpensive electricity to around 5,000 families and 500 businesses. Six communities in the Doma and Lafia local government regions will access electricity [214]. The Sakuri Mine Solar Microgrid Project in Egypt, which will utilize smart grid technologies, is now under construction. The project has a 36MW rated capacity. Juwi is in charge of the smart grid initiative [215].

2.7 Conclusion

The power supply is still very much insufficient in underdeveloped and developing economies. Most of these countries depend on coal and natural gas for power generation. Fossil fuels pollute the environment, are responsible for global warming, and harm people’s health. Developed nations like Germany, the UK, Switzerland, the USA, Canada, and others have significantly reduced carbon emissions from fossil fuel power plants [216,217]. Therefore, as a matter of urgency, there is a need for developing and underdeveloped economies to follow suit. Both developing and underdeveloped nations face the challenge of inadequate power supply, environmental, global warming, and health impacts from their existing power generation mix. All the studies reviewed suggested that having a sustainable power supply mix will address these challenges. Renewable energy sources such as solar, wind, hydro, biomass, tidal, geothermal, and even alternative energy sources such as nuclear energy are insignificant proportion. They should be captured and used for power generation. From literature, it is found that hydropower is the most utilized renewable energy resource, followed by solar power, wind, and then biomass. The slow transition to RE sources in underdeveloped and developing nations is attributed to governments' lack of commitment to significant policies, standards, and regulatory systems, making it difficult for local and foreign investors to invest. Another factor is non-existent or insufficient energy efficiency and conservation policies, social factors, unavailability of skilled workforce, natural causes such as lack of rainfall, land constraint, grants, and subsidies. To achieve a sustainable power supply system, rapid economic growth, and industrialization, factors such as energy efficiency, conservation regulations, microgrid technologies, and smart-grid systems require urgent attention. Determining the power supply mix of an underdeveloped and developing nation depends on the resources available in the region or the ability to import them, the amount of power to be provided, and historical, financial, societal, demographic, conservational, and geopolitical factors all influence the decision. As a result, the power supply mix varies from one country to another. Energy models incorporate these data to develop a power supply mix specific to the country being studied.

The paper then reviewed various energy modelling tools utilized in developing an optimum power generation mix for these upcoming nations. These models used for power sources mix development include TIMES, EnergyPLAN simulation program, LEAP model, NECAL2050, MATLAB & MOSEK, PLEXOS, Network Planner, GAMS, ARDL model, SWITCH, and Portfolio approach. These models were compared to each other considering factors such as low input data requirements, user support, user friendly interface, data set availability, ability to export results, adaptability,

© University of Pretoria

distribution capability, optimization capability, power system tracking, fuel availability, cost availability, etc., for selection criteria. It was found that every power modelling tool has its strength and weakness depending on its application in all the consequences and objectives of planning.

The best way to address insufficient power supply in developing economies while also reducing GHG emissions is to invest in an optimal mix of harnessed sustainable energy sources. As reviewed in this study, developing countries have developed their own optimal power sources mix by utilizing the various energy modelling tools considered in this study. Developing an optimal supply mix involves optimizing various conflicting objectives such as clean and affordable energy (SDG7) that was considered in this study. This is now a multi-objective problem with two objectives (clean and affordable energy) that is solved subject to various constraints such as resource availability, emission factors, costs, etc., to come up with the optimal sources mix a developing country. With regards to power modelling tools, a model should be chosen based on energy characteristics and objectives, and these models can be customized in such a way to meet the peculiarities of developing nations' techno-economic considerations. Energy mix optimization modelling and decision support system premised on systems thinking is an immediate future work being considered to foster the mission of power supply sustainability both in the developing and underdeveloped economies.

This would result in the generation of weights for each specific factor. These weights would in turn be deployed into a multi-objective, multi-constraints optimization model for the conduct of simulation trials. Objectives that can be considered apart from those considered in SDG7 are: jobs, land utilization, water availability, costs, operation and maintenance, etc., subject to constraints such as: available land, water potential, costs constraint, jobs creation factor, and operation and maintenance factor.

Chapter References

[1] Sharifzadeh M, Lubiano-Walochik H, Shah N. Integrated renewable electricity generation considering uncertainties: The UK roadmap to 50% power generation from wind and solar energies. Renewable and Sustainable Energy Reviews 2017;72:385–98. https://doi.org/10.1016/j.rser.2017.01.069.

[2] Muchlis M, Adhi D, Permana D. Pengembangan Sistem Kelistrikan dalam Menunjang Pembangunan Nasional Jangka Panjang Proyeksi Kebutuhan Listrik PLN Tahun 2003.

[3] Abreu Kang TH, da Costa Soares Júnior AM, de Almeida AT. Evaluating electric power generation technologies: A multicriteria analysis based on the FITradeoff method. Energy 2018;165:10–20. https://doi.org/10.1016/j.energy.2018.09.165.

[4] World Energy Outlook 2010 – Analysis - IEA n.d. https://www.iea.org/reports/world-energy-outlook-2010 (accessed March 22, 2022).

[5] Najafi G, Ghobadian B, Tavakoli T, Yusaf T. Potential of bioethanol production from agricultural wastes in Iran. Renewable and Sustainable Energy Reviews 2009;13:1418–27. https://doi.org/10.1016/j.rser.2008.08.010.

[6] HOME - UN Climate Change Conference (COP26) at the SEC – Glasgow 2021 n.d. https://ukcop26.org/ (accessed March 22, 2022).

[7] Web of Science Core Collection Result Analysis. Web of Science n.d.

© University of Pretoria

[8] IEA – International Energy Agency - IEA n.d. https://www.iea.org/reports/%20world-energy-outlook-2019 (accessed March 22, 2022).

[9] 2021 Q1 electricity & other energy statistics | China Energy Portal | 中国能源门户 n.d. https://chinaenergyportal.org/en/2021-q1-electricity-other-energy-statistics/ (accessed March 22, 2022).

[10] Feng Q, Sun X, Hao J, Li J. Predictability dynamics of multifactor-influenced installed capacity: a perspective of country clustering. Energy. 2021 Jan 1;214:118831.

[11] Power Africa in Kenya | Power Africa | U.S. Agency for International Development n.d. https://www.usaid.gov/powerafrica/kenya (accessed March 22, 2022).

[12] UNdata | record view | Electricity, the net installed capacity of electric power plants n.d. http://data.un.org/Data.aspx?d=EDATA&f=cmID%3aEC (accessed March 22, 2022).

[13] 2019 detailed electricity statistics (update of Jan 2021) | China Energy Portal | 中国能源门户 n.d. https://chinaenergyportal.org/en/2019-detailed-electricity-statistics-update-of-jan-2021/ (accessed March 22, 2022).

[14] UNdata | record view | Total Electricity n.d. http://data.un.org/Data.aspx?d=EDATA&f=cmID%3aEL#EDATA (accessed March 22, 2022).

[15] Electricity sector in Mexico - Wikipedia. En.wikipedia.org. https://en.wikipedia.org/wiki/Electricity_sector_in_Mexico. Published 2022. Accessed September 30, 2022.

[16] Electricity sector in Pakistan - Wikipedia. En.wikipedia.org. https://en.wikipedia.org/wiki/Electricity_sector_in_Pakistan. Published 2022. Accessed September 30, 2022.

[17] Republic of Turkey Ministry of Energy and Natural Resources - Electricity. Enerji.gov.tr. https://enerji.gov.tr/infobank-energy-electricity. Published 2022. Accessed September 30, 2022.

[18] Kidmo D, Deli K, Bogno B. Status of renewable energy in Cameroon. Renewable Energy and Environmental Sustainability. 2021;6:2. doi:10.1051/rees/2021001.

[19] Dosm.gov.my. https://www.dosm.gov.my/v1/uploads/files/6_Newsletter/newsletter%202018/Series%2010_Electricity%20Sector.pdf. Published 2022. Accessed September 30, 2022.

[20] Electricity sector in Chile - Wikipedia. En.wikipedia.org. https://en.wikipedia.org/wiki/Electricity_sector_in_Chile. Published 2022. Accessed September 30, 2022.

[21] Afdb.org. https://www.afdb.org/sites/default/files/2021/11/22/cameroon.pdf. Published 2022. Accessed September 30, 2022.

[22] Electricity sector in Argentina - Wikipedia. En.wikipedia.org. https://en.wikipedia.org/wiki/Electricity_sector_in_Argentina. Published 2022. Accessed September 30, 2022.

[23] BNamericas - Brazil added almost 5GW of generation capaci... BNamericas.com. https://www.bnamericas.com/en/news/brazil-added-almost-5gw-of-generation-capacity-in-2020. Published 2022. Accessed September 30, 2022.

© University of Pretoria

[24] Installed power capacity by source Greece 2020 | Statista. Statista. https://www.statista.com/statistics/1153672/installed-power-capacity-greece-by-source/. Published 2022. Accessed September 30, 2022.
[25] Iran's installed electricity generation capacity at 83.35GW. Tehran Times. https://www.tehrantimes.com/news/445967/Iran-s-installed-electricity-generation-capacity-at-83-35GW. Published 2022. Accessed September 30, 2022.
[26] Adb.org. https://www.adb.org/sites/default/files/linked-documents/49087-001-so.pdf. Published 2022. Accessed September 30, 2022.
[27] Fadai D. Utilization of renewable energy sources for power generation in Iran. Renewable and Sustainable Energy Reviews 2007;11:173–81. https://doi.org/10.1016/j.rser.2005.01.011.
[28] N NM. Relationship between global solar radiation and sunshine hours for Calabar, Port Harcourt, and Enugu, Nigeria. vol. 4. 2009.
[29] Promoting Sustainable Energy Development in Nigeria. n.d.
[30] Kemausuor F, Obeng GY, Brew-Hammond A, Duker A. A review of trends, policies, and plans for increasing energy access in Ghana. Renewable and Sustainable Energy Reviews 2011;15:5143–54. https://doi.org/10.1016/j.rser.2011.07.041.
[31] Abd. Aziz PD, Wahid SSA, Arief YZ, Ab. Aziz N. Evaluation of solar energy potential in Malaysia. Trends in Bioinformatics 2016;9:35–43. https://doi.org/10.3923/TB.2016.35.43.
[32] Kaygusuz K, Sarı A. Renewable energy potential and utilization in Turkey. n.d.
[33] Veeraboina P, Ratnam GY. Analysis of the opportunities and challenges of solar water heating system (SWHS) in India: Estimates from the energy audit surveys & review. Renewable and Sustainable Energy Reviews 2012;16:668–76. https://doi.org/10.1016/j.rser.2011.08.032.
[34] Pandey S, Singh VS, Gangwar NP, Vijayvergia MM, Prakash C, Pandey DN. Determinants of success for promoting solar energy in Rajasthan, India. Renewable and Sustainable Energy Reviews 2012;16:3593–8. https://doi.org/10.1016/j.rser.2012.03.012.
[35] Sharma NK, Tiwari PK, Sood YR. Solar energy in India: Strategies, policies, perspectives and future potential. Renewable and Sustainable Energy Reviews 2012;16:933–41. https://doi.org/10.1016/j.rser.2011.09.014.
[36] van der Zwaan B, Boccalon A, Dalla Longa F. Prospects for hydropower in Ethiopia: An energy-water nexus analysis. Energy Strategy Reviews 2018;19:19–30. https://doi.org/10.1016/j.esr.2017.11.001.
[37] International - Laurea-ammattikorkeakoulu n.d. https://www.laurea.fi/en/international/ (accessed March 22, 2022).
[38] Sunny Mexico: An Energy Opportunity | Greentech Media n.d. https://www.greentechmedia.com/articles/read/sunny-mexico-an-energy-opportunity (accessed March 22, 2022).
[39] Solar power in Thailand. - Wikipedia n.d. https://en.wikipedia.org/wiki/Solar_power_in_Thailand. (accessed March 22, 2022).
[40] Letcher T. Future Energy (Third Edition). 3rd ed. Elsevier; 2020.
[41] U Aliyu, S Elegba. Prospects for small hydropower development for rural applications in Nigeria. Nigerian Journal of Renewable Energy 1990;1:74–86.
[42] Talla D, Gaelle F. Current Status of Renewable Energy in Cameroon. 2018.
[43] Demirbaş A. Sustainable developments of hydropower energy in Turkey. Energy Sources 2002;24:27–40. https://doi.org/10.1080/00908310252712280.

© University of Pretoria

[44] Promexico, "Business Intelligence Unit," 2012. - References - Scientific Research Publishing n.d. https://www.scirp.org/(S(i43dyn45teexjx455qlt3d2q))/reference/referencespapers.aspx?referenceid=797963 (accessed March 22, 2022).

[45] Banks D, Consulting R, Schäffler J, Energy N. The potential contribution of renewable energy in South Africa n.d.

[46] Levieux LI, Inthamoussou FA, De Battista H. Power dispatch assessment of a wind farm and a hydropower plant: A case study in Argentina. Energy Conversion and Management. 2019 Jan 15;180:391-400.

[47] MINISTERIAL CONFERENCE ON WATER FOR AGRICULTURE AND ENERGY IN AFRICA: THE CHALLENGES OF CLIMATE CHANGE Sirte, Libyan Arab Jamahiriya, 15-17 HYDROPOWER RESOURCE ASSESSMENT OF AFRICA 2008.

[48] Khan B, Singh P. The Current and Future States of Ethiopia's Energy Sector and Potential for Green Energy: A Comprehensive Study. International Journal of Engineering Research in Africa 2017;33:115–39. https://doi.org/10.4028/WWW.SCIENTIFIC.NET/JERA.33.115.

[49] A01190_Renewable_Energy_Africa_Guide_V2_2019_V9_Zmag n.d. http://viewer.zmags.com/publication/8d9694ae#/8d9694ae/1 (accessed March 23, 2022).

[50] Sanchez RG, Kougias I, Moner-Girona M, Fahl F, Jäger-Waldau A. Assessment of floating solar photovoltaics potential in existing hydropower reservoirs in Africa. Renewable Energy. 2021 May 1;169:687-99.

[51] Introduction To Bioenergetics | PDF | Bioenergetics | Adenosine Diphosphate n.d. https://www.scribd.com/presentation/487455353/1-Introduction-to-Bioenergetics (accessed March 22, 2022).

[52] Turkey | World Energy Council n.d. https://www.worldenergy.org/impact-communities/members/entry/turkey (accessed March 22, 2022).

[53] Final Energy report South Africa Commissioned by the Netherlands Enterprise Agency. n.d.

[54] Country Briefs – GET.invest n.d. https://www.get-invest.eu/market-information/country-briefs/ (accessed March 22, 2022).

[55] Renewable energy sector in Egypt - Open to Export n.d. https://opentoexport.com/article/renewable-energy-sector-in-egypt/ (accessed March 22, 2022).

[56] Renewable Energies in West Africa Regional Report on Potentials and Marktes-17 Country Analyses Energy-policy Framework Papers, Section »Energy and Transport« Promotion of Renewable Energies. 2009.

[57] Engström J, MAARD S. SafeTE final report. Publikation. 2007(2007: 36).

[58] Chidiezie Chineke T, Theo Chineke C. Boosting Electricity Supply in Nigeria: Wind Energy to the Rescue? Spatial and temporal characterization and projections of aerosol loading and impacts over West Africa View project Boosting Electricity Supply in Nigeria: Wind Energy to the Rescue? 2009.

[59] Fadare DA. A Statistical Analysis of Wind Energy Potential in Ibadan, Nigeria, Based on Weibull Distribution Function. n.d.

[60] Oriaku C, Daniel AA, Chukwu G, Kanu C, Oriaku CI, Osuwa JC, et al. Frequency distibution analysis of available wind resources in Umudike, Abia State-Nigeria for WECS design. Effects of climate change in Nigeria View project Joint inversion View project Frequency Distribution

© University of Pretoria

Analysis of Available Wind Resources in Umudike, Abia State, Nigeria, for Wind Energy Conversion System Design. 2006.

[61] Fadare DA. The application of artificial neural networks to mapping of wind speed profile for energy application in Nigeria. Applied Energy 2010;87:934–42. https://doi.org/10.1016/j.apenergy.2009.09.005.

[62] CONCAMIN. Private sector viewpoint on energy management 2012.

[63] Rosnazri Ali, Ismail Daut, Soib Taib. A review on existing and future energy sources for electrical power generation in Malaysia. Renewable and Sustainable Energy Reviews 2012;16:4047–55.

[64] GET.invest. Kenya Renewable Energy Potential n.d. https://www.get-invest.eu/market-information/kenya/renewable-energy-potential/ (accessed March 23, 2022).

[65] Gaddada S, Kodicherla SPK. Wind energy potential and cost estimation of wind energy conversion systems (WECSs) for electricity generation in the eight selected locations of Tigray region (Ethiopia). Renewables: Wind, Water, and Solar 2016;3. https://doi.org/10.1186/s40807-016-0030-8.

[66] Banks D, Consulting R, Schäffler J, Energy N. The potential contribution of renewable energy in South Africa. n.d.

[67] Ibrahim HA, Ayomoh MK. Optimum predictive modelling for a sustainable power supply mix: A case of the Nigerian power system. Energy Strategy Reviews. 2022 Nov 1;44:100962.

[68] İlkiliç C. Wind energy and assessment of wind energy potential in Turkey. Renewable and Sustainable Energy Reviews. 2012 Feb 1;16(2):1165-73.

[69] Sharma S, Sinha S. Indian wind energy & its development-policies-barriers: An overview. Environmental and Sustainability Indicators. 2019 Sep 1;1:100003.

[70] "Dark horse Argentina could challenge Brazil in South America's offshore wind race" | Recharge n.d. https://www.rechargenews.com/wind/dark-horse-argentina-could-challenge-brazil-in-south-americas-offshore-wind-race/2-1-1063328 (accessed March 23, 2022).

[71] L.C.A. Gutiérrez-negrín. Promoting energy efficiency in buildings in East Africa. GRC Trans 2012;36:671–8.

[72] "An Energy Overview of the Republic of Turkey." Fossil Energy International 2003.

[73] Surface Exploration and Capacity Building For Geothermal Development Ethiopia 2013:1–17.

[74] GDC| Geothermal Development Company n.d. http://www.gdc.co.ke/projects_intro.php. (accessed March 23, 2022).

[75] Mas'ud AA, Wirba AV, Muhammad-Sukki F, Mas'ud IA, Munir AB, Yunus NM. An assessment of renewable energy readiness in Africa: Case study of Nigeria and Cameroon. Renewable and Sustainable Energy Reviews. 2015 Nov 1;51:775-84.

[76] Laura Chiodi A, Filipovich R, Agostina CL, Rubén FE, Carlos EL, Abel PH, et al. Monogenetic volcanism in the Andes View project Geothermal Country Update of Argentina: 2015-2020. 2020.

[77] Hui L, Qingjun Z, Puyuan T, Wenguang H. Technologies and Applications of Geophysical Exploration in Deep Geothermal Resources in China. 2015.

[78] Zhao XG, Wan G. Current situation and prospect of China's geothermal resources. Renewable and Sustainable Energy Reviews 2014;32:651–61. https://doi.org/10.1016/j.rser.2014.01.057.

[79] Ferreira, H. L.; Costescu, A.; L'Abbate, A.; Minnebo, P.; Fulli, G. Distributed generation and distribution market diversity in Europe. Energy Pol. 2011, 39(9), 5561-5571.

© University of Pretoria

[80] Bell, M.; Pavitt K. Technological accumulation and industrial growth: contrasts between developed and developing countries. In Technology, globalization and economic performance, Archibugi, D., Michie, J., Eds.; Cambridge University Press, 1997, 83-137 & Fatas, A.; Mihov, I. Policy volatility, institutions, and economic growth. Rev. Econ. Stat. 2013, 95(2), 362-376.
[81] Newman, C.; Rand, J.; Tarp, F. Industry switching in developing countries. World Bank Econ. Rev. 2012, 27(2), 357-388.
[82] Hussein, Z.; Hertel, T.; Golub, A. Climate change mitigation policies and poverty in developing countries. Environ. Res. Lett. 2013, 8(3), 035009.
[83] Pandey, R. Energy policy modelling: agenda for developing countries. Energy Pol. 2002, 30(2), 97-106.
[84] Kammen, D. M.; Kirubi, C. Poverty, energy, and resource use in developing countries. Ann. N. Y. Acad. Sci. 2008, 1136(1), 348-357.
[85] Jairaj, B.; Martin, S.; Ryor, J.; Dixit, S.; Gambhir, A.; Chunekar, A.; Bharvirkar, R.; Jannuzzi, G.; Sukenaliev, S.; Wang, T. The Future Electricity Grid. World Resources Institute, 2016. https://www.wri.org/sites/default/files/The_Future_Electricity_Grid.pdf (accessed Sep 29, 2022).
[86] World development indicators 2016, The World Bank, USA 2016. http://databank.worldbank.org/data/download/site-content (accessed Jul 10, 2017).
[87] Jairaj, B.; Martin, S.; Ryor, J.; Dixit, S.; Gambhir, A.; Chunekar, A.; Bharvirkar, R.; Jannuzzi, G.; Sukenaliev, S.; Wang, T. The Future Electricity Grid. World Resources Institute, 2016. https://www.wri.org/sites/default/files/The_Future_Electricity_Grid.pdf (accessed Sep 29, 2022).
[88] Ibrahim HA, Ayomoh MK. Identification and Prioritisation of Electricity Driving Factors for Power Supply Sustainability: A Case of Developing and Underdeveloped Nations. In2021 IEEE Asia-Pacific Conference on Computer Science and Data Engineering (CSDE) 2021 Dec 8 (pp. 1-6). IEEE.
[89] Scaling Up Energy Efficiency in Developing Countries. Usaid.gov. https://www.usaid.gov/energy/efficiency/building-blocks. Published 2022. Accessed October 3, 2022.
[90] Energy Technology Perspectives 2014 – Analysis - IEA n.d. https://www.iea.org/reports/energy-technology-perspectives-2014 (accessed March 23, 2022).
[91] Barros MV, Piekarski CM, de Francisco AC. Carbon footprint of electricity generation in Brazil: An analysis of the 2016-2026 period. Energies 2018;11. https://doi.org/10.3390/en11061412.
[92] Environmental and Health Impacts of Air Pollution_ A Review _ Enhanced Reader n.d.
[93] de Souza Henriques R, Saldanha RR, Coelho LMG. An air pollutant emission analysis of Brazilian electricity production projections and other countries. Energies 2019;12. https://doi.org/10.3390/en12152851.
[94] Levieux LI, Inthamoussou FA, de Battista H. Power dispatch assessment of a wind farm and a hydropower plant: A case study in Argentina. Energy Conversion and Management 2019;180:391–400. https://doi.org/10.1016/j.enconman.2018.10.101.
[95] Aprea JL, Bolcich JC. The energy transition towards hydrogen utilization for green life and sustainable human development in Patagonia. International Journal of Hydrogen Energy 2020;45:25627–45. https://doi.org/10.1016/j.ijhydene.2020.01.246.

© University of Pretoria

[96] Rodríguez-Monroy C, Mármol-Acitores G, Nilsson-Cifuentes G. Electricity generation in Chile using non-conventional renewable energy sources – A focus on biomass. Renewable and Sustainable Energy Reviews 2018;81:937–45. https://doi.org/10.1016/j.rser.2017.08.059.

[97] Gaete-Morales C, Gallego-Schmid A, Stamford L, Azapagic A. Assessing the environmental sustainability of electricity generation in Chile. Science of the Total Environment 2018;636:1155–70. https://doi.org/10.1016/j.scitotenv.2018.04.346.

[98] Vega MI, Zaror CA. The effect of solar energy on the environmental profile of electricity generation in Chile: A midterm scenario. International Journal of Energy Production and Management 2018;3:110–21. https://doi.org/10.2495/EQ-V3-N2-110-121.

[99] Pérez-Denicia E, Fernández-Luqueño F, Vilariño-Ayala D, Manuel Montaño-Zetina L, Alfonso Maldonado-López L. Renewable energy sources for electricity generation in Mexico: A review. Renewable and Sustainable Energy Reviews 2017;78:597–613. https://doi.org/10.1016/j.rser.2017.05.009.

[100] Vidal-Amaro JJ, Sheinbaum-Pardo C. A transition strategy from fossil fuels to renewable energy sources in the mexican electricity system. Journal of Sustainable Development of Energy, Water and Environment Systems 2018;6:47–66. https://doi.org/10.13044/j.sdewes.d5.0170.

[101] Rodríguez-Serrano I, Caldés N, Rúa C de la, Lechón Y. Assessing the three sustainability pillars through the Framework for Integrated Sustainability Assessment (FISA): Case study of a Solar Thermal Electricity project in Mexico. Journal of Cleaner Production 2017;149:1127–43. https://doi.org/10.1016/j.jclepro.2017.02.179.

[102] Ogunmodimu O, Okoroigwe EC. Concentrating solar power technologies for solar thermal grid electricity in Nigeria: A review. Renewable and Sustainable Energy Reviews 2018;90:104–19. https://doi.org/10.1016/j.rser.2018.03.029.

[103] Oyedepo SO, Babalola OP, Nwanya SC, Kilanko O, Leramo RO, Aworinde AK, et al. Towards a Sustainable Electricity Supply in Nigeria: The Role of Decentralized Renewable Energy System. European Journal of Sustainable Development Research 2018;2. https://doi.org/10.20897/ejosdr/3908.

[104] Oyewo AS, Aghahosseini A, Bogdanov D, Breyer C. Pathways to a fully sustainable electricity supply for Nigeria in the mid-term future. Energy Conversion and Management 2018;178:44–64. https://doi.org/10.1016/j.enconman.2018.10.036.

[105] Naicker P, Thopil GA. A framework for sustainable utility scale renewable energy selection in South Africa. Journal of Cleaner Production 2019;224:637–50. https://doi.org/10.1016/j.jclepro.2019.03.257.

[106] Monyei CG, Jenkins KEH, Viriri S, Adewumi AO. Policy discussion for sustainable integrated electricity expansion in South Africa. Energy Policy 2018;120:132–43. https://doi.org/10.1016/j.enpol.2018.05.021.

[107] Sakah M, Diawuo FA, Katzenbach R, Gyamfi S. Towards a sustainable electrification in Ghana: A review of renewable energy deployment policies. Renewable and Sustainable Energy Reviews 2017;79:544–57. https://doi.org/10.1016/j.rser.2017.05.090.

[108] Ghana’s electricity supply mix has improved, but reliability and cost is still a challenge n.d. https://theconversation.com/ghanas-electricity-supply-mix-has-improved-but-reliability-and-cost-is-still-a-challenge-161762 (accessed March 23, 2022).

© University of Pretoria

[109] Ahmed A, Gong J. Assessment of the Electricity Generation Mix in Ghana: the Potential of Renewable Energy.

[110] Mondal MAH, Ringler C, Al-Riffai P, Eldidi H, Breisinger C, Wiebelt M. Long-term optimization of Egypt’s power sector: Policy implications. Energy 2019;166:1063–73. https://doi.org/10.1016/j.energy.2018.10.158.

[111] Abdulrahman AO, Huisingh D. The role of biomass as a cleaner energy source in Egypt’s energy mix. Journal of Cleaner Production 2018;172:3918–30. https://doi.org/10.1016/j.jclepro.2017.05.049.

[112] Rady YY, Rocco M v., Serag-Eldin MA, Colombo E. Modelling for power generation sector in Developing Countries: Case of Egypt. Energy 2018;165:198–209. https://doi.org/10.1016/j.energy.2018.09.089.

[113] Muh E, Amara S, Tabet F. Sustainable energy policies in Cameroon: A holistic overview. Renewable and Sustainable Energy Reviews 2018;82:3420–9. https://doi.org/10.1016/j.rser.2017.10.049.

[114] Nsafon BEK, Owolabi AB, Butu HM, Roh JW, Suh D, Huh JS. Optimization and sustainability analysis of PV/wind/diesel hybrid energy system for decentralized energy generation. Energy Strategy Reviews 2020;32. https://doi.org/10.1016/j.esr.2020.100570.

[115] Nemzoue PN, Keutchafo NA, Tchouankoue JP. Geothermal development in Cameroon. Revista de Engenharia Térmica. 2020 Sep 9;19(1):32-41.

[116] Umar MS, Urmee T, Jennings P. A policy framework and industry roadmap model for sustainable oil palm biomass electricity generation in Malaysia. Renewable Energy 2018;128:275–84. https://doi.org/10.1016/j.renene.2017.12.060.

[117] Haiges R, Wang YD, Ghoshray A, Roskilly AP. Optimization of Malaysia’s power generation mix to meet the electricity demand by 2050. Energy Procedia, vol. 142, Elsevier Ltd; 2017, p. 2844–51. https://doi.org/10.1016/j.egypro.2017.12.431.

[118] Valasai G das, Uqaili MA, Memon HUR, Samoo SR, Mirjat NH, Harijan K. Overcoming electricity crisis in Pakistan: A review of sustainable electricity options. Renewable and Sustainable Energy Reviews 2017;72:734–45. https://doi.org/10.1016/j.rser.2017.01.097.

[119] Arshad M, Bano I, Khan N, Shahzad MI, Younus M, Abbas M, et al. Electricity generation from biogas of poultry waste: An assessment of potential and feasibility in Pakistan. Renewable and Sustainable Energy Reviews 2018;81:1241–6. https://doi.org/10.1016/j.rser.2017.09.007.

[120] Baloch MH, Abro SA, Kaloi GS, Mirjat NH, Tahir S, Nadeem MH, et al. A research on electricity generation from wind corridors of Pakistan (two provinces): A technical proposal for remote zones. Sustainability (Switzerland) 2017;9. https://doi.org/10.3390/su9091611.

[121] Tiewsoh LS, Jirásek J, Sivek M. Electricity generation in India: Present state, future outlook and policy implications. Energies 2019;12. https://doi.org/10.3390/en12071361.

[122] Gulagi A, Bogdanov D, Breyer C. The role of storage technologies in energy transition pathways towards achieving a fully sustainable energy system for India. Journal of Energy Storage 2018;17:525–39. https://doi.org/10.1016/j.est.2017.11.012.

[123] Manju S, Sagar N. Progressing towards the development of sustainable energy: A critical review on the current status, applications, developmental barriers and prospects of solar photovoltaic systems in India. Renewable and Sustainable Energy Reviews 2017;70:298–313. https://doi.org/10.1016/j.rser.2016.11.226.

© University of Pretoria

[124] Safieddin Ardebili SM. Green electricity generation potential from biogas produced by anaerobic digestion of farm animal waste and agriculture residues in Iran. Renewable Energy 2020;154:29–37. https://doi.org/10.1016/j.renene.2020.02.102.

[125] Aryanpur V, Atabaki MS, Marzband M, Siano P, Ghayoumi K. An overview of energy planning in Iran and transition pathways towards sustainable electricity supply sector. Renewable and Sustainable Energy Reviews 2019;112:58–74. https://doi.org/10.1016/j.rser.2019.05.047.

[126] Kok B, Benli H. Energy diversity and nuclear energy for sustainable development in Turkey. Renewable Energy 2017;111:870–7. https://doi.org/10.1016/j.renene.2017.05.001.

[127] Yilan G, Kadirgan MAN, Çiftçioğlu GA. Analysis of electricity generation options for sustainable energy decision making: The case of Turkey. Renewable Energy 2020;146:519–29. https://doi.org/10.1016/j.renene.2019.06.164.

[128] Peerapong P, Limmeechokchai B. Optimal electricity development by increasing solar resources in diesel-based micro grid of island society in Thailand. Energy Reports 2017;3:1–13. https://doi.org/10.1016/j.egyr.2016.11.001.

[129] Chaichana C, Wongsapai W, Damrongsak D, Ishihara KN, Luangchosiri N. Promoting Community Renewable Energy as a tool for Sustainable Development in Rural Areas of Thailand. Energy Procedia, vol. 141, Elsevier Ltd; 2017, p. 114–8. https://doi.org/10.1016/j.egypro.2017.11.022.

[130] Grande-Acosta G, Islas-Samperio J. Towards a low-carbon electric power system in Mexico. Energy for Sustainable Development 2017;37:99–109. https://doi.org/10.1016/j.esd.2017.02.001.

[131] Gallardo RP, Ríos AM, Ramírez JS. Analysis of the solar and wind energetic complementarity in Mexico. Journal of Cleaner Production 2020;268. https://doi.org/10.1016/j.jclepro.2020.122323.

[132] Després J, Hadjsaid N, Criqui P, Noirot I. Modelling the impacts of variable renewable sources on the power sector: Reconsidering the typology of energy modelling tools. Energy 2015;80:486–95. https://doi.org/10.1016/j.energy.2014.12.005.

[133] Martins F, Patrão C, Moura P, de Almeida AT. A review of energy modelling tools for energy efficiency in smart cities. Smart Cities 2021;4:1420–36. https://doi.org/10.3390/smartcities4040075.

[134] Energy Systems (Chapter 7) - Climate Change 2014: Mitigation of Climate Change n.d. https://www.cambridge.org/core/books/abs/climate-change-2014-mitigation-of-climate-change/energy-systems/EE273BA73944F60FEAF520F2431DD4AE (accessed March 24, 2022).

[135] Lai CS, Locatelli G, Pimm A, Wu X, Lai LL. A review on long-term electrical power system modelling with energy storage. Journal of Cleaner Production 2021;280. https://doi.org/10.1016/J.JCLEPRO.2020.124298.

[136] Tambari IT, Dioha MO, Failler P. Renewable energy scenarios for sustainable electricity supply in Nigeria. Energy and Climate Change 2020;1:100017. https://doi.org/10.1016/j.egycc.2020.100017.

[137] Bamisile O, Huang Q, Xu X, Hu W, Liu W, Liu Z, et al. An approach for sustainable energy planning towards 100 % electrification of Nigeria by 2030. Energy 2020;197. https://doi.org/10.1016/j.energy.2020.117172.

© University of Pretoria

[138] Dioha MO, Emodi N v., Dioha EC. Pathways for low carbon Nigeria in 2050 by using NECAL2050. Renewable Energy Focus 2019;29:63–77. https://doi.org/10.1016/j.ref.2019.02.004.

[139] Emodi NV, Emodi CC, Murthy GP, Emodi ASA. Energy policy for low carbon development in Nigeria: A LEAP model application. Renewable and Sustainable Energy Reviews 2017;68:247–61. https://doi.org/10.1016/j.rser.2016.09.118.

[140] Oyewo AS, Aghahosseini A, Ram M, Lohrmann A, Breyer C. Pathway towards achieving 100% renewable electricity by 2050 for South Africa. Solar Energy 2019;191:549–65. https://doi.org/10.1016/j.solener.2019.09.039.

[141] Wright JG, Bischof-Niemz T, Calitz JR, Mushwana C, van Heerden R. Long-term electricity sector expansion planning: A unique opportunity for a least cost energy transition in South Africa. Renewable Energy Focus 2019;30:21–45. https://doi.org/10.1016/j.ref.2019.02.005.

[142] Kemausuor F, Nygaard I, Mackenzie G. Prospects for bioenergy use in Ghana using Long-range Energy Alternatives Planning model. Energy 2015;93:672–82. https://doi.org/10.1016/j.energy.2015.08.104.

[143] Kemausuor F, Adkins E, Adu-Poku I, Brew-Hammond A, Modi V. Electrification planning using Network Planner tool: The case of Ghana. Energy for Sustainable Development 2014;19:92–101. https://doi.org/10.1016/j.esd.2013.12.009.

[144] Awopone AK, Zobaa AF, Banuenumah W. Techno-economic and environmental analysis of power generation expansion plan of Ghana. Energy Policy 2017;104:13–22. https://doi.org/10.1016/j.enpol.2017.01.034.

[145] Bouckaert S, Assoumou E, Selosse S, Maïzi N. A prospective analysis of waste heat management at power plants and water conservation issues using a global TIMES model. Energy 2014;68:80–91. https://doi.org/10.1016/j.energy.2014.02.008.

[146] Guta D, Börner J. Energy security, uncertainty and energy resource use options in Ethiopia: A sector modelling approach. International Journal of Energy Sector Management 2017;11:91–117. https://doi.org/10.1108/IJESM-04-2015-0005.

[147] Usama A mulali, Solarin SA, Salahuddin M. The prominence of renewable and non-renewable electricity generation on the environmental Kuznets curve: A case study of Ethiopia. Energy 2020;211. https://doi.org/10.1016/j.energy.2020.118665.

[148] Carvallo JP, Shaw BJ, Avila NI, Kammen DM. Sustainable Low-Carbon Expansion for the Power Sector of an Emerging Economy: The Case of Kenya. Environmental Science & Technology 2017;51:10232–42. https://doi.org/10.1021/ACS.EST.7B00345.

[149] Irungu D. KENYA POWER SECTOR DEVELOPNET SCENARIOS–ANALYSIS USING LONG RANGE ENERGY ALTERNATIVE PLANNING SYSTEM. InScientific Conference Proceedings 2014 Jan 7.

[150] Avrin A-P, Johnston JL. SWITCH-China: A Systems Approach to Decarbonizing China's Power System_SI. 2016.

[151] Cai W, Wang C, Wang K, Zhang Y, Chen J. Scenario analysis on CO2 emissions reduction potential in China's electricity sector. Energy Policy 2007;35:6445–56. https://doi.org/10.1016/j.enpol.2007.08.026.

[152] Zhang S, Zhao T, Xie BC. What is the optimal power generation mix of China? An empirical analysis using portfolio theory. Applied Energy 2018;229:522–36. https://doi.org/10.1016/j.apenergy.2018.08.028.

© University of Pretoria

[153] Dranka G, Ferreira P. Planning for a renewable future in the Brazilian power system. Energy. 2018;164:496-511. doi:10.1016/j.energy.2018.08.164.

[154] Howard D, Soria R, Thé J, Schaeffer R, Saphores J. The energy-climate-health nexus in energy planning: A case study in Brazil. Renewable and Sustainable Energy Reviews. 2020;132:110016. doi:10.1016/j.rser.2020.110016.

[155] Di Sbroiavacca N, Nadal G, Lallana F, Falzon J, Calvin K. Emissions reduction scenarios in the Argentinean Energy Sector. Energy Econ. 2016;56:552-563. doi:10.1016/j.eneco.2015.03.021.

[156] Lallana F, Bravo G, Le Treut G, Lefèvre J, Nadal G, Di Sbroiavacca N. Exploring deep decarbonization pathways for Argentina. Energy Strategy Reviews. 2021;36:100670. doi:10.1016/j.esr.2021.100670.

[157] Simsek Y, Sahin H, Lorca Á, Santika W, Urmee T, Escobar R. Comparison of energy scenario alternatives for Chile: Towards low-carbon energy transition by 2030. Energy. 2020;206:118021. doi:10.1016/j.energy.2020.118021

[158] O'Ryan R, Nasirov S, Álvarez-Espinosa A. Renewable energy expansion in the Chilean power market: A dynamic general equilibrium modeling approach to determine CO2 emission baselines. J Clean Prod. 2020;247:119645. doi:10.1016/j.jclepro.2019.119645.

[159] Vidal-Amaro J, Sheinbaum-Pardo C. A Transition Strategy from Fossil Fuels to Renewable Energy Sources in the Mexican Electricity System. Journal of Sustainable Development of Energy, Water and Environment Systems. 2017;6(1):47-66. doi:10.13044/j.sdewes.d5.0170

[160] Manzini F. Reduction of greenhouse gases using renewable energies in Mexico 2025. Int J Hydrogen Energy. 2001;26(2):145-149. doi:10.1016/s0360-3199(00)00042-2

[161] Castrejón D, Zavala A, Flores J, Flores M, Barrón D. Analysis of the contribution of CCS to achieve the objectives of Mexico to reduce GHG emissions. International Journal of Greenhouse Gas Control. 2018;71:184-193. doi:10.1016/j.ijggc.2018.02.019.

[162] Meukam, Pierre and Kouer, Joel Placide, Contribution of Biomass to the Mitigation of Greenhouse Gas Emissions During Electricity Production by 2050 in Cameroon. Available at SSRN: https://ssrn.com/abstract=4024958 or http://dx.doi.org/10.2139/ssrn.4024958.

[163] Haiges R, Wang Y, Ghoshray A, Roskilly A. Forecasting Electricity Generation Capacity in Malaysia: An Auto Regressive Integrated Moving Average Approach. Energy Procedia. 2017;105:3471-3478. doi:10.1016/j.egypro.2017.03.795.

[164] M. S. N. . Samsudin, M. M. . Rahman, and M. A. . Wahid, "Sustainable Power Generation Pathways in Malaysia: Development of Long-range Scenarios ", J. Adv. Res. Appl. Mech. , vol. 24, no. 1, pp. 22–38, Oct. 2020.

[165] Mengal A, Mirjat NH, Walasai GD, Khatri SA, Harijan K, Uqaili MA. Modeling of Future Electricity Generation and Emissions Assessment for Pakistan. Processes. 2019; 7(4):212. https://doi.org/10.3390/pr7040212

[166] Shahid M, Ullah K, Imran K, Mahmood I, Mahmood A. Electricity supply pathways based on renewable resources: A sustainable energy future for Pakistan. Journal of Cleaner Production. 2020 Aug 1;263:121511.

[167] Bölük G, Mert M. The renewable energy, growth and environmental Kuznets curve in Turkey: an ARDL approach. Renewable and Sustainable Energy Reviews. 2015 Dec 1;52:587-95.

[168] Saygın H, Oral HV, Kardaşlar S. Environmental assessment of renewable energy scenarios for a sustainable future in Turkey. Energy & Environment. 2020 Mar;31(2):237-55.

© University of Pretoria

[169] Kumar S. Assessment of renewables for energy security and carbon mitigation in Southeast Asia: The case of Indonesia and Thailand. Applied Energy. 2016 Feb 1;163:63-70.

[170] Aryanpur V, Shafiei E. Optimal deployment of renewable electricity technologies in Iran and implications for emissions reductions. Energy. 2015 Nov 1;91:882-93.

[171] Sustainable Bioenergy: A Framework for Decision Makers n.d. https://www.fao.org/3/a1094e/a1094e00.htm (accessed March 24, 2022).

[172] Akuru UB, Animalu AO. Alternative means of energy sector investments in Nigeria. African Journal of Physics Vol. 2009;2:161-71.

[173] Jacobson MZ, Delucchi MA, Bauer ZAF, Goodman SC, Chapman WE, Cameron MA, et al. 100% Clean and Renewable Wind, Water, and Sunlight All-Sector Energy Roadmaps for 139 Countries of the World. Joule 2017;1:108–21. https://doi.org/10.1016/j.joule.2017.07.005.

[174] Dioha MO, Kumar A. Rooftop solar PV for urban residential buildings of Nigeria: A preliminary attempt towards potential estimation. AIMS Energy 2018;6:710–34. https://doi.org/10.3934/energy.2018.5.710.

[175] Ali G, Bashir MK, Ali H, Bashir MH. Utilization of rice husk and poultry wastes for renewable energy potential in Pakistan: An economic perspective. Renewable and Sustainable Energy Reviews 2016;61:25–9. https://doi.org/10.1016/j.rser.2016.03.014.

[176] Studies on optimization of transesterification of certain oils to produce biodiesel | Request PDF n.d. https://www.researchgate.net/publication/281177382_Studies_on_optimization_of_transesterification_of_certain_oils_to_produce_biodiesel (accessed March 24, 2022).

[177] Harrache D, Mir A. Miguel de la Guardia, Fatima-Zahra Benhachem. Bioaccumulation of trace metals by red alga Corallina elongata in the coast of Beni Saf, west coast, Algeria. Chemistry International 2017;3:220–31.

[178] Nisar J, Razaq R, Farooq M, Iqbal M, Khan RA, Sayed M, et al. Enhanced biodiesel production from Jatropha oil using calcined waste animal bones as catalyst. Renewable Energy 2017;101:111–9. https://doi.org/10.1016/j.renene.2016.08.048.

[179] Csir SS, Lennard -Uct C. Project overview and status. n.d.

[180] Aliyu UO, Elegba SB. Prospects for small hydropower development for rural application in Nigeria. Niger J Renew Energy 1990;1:8658.

[181] brahim A. Renewable energy sources in the Egyptian electricity market: A review. Renewable and Sustainable Energy Reviews 2012;16:216–30. https://doi.org/10.1016/J.RSER.2011.07.149.

[182] Elshennawy T. 2 th International Conference on The Role Of Engineering Towards A Better Environment (RETBE'21) Can Egypt achieve its target of 20% of electric energy from renewables by 2022? n.d.

[183] Hydropower made up 66% of Brazil's electricity generation in 2020. Eia.gov. https://www.eia.gov/todayinenergy/detail.php?id=49436. Published 2022. Accessed October 2, 2022.

[184] Renewable Capacity Statistics 2022. Irena.org. https://www.irena.org/publications/2022/Apr/Renewable-Capacity-Statistics-2022. Published 2022. Accessed October 2, 2022.

© University of Pretoria

[185] Iran’s 9-month hydropower output up over 200%. Tehran Times. https://www.tehrantimes.com/news/444445/Iran-s-9-month-hydropower-output-up-over-200. Published 2022. Accessed October 2, 2022.

[186] Mexico. Hydropower.org. https://www.hydropower.org/country-profiles/mexico. Published 2022. Accessed October 2, 2022.

[187] Hydroelectricity in Thailand - Wikipedia. En.wikipedia.org. https://en.wikipedia.org/wiki/Hydroelectricity_in_Thailand. Published 2022. Accessed October 2, 2022].

[188] Malaysia. Hydropower.org. https://www.hydropower.org/country-profiles/malaysia#:~:text=There%20is%20a%20further%201%2C700%20MW%20of%20hydropower,the%20country%E2%80%99s%20electricity%20supply%2C%20especially%20in%20rural%20areas. Published 2022. Accessed October 2, 2022.

[189] List of Hydroelectric Power Plants in India - UPSC Notes. BYJUS. https://byjus.com/free-ias-prep/hydroelectric-power-plants-in-india-for-upsc-prelims/. Published 2022. Accessed October 2, 2022.

[190] Cameroon. Hydropower.org. https://www.hydropower.org/country-profiles/cameroon. Published 2022. Accessed October 2, 2022.

[191] The Grand Renaissance Hydroelectric Project. Power Technology. https://www.power-technology.com/projects/the-grand-renaissance-hydroelectricproject/#:~:text=The%20Grand%20Renaissance%20Hydroelectric%20Project%20%28GRHEP%29%2C%20formerly%20known,the%20world%20with%20an%20installed%20capacity%20of%206%2C450MW. Published 2022. Accessed October 2, 2022.

[192] Banks D, Consulting R, Schäffler J, Energy N. The potential contribution of renewable energy in South Africa n.d.

[193] Total targets 1,000mw solar power project in Nigeria - Nigeria Business News n.d. https://businessnews.com.ng/2014/09/10/total-targets-1000mw-solar-power-project-nigeria/ (accessed March 24, 2022).

[194] Egypt aims to produce 20% of power from renewables by 2020 n.d. https://www.egypt-business.com/web/details/1441-xg-Egypt-aims-to-produce-20-of-power-from-renewables-by-2020/9961 (accessed March 24, 2022).

[195] Ritchie H, Roser M, Rosado P. Energy. Our World in Data. https://ourworldindata.org/renewable-energy. Published 2022. Accessed October 2, 2022.

[196] Enel Starts Operation of South America`s Two Largest Solar Parks in Brazil. WebWire. https://www.webwire.com/ViewPressRel.asp?aId=213780. Published 2022. Accessed October 2, 2022.

[197] Thai Solar Energy Market Size, Share | 2022 - 27 | Industry Growth. Mordorintelligence.com. https://www.mordorintelligence.com/industry-reports/thailand-solar-energy market#:~:text=The%20Electricity%20Generating%20Authority%20of%20Thailand%20is%20developing,expected%20to%20enter%20into%20commercial%20operation%20in%202026. Published 2022. Accessed October 2, 2022.

[198] Top 15 Biggest Solar Power Projects in India. Walkthroughindia.com. http://www.walkthroughindia.com/walkthroughs/top-15-biggest-solar-power-projects-in-india/#:~:text=Jalaun%20Solar%20Power%20Project%20is%20another%20solar%20photo-

© University of Pretoria

voltaic,railways%20also%20launched%20first%20solar%20powered%20DEMU%20train. Published 2022. Accessed October 2, 2022.

[199] Banks D, Consulting R, Schäffler J, Energy N. The potential contribution of renewable energy in South Africa n.d.

[200] Artin J, Valizadeh A, Ahmadi M, Kumar SA, Sharifi A. Presentation of a novel method for prediction of traffic with climate condition based on ensemble learning of neural architecture search (NAS) and linear regression. Complexity. 2021 Aug 31;2021.

[201] Katsina State will be home to First Nigerian wind farm | ECOWREX n.d. http://www.ecowrex.org/pt-pt/node/14309 (accessed March 24, 2022).

[202] Ibrahim HA, Kirkil G. Electricity demand and supply scenario analysis for Nigeria using long range energy alternatives planning (LEAP). J. Sci. Res. Rep. 2018 May;19(2):1-2.

[203] Ritchie H, Roser M, Rosado P. Energy. Our World in Data. https://ourworldindata.org/renewable-energy. Published 2022. Accessed October 2, 2022.

[204] Top five wind power producing countries of South America. Nsenergybusiness.com. https://www.nsenergybusiness.com/features/top-five-wind-power-countries-south-america/. Published 2022. Accessed October 2, 2022.

[205] Solar Stuns in Mexico's First Clean Energy Auction: 1,860MW Won at $50.7 per MWh. Greentechmedia.com. http://www.greentechmedia.com/articles/read/Solar-Stuns-in-Mexicos-First-Clean-Energy-Auction-1860-MW-Won-at-50.7-P. Published 2022. Accessed October 2, 2022.

[206] Oyedepo SO. On energy for sustainable development in Nigeria. Renewable and Sustainable Energy Reviews 2012;16:2583–98. https://doi.org/10.1016/j.rser.2012.02.010.

[207] Banks D, Consulting R, Schäffler J, Energy N. The potential contribution of renewable energy in South Africa n.d.

[208] Renewable Capacity Statistics 2022. Irena.org. https://www.irena.org/publications/2022/Apr/Renewable-Capacity-Statistics-2022. Published 2022. Accessed October 2, 2022.

[209] Energy mix: Smart grid development in South Africa–The real story n.d. https://www.smart-energy.com/magazine-article/energy-mix-sanedi-south-africa/ (accessed March 24, 2022).

[210] Barsali S, Ceraolo M, Giglioli R, Poli D. Storage applications for Smartgrids. Electric Power Systems Research. 2015 Mar 1;120:109-17.

[211] Patrick O, Tolulolope O, Sunny O, Patrick O, Tolulolope O, Sunny O. Smart Grid Technology and Its Possible Applications to the Nigeria 330 kV Power System. Smart Grid and Renewable Energy 2013;4:391–7. https://doi.org/10.4236/SGRE.2013.45045.

[212] Egyptian state utility to create Middle East's first-ever smart grid n.d. https://www.smart-energy.com/industry-sectors/smart-grid/egyptian-state-utility-to-create-middle-easts-first-ever-smart-grid/ (accessed March 24, 2022).

[213] Africa Microgrids | Microgrid Projects n.d. http://microgridprojects.com/africa-microgrids/ (accessed March 24, 2022).

[214] David Appleyard. Nigerian Rollout of Multiple Microgrids Shows Opportunity for Scale 2021. https://microgridknowledge.com/nigeria-microgrids-electrification-world-bank/ (accessed March 24, 2022).

© University of Pretoria

[215] Sakuri Mine Solar Microgrid Project, Egypt n.d. https://www.power-technology.com/marketdata/sakuri-mine-solar-microgrid-project-egypt-2/ (accessed March 24, 2022).

[216] Prasad RD, Bansal RC, Raturi A. Multi-faceted energy planning: A review. Renewable and Sustainable Energy Reviews 2014;38:686–99. https://doi.org/10.1016/j.rser.2014.07.021.

[217] Shah R, Mithulananthan N, Bansal RC, Ramachandaramurthy VK. A review of key power system stability challenges for large-scale PV integration. Renewable and Sustainable Energy Reviews 2015;41:1423–36. https://doi.org/10.1016/j.rser.2014.09.027.

© University of Pretoria

Chapter 3

Identification and Prioritization of Electricity Driving Factors for Power Supply Sustainability: A Case of Developing and Underdeveloped Nations

3.0 Chapter Overview

The importance of addressing the increasing demand for electricity in developing and underdeveloped countries, particularly in the context of the current pandemic-driven migration to virtual transactions and operations, cannot be overstated. The rapid rise in electricity demand has resulted in a significant supply deficit, which poses challenges to power availability and sustainability in these economies. Identifying and prioritizing the factors that drive power availability and sustainability is crucial for informed decision-making by policy makers and researchers in allocating resources effectively.

The Hybrid Structural Interaction Matrix (HSIM) used in this chapter provides a weight-based prioritization model with a hierarchical structural layout of interacting factors, which can aid in determining the most significant drivers of power availability and sustainability. This approach allows for a systematic analysis and understanding of the complex interactions between various factors contributing to the booming electricity demand in developing economies.

By prioritizing these factors, policy makers and researchers can make informed decisions and develop targeted strategies to address the issues of growing electricity demand and inadequate supply. This may involve investing in infrastructure development, diversifying the power generation mix, promoting renewable energy sources, improving transmission and distribution networks, and implementing demand-side management measures. Optimum predictive modeling based on weighted prioritized driving factors can provide valuable insights for formulating effective policies and strategies to ensure a sustainable power supply mix in developing and underdeveloped countries like Nigeria.

This chapter will provide a roadmap for the implementation of the power supply mix developed in Chapter 5, with a strong emphasis on the importance of addressing the increasing electricity demand in developing nations. It cannot be emphasized enough that reducing electricity demand is a fundamental step towards realizing a sustainable power supply mix that is predominantly based on renewable energy sources. This chapter will outline strategies for decreasing electricity demand, which serves as a foundational step towards achieving higher levels of renewable energy penetration in developing nations.

© University of Pretoria

3.1 Introduction

One of the most important drivers for development in any nation is its ability to attain sustainable power supply. As a result of its versatility and direct affiliation with the functionability and operations of systems, electricity is used in a wide range of activities in our daily lives and in all sectors of the economy. This ranges from industrial through transportation, defence, agriculture and domestic applications amongst others. Inadequate power availability is the major reason for underdevelopment and unemployment in Sub-Saharan Africa and several Asian countries. Insecurity and insurgency, which has bedevilled most developing and underdeveloped economies, are inextricably linked to unemployment. The unemployment situation is often aggravated with incessant electricity supply following the recent trend of globalisation. As a result of this, an equilibrium between supply and demand for electricity is required. To accomplish this, all a country's energy resources must be harnessed into an optimal electricity supply system.

The demand for electricity in developing and underdeveloped economies is growing like never before, with low per capita electricity consumption and approximately 620 million people in Sub-Saharan Africa without access to electricity [1]. Power supply is insufficient in Sub-Saharan Africa and certain Asian countries, such as India and Pakistan. This will continue to increase over the next 25 years according to the International Energy Agency (IEA) new policy scenario [2]. As a result of the rising demand for electricity, economic losses from power outages are expected to range from 1 percent to 5 percent of these nations' GDP every year [2,3]. The stumbling block to these developing and underdeveloped countries' economic development is believed to be hinged on poor electricity supply [4,5]. As population, urbanization, income levels etc., increases, power consumption will surely skyrocket in years to come, this will worsen the situation of electricity deficit in these developing and underdeveloped nations.

Studies conducted by the United States, Energy Information Administration (U.S. EIA), showed that demand for electricity by non-Organisation for Economic Co-operation and Development (OECD) countries will exceed that of the OECD countries by 89 percent in 2040 [6]. Due to several factors such as electricity access, GDP growth, industrialisation etc., there is an anticipated increase in power consumption. There are other factors which lead to the inclusion of other energy sources such as renewables and alternative energy sources to meet the electricity demand which include: energy efficiency and conservation, energy security, literacy, pollution etc. To provide universal access to modern energy, the World Bank estimates that 2.6 billion people would need access to electrification by 2030, with 4.4 billion requiring electrical cooking services. This contributes to the causes for the non-OECD region's projected demand increase [7].

This study has identified electricity driving factors and prioritised them for optimal allocation of resources based on the order of hierarchy or importance. This will minimise or eliminate the wasteful allocation of resources to driving factors in a bid to control their respective deployment. Policy makers, researchers and students will also find this research to be of great importance, because incorporating the most important electricity driving factors in determining electricity demand and optimum supply for a nation, will certainly provide an insight into the development of an effective management policy.

© University of Pretoria

3.2 Methodology for Research

The HSIM concept offers a method for investigating the impact of electrical driving variables on rising electricity demand in emerging and underdeveloped nations. A weighted component will be used to do a numerical analysis of ranking factors. Based on the HSIM concept, dynamic models in resource allocation can be created. Resource decision making in such domains is ideal in the planning of water resources [8], as well as data mining approaches [9].

A multi-objective optimisation approach is another related technology allocation of resources [10]. Prioritization and planning of maintenance resources of safety engineering resources, [11] and [12] used the HSIM approach effectively.

Some recognisable electricity demand driving variables in developing and underdeveloped countries were identified, prioritised, and ranked in order of significance using the principle of subordination. The normalised weight of variables was determined based on the estimated normalised weight of variables; the basic model of resource allocation was used to allot resources to the elements that have been identified. By directing more resources to the most weighted energy demand driving causes, the HSIM idea suggested in this work takes a method of dealing with the problem at its source.

3.3 Assumptions, limitations, and constraints of study

Limitations of the Study:

1. Data Availability and Reliability: The study may rely on limited or incomplete data on renewable energy transition barriers in developing economies, which could affect the accuracy and reliability of the findings.
2. Methodological Limitations: The use of the Hybrid Structural Interaction Matrix (HSIM) for prioritizing barriers may have inherent limitations, such as subjectivity in assigning weights or assumptions made in the modelling process.
3. Time Constraints: The study may be limited by time constraints, which may affect the depth or comprehensiveness of the analysis and findings.

Constraints:

1. Access to Information: Constraints in accessing reliable and comprehensive data on renewable energy transition barriers in developing economies could limit the accuracy and robustness of the findings.
2. Resource Limitations: Constraints in terms of funding, time, and human resources may affect the scope and quality of the study, including data collection, analysis, and interpretation.

Assumptions:

1. Homogeneity of Developing Economies: The study may assume that developing economies share similar characteristics or face similar barriers to renewable energy

© University of Pretoria

transition, which may not always be the case due to the diversity and heterogeneity among developing economies.

2. Validity of the HSIM Model: The study may assume that the HSIM model is a valid and appropriate method for prioritizing renewable energy transition barriers, without considering potential limitations or criticisms of the model.
3. Policy Relevance: The study may assume that the identified barriers are relevant to policymakers and academics without considering variations in policy contexts or stakeholder perspectives.
4. Future Projections: The study may make assumptions about future trends and projections related to renewable energy transition in developing economies, which may be uncertain and subject to change.

3.3.1 Identified Electricity Driving Factors

In this section, the electricity driving factors which are responsible for the increase in electricity demand are presented in brief. Based on the identified factors, the suggested model's conceptual framework is presented. The sources of data utilized for this study were obtained from secondary, tertiary, and internet websites. The factors, which are listed from one to twenty-two are presented below:

1. *Gross Domestic Product (GDP):* With a high GDP, a developing or underdeveloped country will have a high need for electricity. Because of the country's prosperity, demand for electrical products like air conditioners, freezers, heaters etc. will significantly increase [13].
2. *GDP growth rate*: The monetary worth of a country's goods and services is proportional to the consumption of electricity. As a country's GDP grows, so does its need for power [13].
3. *Income*: The money earned from salary, investments, perks, and gifts, among other things, directly influences the demand for power [14, 15, 16, 17].
4. *Income growth rate*: With an increase in earnings and pay, the demand for electrical gadgets and equipment will rise, as will the need for power [14, 15, 16, 17].
5. *Population*: Being a major driver for the increase in electricity demand, it places enormous strain on the limited power supply [13,15].
6. *Population growth rate*: The rapid rate of population growth is a serious concern for developing and underdeveloped countries. As the population grows, so does the need for power [13,15].
7. *Energy efficiency and conservation*: This is a strong motivator for incorporating renewable energy power into the existing power supply mix of these developing and underdeveloped nations [18].
8. *Health*: A healthy society is an active society, which means greater activity in the manufacturing, service, agricultural, and transportation sector [14, 19].
9. *Energy security*: It is vital to lessen reliance on other nations for power, which increases demand for domestically generated electricity [18].
10. *Literacy*: This will enable countries to come up with new power generation sources. For instance, some countries have the human capacity to design, develop, operate, maintain, dispose and decommission nuclear power generation. Therefore, literacy is a driver for emerging and alternative energy sources [13, 15].
11. *Life expectancy:* The life expectancy of a population has a significant influence on the power consumption of a particular nation [20].

© University of Pretoria

12. *Export trends:* The possibility of producing power and profitably exporting it to bordering countries [18].
13. *Pollution:* Reducing or eliminating environmental pollution from fossil fuels used for power generation, whether on land or in the sea, is a primary cause for the rise in demand for renewable energy [21].
14. *Transportation:* The need for electricity will rise as more electric forms of transportation are introduced, such as electric vehicles, electric railways, and electric airplanes [22].
15. *Households:* The number of households has a major impact on the demand for electricity [13, 15].
16. *Household growth rate:* As the nation's household rate rises, so does demand for electrical appliances and devices, which has a direct influence on power consumption [13, 15].
17. *Urbanization growth rate:* Migration from rural to urban regions of a country is a driver of power consumption [13, 23, 24].
18. *Industry growth rate:* A key reason for becoming a part of the expanding electricity demand is that developing and underdeveloped nations are seeking for ways to be self-sufficient in terms of production/manufacturing [14, 25].
19. *Commercial/services growth rate:* Commercial/service activity are increasing in emerging and underdeveloped countries, which is a key contributor to rising electricity consumption [14].
20. *Agricultural growth rate:* As agricultural operations expand, so will the demand for electricity for pumps used in irrigation, fumigation, lighting, farm machinery, and so on. [14].
21. *Weather*: Weather patterns are changing all throughout the world as a result of climate change. Temperatures are rising, demanding further and sustained cooling [26].
22. *Human activities*: Activities such as turning off electrical equipment while not in use or leaving them on influence the pattern of power consumption [13, 15].

3.3.2 Electricity Driving Factors Prioritization

3.3.2.1 *Concept of the HSIM Approach*

The concept of HSIM as stated in this paper, highlights the interaction between electricity driving factors and the growing demand for electricity. “The HSIM contains a weighting factor for further numerical examination of the components in the hierarchy, unlike the structural interaction matrix (SIM) idea, it illustrates the hierarchical organization of components using the subordination principle, and the hierarchical tree structured diagram (HTSD).” A given element pair can interact in a variety of ways, according to the HSIM principle. Only an interaction based on a specific contextual relationship, on the other hand, is relevant to the situation at hand. In contextual connections, the orientations of the elements that influence a system are frequently taken into account. As a result, the HSIM operational model is inextricably linked to the concepts of orientation and direction. As a result, if e_{ij}=1, e_{ji}=0, implying transitivity. As a result, elements *i* and *j* cannot interact meaningfully if elements *j* and *i* interact meaningfully.

This is expressed mathematically in Eq. (1) as:

© University of Pretoria

$$e_{ij} = \begin{cases} 1 & \text{if } i \text{ depends on activity } j, \\ 0 & \text{if } i \text{ does not depend on activity } j, \end{cases} \qquad 1$$

where e_{ij} denotes a row *i* and column *j* element.

The procedure is laid out in a step-by-step manner for establishing the HSIM for a given collection of variables as depicted in **Fig. 3.1**. The following **Fig. 3.2**, depicts the essential processes necessary to obtain the HTSD. “In a hierarchical fashion, the HTSD illustrates the prioritization order premised on a tree structural diagram. It is built on the findings of the HSIM approach. It's often organized in such a way that line segments or edges connect a collection of components or vertices. Any two vertices can only have one route between them”.

© University of Pretoria

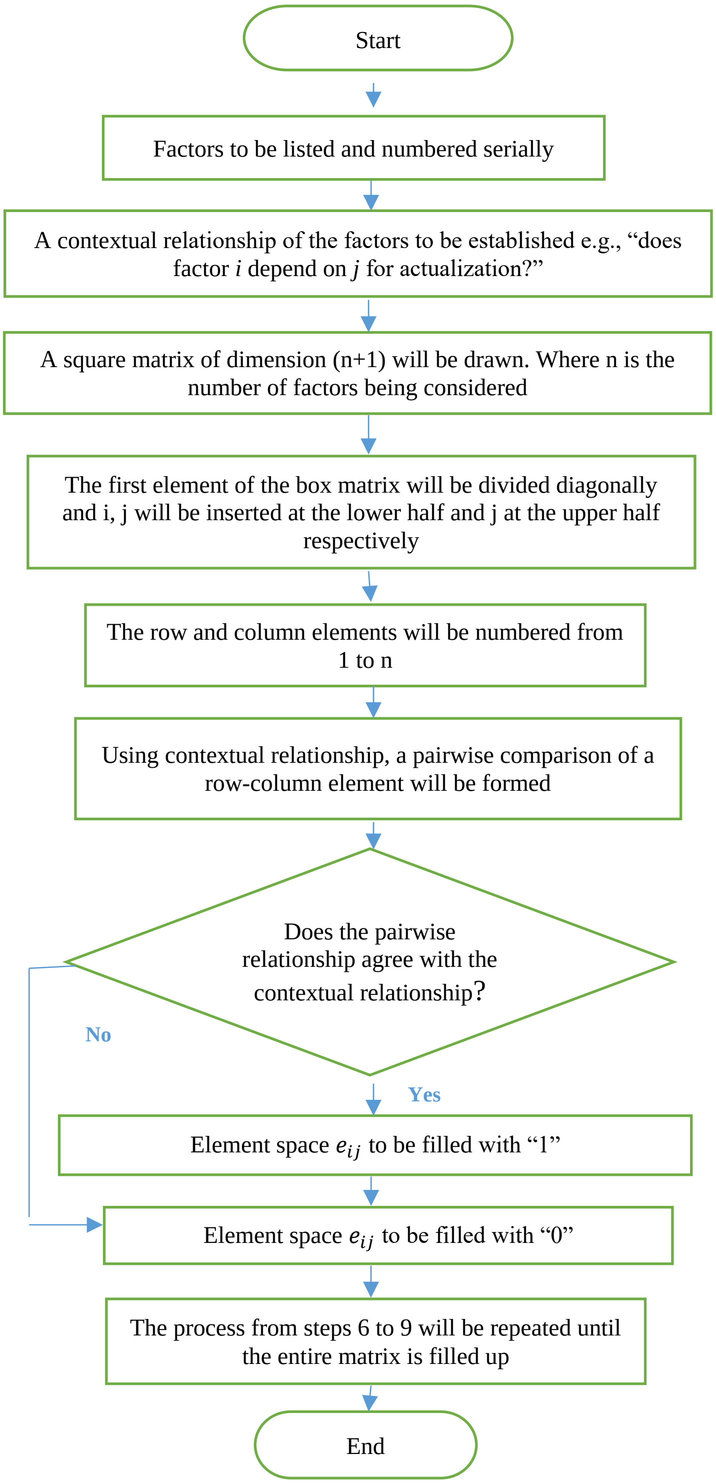

Fig. 3.1 HSIM development process [31]

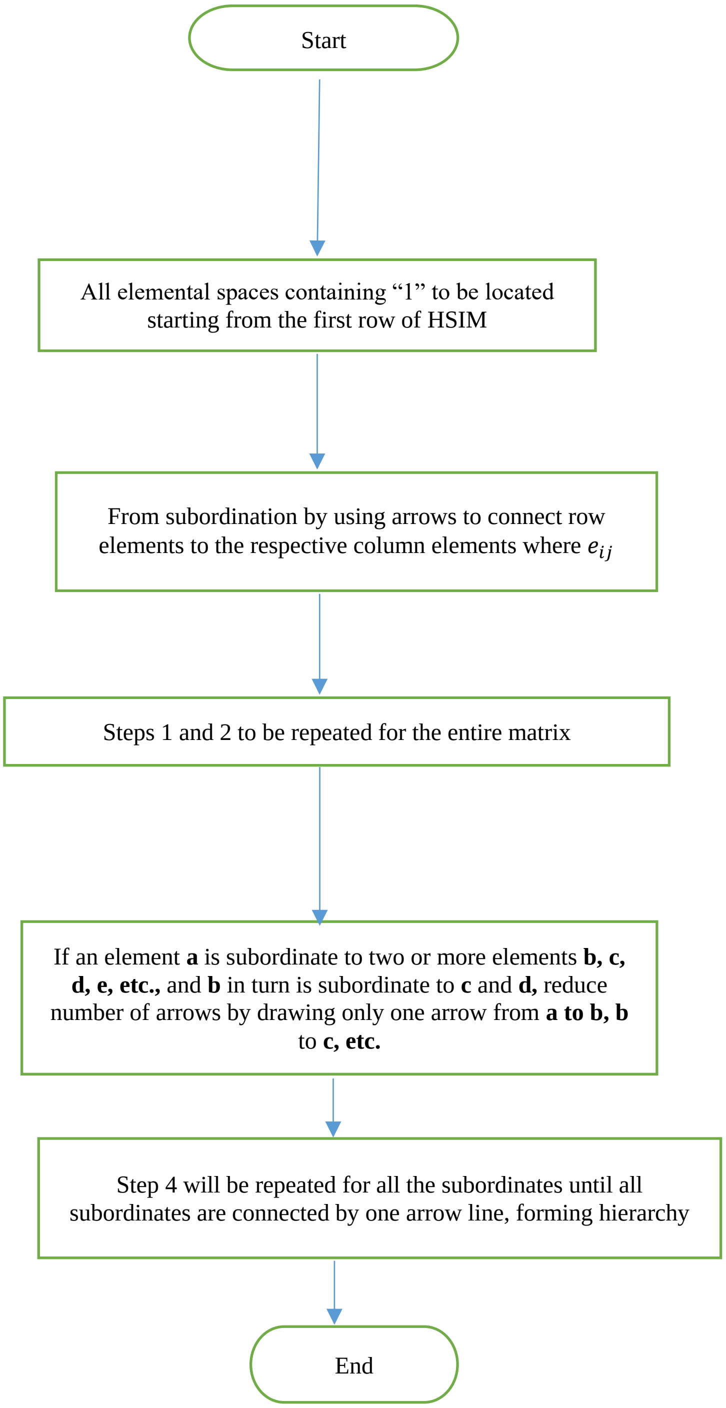

Fig. 3.2 The HTSD framework's flow diagram [31]

© University of Pretoria

3.3.2.2 Weight Determination of Electricity Driving Factors

Model for calculating weight: the methodology below was used to determine the weight/intensity of significance of the priority criterion in Eq. (2):

$$I_{RFi} = \left\{\frac{N_{SFi}}{T_{NF}} x M_{SR}\right\} + \left\{\frac{b}{T_{NF}}(M_{SR} - C)\right\}, \tag{2}$$

$$c = \frac{M_{PSF}}{T_{NF}} x M_{SR}, \tag{3}$$

$$b = N_{SFi} + 1, \tag{4}$$

where I_{RFi} is the intensity of factor i's significance rating, N_{SFi} is the number of subordinate factors to a particular factor *i*, M_{PSF} is the most number of subordinate elements that can be considered, C constant, b=T_{NF} the proportion of variations, T_{NF} is the number of variables in total, M_{SR} the highest possible scale rating.

3.3.2.3 Normalization of Weight

The following technique was used to carry out the normalization process:

1. For each of the twenty-two variables, the ratings were organized into a column matrix, as illustrated in **Table 3.2**.
2. Each rating's *n*th root was calculated, where n denotes the total number of variables considered.
3. Step 2's findings were added together, and a total was calculated.
4. Step 2's nth root for each factor was divided by step 3's summation.

These stages are combined to create the following model:

$$N_{wi} = \frac{x_i^{1/n}}{\sum_{i=1}^{n} x_i^{1/n}}, \tag{5}$$

where N_{wi} is the factor's normalised weight *i*, N number of variables, and x_i is the original rate of factor *i* before normalization.

3.3.2.4 Resource Allocation Model

A model that can efficiently distribute resources based on the priority ordering of the various variables is required to reduce the negative consequences of the indicated electricity demand driving factors. The weight of each component is considered in the simplified resource allocation model below for an optimal resource distribution. It indicates that variables with a high priority and a high likelihood of being the root cause or beginning factor demand more resources. Rather of focusing on symptoms, this

© University of Pretoria

paradigm focuses on resolving issues that stem from the root cause. The following is a generalized version of the model for optimal resource distribution:

$$C_i = \frac{N_{wi}}{\sum_{i=1}^{n} N_{wi}} x\, C_T, \qquad 6$$

$$C_T = \sum_{i=1}^{n} C_i\, N_{wi} = C_i N_{wi} + C_{i+1}N_{wi+1} + C_{i+2}N_{wi+2} + \cdots + C_{i+n-1s}N_{wi+n-1} + C_{i+n}N_{wi+n}, \qquad 7$$

where CT represents the total number of resources available, N_{wi} means the factor I's normalized weight, and C_i signifies the number of resources accessible to each component. On the other hand, the model implies that the components are easily identifiable. One disadvantage of the method is that its impartiality cannot be guaranteed.

3.3.2.5 Identified Electricity Demand Driving Factors Resource Allocation

The normalised weights of the elements to be examined are input into the created resource allocation model in this phase. C_i values vary from one component to the next, as previously indicated. However, elements with the same priority level are believed to be equally important, therefore they are allotted the same number of resources.

$$\begin{aligned} C_T = \sum_{i=1}^{22} C_i\, N_{wi} &= C_1N_{w1} + C_2N_{w2} + C_3N_{w3} + C_4N_{w4} + C_5N_{w5} + C_6N_{w6} + C_7N_{w7} + C_8N_{w8} \\ &+ C_9N_{w9} + C_{10}N_{w10} + C_{11}N_{w11} + C_{12}N_{w12} + C_{13}N_{w13} + C_{14}N_{w14} + C_{15}N_{w15} \\ &+ C_{16}N_{w16} + C_{17}N_{w17} + C_{18}N_{w18} + C_{19}N_{w19} + C_{20}N_{w20} + C_{21}N_{w21} + C_{22}N_{w22}, \qquad 8 \end{aligned}$$

3.4 Results

From the study carried out, **Table 3.1** highlights the HSIM, demonstrating the pair-wise connection between electricity demand drivers that were adopted for the benefit of this research. Then, the HTSD developmental guide is shown in **Fig. 3.2**.

Tables 3.2 and **3.3** illustrate the HTSD framework's auxiliary variables and factor significance ratings are weighted respectively.

The most rated element is 18, which is jointly followed by elements 1, 19 and 20 as highlighted in **Table 3.3**, whilst elements number 11, 14, 21 and 22 are the jointly least rated elements in respect to significance of driving electricity demand. The factor weights normalised for the considered electricity driving factors are shown in Table 4. The normalised weights are calculated using the following mathematical model:

$$\begin{aligned} C_T = \sum_{i=1}^{22} C_i\, N_{wi} &= 0.049C_1 + 0.048C_2 + 0.048C_3 + 0.047C_4 + 0.047C_5 + 0.046C_6 + 0.045C_7 + 0.045C_8 + 0.045C_9 \\ &+ 0.048C_{10} + 0.039C_{11} + 0.045C_{12} + 0.047C_{13} + 0.039C_{14} + 0.046C_{15} + 0.045C_{16} + 0.045C_{17} \\ &+ 0.049C_{18} + 0.049C_{19} + 0.049C_{20} + 0.039C_{21} + 0.039C_{22}, \qquad 9 \end{aligned}$$

© University of Pretoria

"Despite using the same constant value C to compute the normalization factor weights, different nth roots of x_i and normalised weights for the factors were obtained. Factor 18 has the most important rating intensity, as well as the highest joint normalized weight for factors N_{wi}".

3.5 Discussion

In this study, electricity demand drivers for developing and underdeveloped nations were identified and prioritised. This was followed by the development of a hierarchical tree diagram and a resource allocation model [12]. The top-most priority level was given to rated items 13, 17, 18, 19, 20, as indicated in **Fig. 3.3**. They are elements that are directly responsible for rising electricity demand in emerging and developing economies. These variables are at the root of every increase in electricity demand. Elements 21 and 12 make up the second level of importance. These elements are a direct result of the components at the top of the hierarchy. Second-level factors are directly engaged in the beginning of following factors on the third, fourth, and fifth hierarchy levels, and so on.

Table 3.3 shows the weight of each element in respect of both the subject matter and other variables examined, and it shows the intensity of relevance of the various electrical driving factors. The scale rating was believed to be in the range of 0 to 9, with 0 being the lowest and 9 being the highest [11]. The number of subordinate factors accessible to a component determines the principle of weighing or assigning degree of relevance to those factors. The goal is to make subsequent numerical analysis of prioritised elements easier.

In summary, electricity demand amongst developing and underdeveloped economies is on the rise because of the direct impact of urbanisation, industrial, agricultural, commercial/services growth rates, and pollution. Therefore, in order to achieve sustainable power supply in these countries, the abovementioned electricity demand drivers need to be prioritised over other factors whether for policy making in the power sector, research or even designing an electricity supply mix that will be able to match the growing demand.

The order or preference for implementing solutions to address rising electricity demand is expressed in the hierarchy of factors, whereas the number of subordinates assigned to a factor defines its degree of relevance or weight value. One of the most important advantages of activity prioritization is that it acts as a guide for successful power demand and supply forecasting by aiding policymakers, researchers, and students in choosing which set of systemic aspects should be addressed at various periods and to what extent. Knowing the elements' ranking order is one thing; knowing their various weights of importance in order to aid management decision-making is quite another.

© University of Pretoria

Table 3.1: HSIM demonstrating the pair-wise connection between electricity demand drivers

i	*j*																					
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22
1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	0	0
2	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	0	0
3	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	0	0
4	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	0	0
5	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0
6	0	0	0	0	1	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0
7	0	0	0	0	0	0	0	0	1	1	0	0	0	0	0	0	0	0	0	0	0	0
8	1	1	1	1	0	0	0	0	0	1	0	0	1	0	0	0	0	0	0	0	0	0
9	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	1	1	1	0	0
10	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
11	0	0	0	0	0	0	0	1	0	0	0	0	1	0	0	0	0	0	0	0	0	0
12	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0
13	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
14	1	1	1	1	0	0	0	0	0	0	0	0	0	0	1	1	1	1	1	1	0	0
15	0	0	0	0	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
16	0	0	0	0	1	1	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0
17	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
18	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
19	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
20	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
21	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0
22	0	0	0	0	0	0	1	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0

Table 3.2: The HTSD subordination table

Element number	Number of subordinate factors	Element number	Number of subordinate factors
1	6	12	1
2	5	13	3
3	4	14	0
4	3	15	2
5	3	16	1
6	2	17	1
7	1	18	7
8	1	19	6
9	1	20	6
10	5	21	0
11	0	22	0

© University of Pretoria

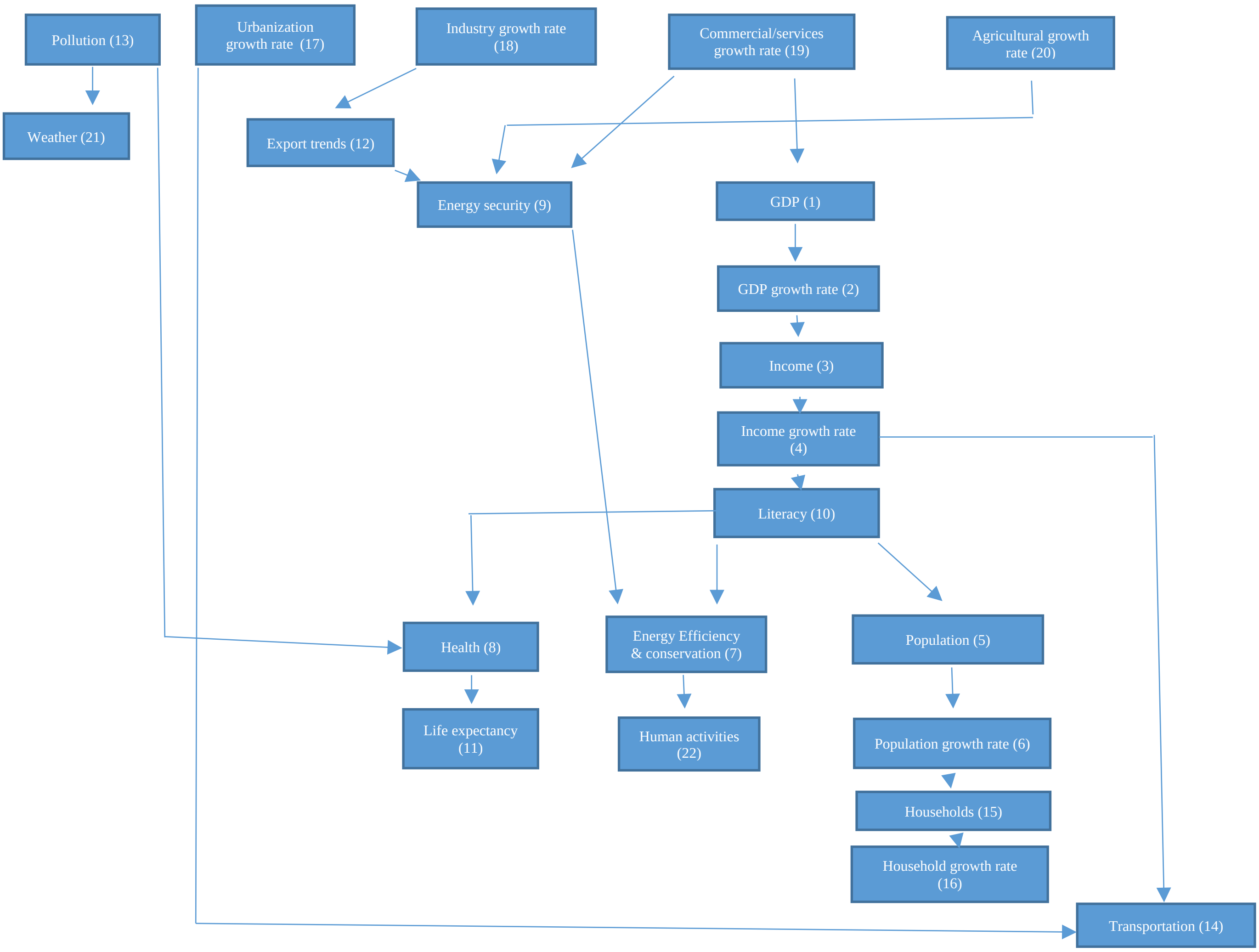

Fig. 3.3: HTSD for electricity driving factors

Table 3.3: Significance rating of factors

Element number	Rating	Element number	Rating
1	2.59	12	0.45
2	2.16	13	1.30
3	1.73	14	0.02
4	1.30	15	0.87
5	1.30	16	0.45
6	0.87	17	0.45
7	0.45	18	3.01
8	0.45	19	2.59
9	0.45	20	2.59
10	2.16	21	0.02
11	0.02	22	0.02

© University of Pretoria

Table 3.4: Normalized weights for factors

Element number	C	I_{RFi}	$\frac{1}{n}x_i$	N_{wi}
1	8.59	2.59	1.04	0.049
2	8.59	2.16	1.04	0.048
3	8.59	1.73	1.03	0.048
4	8.59	1.30	1.01	0.047
5	8.59	1.30	1.01	0.047
6	8.59	0.87	0.99	0.046
7	8.59	0.45	0.96	0.045
8	8.59	0.45	0.96	0.045
9	8.59	0.45	0.96	0.045
10	8.59	2.16	1.04	0.048
11	8.59	0.02	0.83	0.039
12	8.59	0.45	0.96	0.045
13	8.59	1.30	1.01	0.047
14	8.59	0.02	0.83	0.039
15	8.59	0.87	0.99	0.046
16	8.59	0.45	0.96	0.045
17	8.59	0.45	0.96	0.045
18	8.59	3.01	1.05	0.049
19	8.59	2.59	1.04	0.049
20	8.59	2.59	1.04	0.049
21	8.59	0.02	0.83	0.039
22	8.59	0.02	0.83	0.039
		Total	**21.43**	

© University of Pretoria

3.6 Conclusion

This study has presented an objective measure for effective planning and decision making in respect of electricity driving factors in developing economies following the rising demand for electricity. The HSIM method was utilized to illustrate priority ordering via weight determination for the identified electricity driving factors. The proposed HSIM approach was adapted to a resource allocation model for optimum distribution of scarce resources the management and control of the driving factors. The research has incorporated many electricity-driving factors and demonstrated how they contribute to growing power demand levels. This study aims to establish a framework for power sector planning and decision-making. This would be especially beneficial in the development of a long-term solution towards the rising demand for power. Instead of wasting precious resources on trial-and-error approaches in addressing such problems, a root-cause approach premised on system drivers have been proposed.

This study has identified and prioritized factors that contribute to the growing demand for electricity in developing and underdeveloped countries. These factors were discovered through various studies conducted for developing and underdeveloped countries such as Nigeria, South Africa, India, China, and Egypt, Ethiopia, among others. A future study related to this research would include a specific case study in a chosen developing or underdeveloped economy. This will help to achieve a more targeted outcome for a specific country.

Chapter References

[1] [Ouedraogo, N., 2017. Modeling sustainable long-term electricity supply-demand in Africa. *Applied Energy*, 190, pp.1047-1067.

[2] IEA, India Energy Outlook, 2015. Paris, https://www.iea.org/publications/ free publications/publication/africa-energy-outlook.html.

[3] International Renewable Energy Agency (IRENA). East African Power Pool: Planning and Prospects for Renewable Energy. Abu Dhabi/Bonn: IRENA; 2015.

[4] Ouedraogo N., 2013. Energy consumption and human development: evidence from a panel cointegration and error correction model. Energy 63:28–41 [15 December].

[5] Ouedraogo N., 2012. Energy consumption and economic growth: evidence from ECOWAS. Energy Econ 36:637–47.

[6] U.S. Energy Information Administration, International Energy Outlook 2016, 2016. www.eia.gov/forecasts/ieo/pdf/0484(2016).pdf.

[7] IEA, World Bank, Sustainable Energy for All 2015-Progress toward Sustainable Energy, World Bank, 2015, https://doi.org/10.1596/978-1-4648-0690-2. Washington, DC.

[8] Hyde, K.M., Maier, H.R., Colby, C.B., 2005. A distance-based uncertainty analysis approach to multi-criteria decision analysis for water resource decision making. Journal of Environmental Management 77 (4), 278–290.

[9] kasingh, B., Ngamsomsuke, K., Letcher, R.A., Spate, J., 2005. A data mining approach to simulating farmers' crop choices for integrated water resources management. Journal of Environmental Management 77 (4), 315–325.

[10] Xevi, E., Khan, S., 2005. A multi-objective optimisation approach to water management. Journal of Environmental Management 77 (4), 269–277.

[11] Oke, S.A., Ayomoh, M.K.O., 2005. The hybrid structural interaction matrix (HSIM): a new prioritising tool for maintenance. International Journal of Quality and Reliability Management 22 (6), 607–625.

[12] Ayomoh, M.K.O., Oke, S.A., 2006. A framework for measuring safety level for production environments. Safety Science 44, 221–239.

[13] Magnani, N., Vaona, A., 2016. Access to electricity and socio-economic characteristics: panel data evidence at the country level. Energy 103, 447–455. https://doi.org/10.1016/j.energy.2016.02.106.

[14] Cook, P., 2011. Infrastructure, rural electrification and development. Energy Sustain. Dev. 15, 304–313. https://doi.org/10.1016/j.esd.2011.07.008.

[15] Khandker, S.R., Barnes, D.F., Samad, H.A., 2013. Welfare impacts of rural electrification: a panel data analysis from Vietnam. Econ. Dev. Cult. Change 61, 659–692. https:// doi.org/10.1086/669262.

[16] Kwakwa PA, Alhassan H, Adu G., 2019. Effect of natural resources extraction on energy consumption and carbon dioxide emission in Ghana. Int J Energy Sector Manage. Available from: https://doi.org/10.1108/IJESM-09-2018-0003.

[17] Belloumi M, Alshehry AS., 2018. The Impact of Urbanization on Energy Intensity in Saudi Arabia. *Sustainability* 8: 1-17. doi:10.3390/su8040375.

[18] Khennas, S., 2012. Understanding the political economy and key drivers of energy access in addressing national energy access priorities and policies: African Perspective. Energy Policy 47, 21–26. https://doi.org/10.1016/j.enpol.2012.04.003.

[19] Kemmler, A., 2007. Factors influencing household access to electricity in India. Energy Sustain. Dev. 11, 13–20. https://doi.org/10.1016/S0973-0826(08)60405-6.

[20] Javadi, F.S., Rismanchi, B., Sarraf, M., Afshar, O., Saidur, R., Ping, H.W., Rahim, N.A., 2013. Global policy of rural electrification. Renew. Sustain. Energy Rev. https://doi.org/10.1016/j.rser.2012.11.053.

[21] Aragaw, M.L., 2013. Assessing the impacts of rural electrification in Sub-Saharan Africa: the case of Ethiopia. Diss. Abstr. Int. Sect. B Sci. Eng. 1–288.

[22] Annual Energy Outlook., 2021. Retrieved 7 November 2021, from https://www.eia.gov/outlooks/aeo/.

[23] Li K, Lin B., 2015 Impacts of urbanization and industrialization on energy consumption/CO_2 emissions: Does the level of development matter? *Renew Sust Energ Rev* 52: 1107-1122. doi: 10.1016/j.rser.2015.07.185.

[24] Chan S, Jin H, Lu Y., 2019. Impact of urbanization on CO_2 emissions and energy consumption structure: A panel data analysis for Chinese prefecture-level cities. *Struct Change Econ Dyn* 49:107-119. doi: 10.1016/j.strueco.2018.08.009.

[25] Adom PK, Kwakwa PA., 2014. Effects of changing trade structure and technical characteristics of the manufacturing sector on energy intensity in Ghana. *Renew Sust Energ Rev* 35: 475-483. doi: 10.1016/j.rser.2014.04.014.

[26] Prices and factors affecting prices - U.S. Energy Information Administration (EIA)., 2021. Retrieved 7 November 2021, from

https://www.eia.gov/energyexplained/electricity/prices-and-factors-affecting-prices.php.

[27] Oke, S., Ayomoh, M., Akanbi, O., & Oyawale, F., 2008. Application of hybrid structural interaction matrix to quality management. *International Journal Of Productivity And Quality Management*, *3*(3), 275. doi: 10.1504/ijpqm.2008.017499.

Chapter 4

Identification and prioritization of factors affecting the transition to renewables in developing economies

4.0 Chapter Overview

The significance of this chapter, focused at the identification and prioritization of factors affecting the transition to renewables in developing economies lies in its role as a roadmap towards the implementation of optimum predictive modeling for a sustainable power supply mix, specifically in the context of the Nigerian power system.

This chapter serves as a critical foundation for the subsequent chapter on optimum predictive modeling by identifying and prioritizing the key factors that impact the successful integration of renewable energy sources in developing economies like Nigeria. It provides a comprehensive understanding of the challenges, opportunities, and potential barriers that need to be addressed in order to develop an effective predictive modeling approach for a sustainable power supply mix in the Nigerian context.

By identifying and prioritizing these factors, such as regulatory frameworks, technological readiness, financial considerations, social and cultural aspects, and environmental considerations, this chapter helps to highlight the critical aspects that need to be considered during the implementation of optimum predictive modeling. It provides guidance and insights for decision-makers, policymakers, and stakeholders on the key areas that require attention in order to ensure a successful transition to renewable energy sources in the Nigerian power system.

Furthermore, this chapter serves as a roadmap by outlining the necessary strategies that need to be taken into account to address the identified factors and implement the optimum predictive modeling approach of chapter 5. It provides a framework for developing a contextually relevant and sustainable predictive modeling approach that takes into account the unique dynamics of renewable energy integration in developing economies like Nigeria.

4.1Introduction

The developed economies of the world are making a significant shift towards the use of renewable energy sources because of their low impact on the environment, capacity to regenerate, ability to provide jobs, price stability, improved health, reliability, resilience, and energy security. Developing and underdeveloped nations continue to rely on fossil fuels for their lighting, air conditioning, and heating needs, among other things. Consequently, it is necessary to determine the factors impeding the transition to renewables in developing countries and then rank them in order of importance. The process of transitioning to an energy mix made up of renewable energy sources will be sped up as a result and developing economies will be able to take advantage of all the benefits outlined above.

The use of energy in developing countries is increasing at an unparalleled rate. There are about 620 million people who do not have access to electricity in Africa and several Asian nations; this number is expected to continue to rise over the next 25 years [1, 2]. It is well acknowledged that these developing countries have significant challenges in terms of achieving economic growth [3, 4]. As the population, economic growth, and a host of other factors continue to increase in these developing nations, the existing energy gap will only worsen. Sources of energy such as natural gas, biomass, coal, uranium, sunlight, wind, and tidal energy, among others, are utilized for various applications ranging from electricity generation, transportation, agriculture, etc. Electricity demand constitutes about 18% of the world's total energy consumption in 2013, making it an extremely important factor in both the social and economic well-being of countries [4].

According to research carried out by the EIA of the United States, the demand for energy in non-OECD countries would be 89% higher than that of OECD nations in the year 2040 [5]. Because of these alarming energy demand projections, it is of utmost importance for developing economies to transition towards renewable energy sources. This will enable developing countries to reduce their carbon footprint, and ensure that people have access to energy, improved health, and increased employment opportunities, among other benefits. Despite sensitizations and enlightenments, the contribution of renewable energy sources to the energy mix is just 23% in Nigeria [6], 10% in South Africa [7], 12% in Egypt [8], 4.5% in Malaysia [9], 36% in Pakistan [10], and 7% in Iran [11].

This study identified and prioritized the factors that affect the transition to renewables in developing countries. This will ensure that resources are distributed in a hierarchical or priority manner. This study will be of substantial benefit to policymakers, academics, and students to establish an effective management strategy based on the most essential factors impacting the transition to renewables.

4.2 Methodology for the research

The Hybrid Structural Interaction Matrix (HSIM) approach was used for the prioritization of factors impeding the transition to renewable energy in developing countries. The analytical hierarchy process (AHP) is utilized for prioritization in sectors including maintenance, health, safety, and energy. With the incorporation of a weighting model into the prioritizing model, the

HSIM has a major advantage over AHP's inherent shortcomings due to its ability to formulate dynamic models in resource allocation and the adoption of a root-cause approach. Resource decision-making in such context benefits water resource planning [12] and data mining approaches [13]. The multi-objective optimization technique is another analogous strategy for resource allocation [14]. [15] and [16] effectively used the HSIM technique to prioritize and plan for safety engineering maintenance resources.

To prioritize barriers responsible for the slow transition to renewables in developing economies, the concept of subordination inherent in the HSIM approach was used to effect the ranking order. Hence, to allocate resources to the identified barriers, the fundamental model of resource allocation was used with the normalized weight of variables.

4.2.1 Identified barriers to renewable energy transition

The barriers to renewable energy transition in developing countries as identified from various literature are briefly discussed in this section. The following are the barriers which are listed from one to eighteen:

1. ***Competing against fossil fuels****:* Fossil fuels are still a cheaper alternative to renewables, making them very competitive in developing countries.
2. ***Subsidies and government grants***: More subsidies for fossilized energy sources put renewable energy sources at a significant disadvantage, impeding the transition to renewables in developing economies.
3. ***Non or few renewables financing institutions***: There is a restricted number of organizations and financial methods available to provide finance for renewable energy projects [17, 18].
4. ***High capital cost***: Investors are forced to take a defensive stance owing to the comparatively high initial capital costs associated with renewable technologies [17].
5. ***Intangible expenses***: At present, the total cost of fuel in practically all countries includes the cost of discovery, production, distribution, and usage, but it does not include the cost of the damage that it does to the environment and society [19].
6. ***Inadequate infrastructure and facilities***: A hurdle to the penetration of renewable energy sources is the limited availability of advanced technology that is required for renewable energy [20].
7. ***Poor attitude towards operation and maintenance***: Because the technology behind renewable energy sources is still in its initial stages and has not been developed to its full potential, there is a paucity of knowledge surrounding its management and maintenance [21].
8. ***Inadequate R&D capabilities***: Renewables in developing countries are still in their initial stages, making governments and investors cautious about investing [22].
9. ***Technology complexity***: Renewable energy technologies lack standards, protocols, and recommendations for durability, dependability, performance, and other issues. This prevents the large-scale commercialization of renewable energy [23].
10. ***Barriers to public awareness and information***: Understanding of renewable energy technologies, the environmental and economic benefits, and the financial viability constitute the major barriers to public awareness [23].

11. ***'Not in my backyard.' (NIMB) syndrome***: Various people and organizations are in favor of renewable energy, but not in their backyards [24].
12. ***Loss of other/impact on other***: Renewable energy sources need far more land than fossil fuels to provide the same quantity of energy [25].
13. ***Experienced professionals are scarce***: Reducing dependence on fossil fuels requires a skilled workforce which is inadequate in developing countries [17].
14. ***Ineffective government policies***: Energy policy instability, lack of belief in renewable energy technology, and under-equipped government institutions [26].
15. ***Inadequate financial incentives***: Feed-in tariffs are government-sponsored subsidies designed to make renewables competitive but are absent in nearly all developing nations [27].
16. ***Administrative and bureaucratic complexities***: Lobbying also results in higher expenses which in turn delay renewable energy projects [28].
17. ***Government commitments are impractical***: There is a disconnect between the policy objectives governments choose to pursue and the actual outcomes accomplished via implementation [29].

18. ***Standards and certifications are lacking***: Uncertainty arises as a result of the unavailability of standards, which forces energy suppliers to contend with additional impediments [30].

4.2.2 Limitations, constraints, and assumptions of study

Limitations of the Study:

1. Data Availability and Reliability: The study may rely on limited or incomplete data on renewable energy transition barriers in developing economies, which could affect the accuracy and reliability of the findings.
2. Methodological Limitations: The use of the Hybrid Structural Interaction Matrix (HSIM) for prioritizing barriers may have inherent limitations, such as subjectivity in assigning weights or assumptions made in the modeling process.
3. Time Constraints: The study may be limited by time constraints, which may affect the depth or comprehensiveness of the analysis and findings.

Constraints:

1. Access to Information: Constraints in accessing reliable and comprehensive data on renewable energy transition barriers in developing economies could limit the accuracy and robustness of the findings.
2. Resource Limitations: Constraints in terms of funding, time, and human resources may affect the scope and quality of the study, including data collection, analysis, and interpretation.

Assumptions:

1. Homogeneity of Developing Economies: The study may assume that developing

economies share similar characteristics or face similar barriers to renewable energy transition, which may not always be the case due to the diversity and heterogeneity among developing economies.

2. Validity of the HSIM Model: The study may assume that the HSIM model is a valid and appropriate method for prioritizing renewable energy transition barriers, without considering potential limitations or criticisms of the model.
3. Policy Relevance: The study may assume that the identified barriers are relevant to policymakers and academics without considering variations in policy contexts or stakeholder perspectives.
4. Future Projections: The study may make assumptions about future trends and projections related to renewable energy transition in developing economies, which may be uncertain and subject to change.

4.2.3 Prioritization of factors affecting renewable energy transition

4.2.3.1 Concept of the HSIM

As mentioned in this study, the concept of HSIM highlights the interaction between barriers responsible for the renewable energy transition in developing countries. Unlike the structural interaction matrix (SIM) concept, a weighting factor for arithmetical investigation of the factors in the hierarchy is contained in the HSIM, and it illustrates the hierarchical organization using the subordination principle and the hierarchical tree-structure diagram (HTSD). According to the HSIM, a given element pair may interact in several ways. In contrast, an interaction based on a specific contextual relationship is relevant.

The HSIM operational model is inextricably linked to the concepts of orientation and direction. As a result, if e_{ij}=1, e_{ji} =0, implying transitivity and if elements *j* and *i* interact effectively, elements *i* and *j* will not be able to interact effectively.

This is mathematically stated as Eq. (1):

$$e_{ij} = \begin{cases} 1 & if\ i\ depends\ on\ activity\ j, \\ 0 & if\ i\ doesn't\ depend\ on\ activity\ j, \end{cases} \tag{1}$$

where e_{ij} represents elements that are in row *i* and column *j*. The procedure for determining the HSIM is represented in **Fig. 4.1** in a step-by-step way. The essential procedure to develop the HTSD is illustrated in **Fig. 4.2**. Which represents the priority order of a set of barriers, factors, or elements in a hierarchical order.

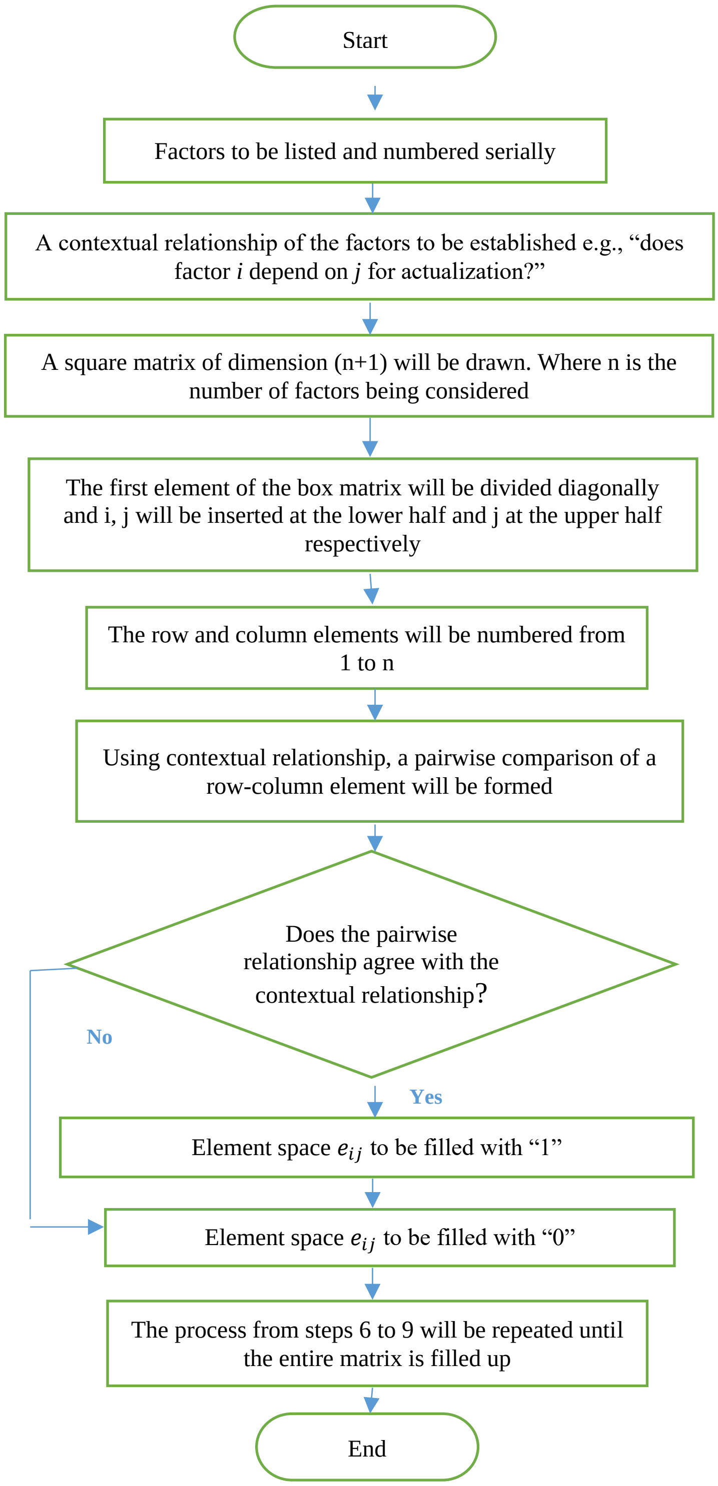

Fig. 4.1. HSIM development process [31]

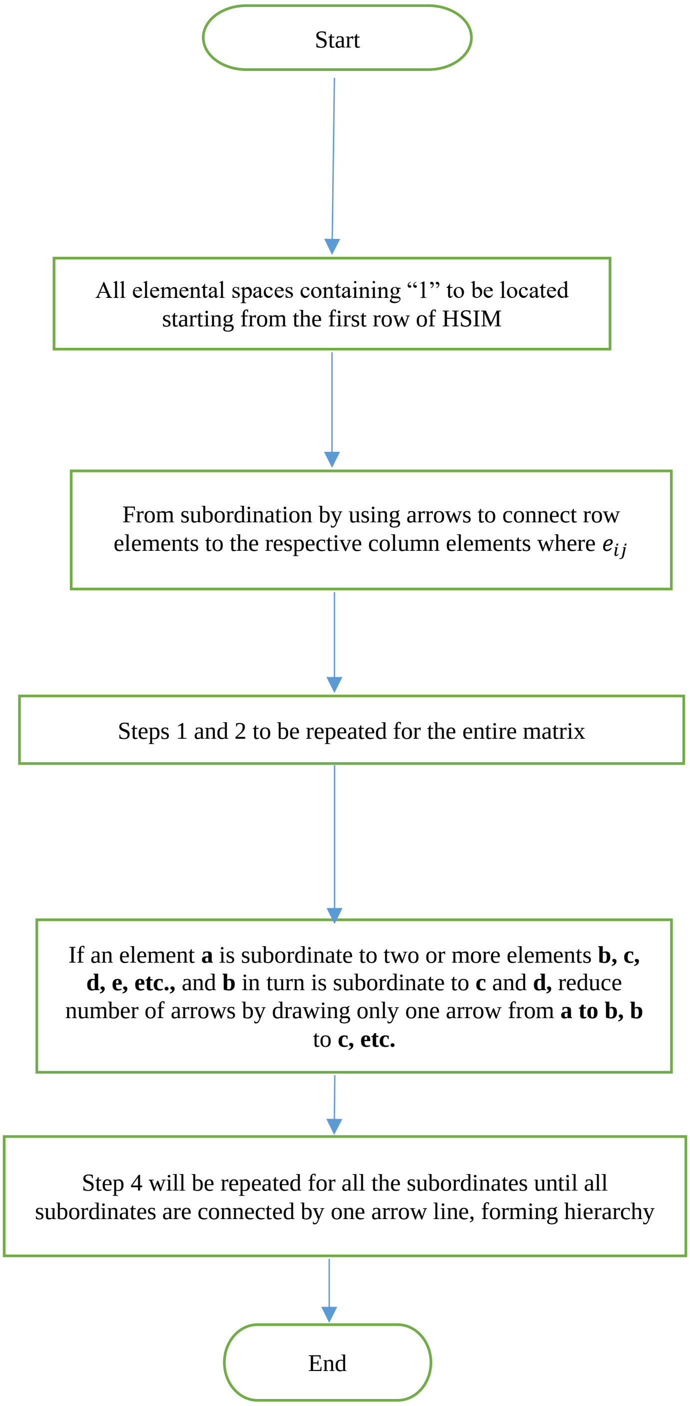

Fig. 4.2. The HTSD framework's flow diagram [31]

4.2.3.2 Factors impacting renewable energy transition weighted

The weight calculation model: the following methodology was used to calculate the priority criterion's weight/intensity of significance in Eq. (2):

$$I_{RFi} = \left\{\frac{N_{SFi}}{T_{NF}} x M_{SR}\right\} + \left\{\frac{b}{T_{NF}}(M_{SR} - C)\right\} \tag{2}$$

$$c = \frac{M_{PSF}}{T_{NF}} x M_{SR} \tag{3}$$

$$b = N_{SFi} + 1 \tag{4}$$

N_{SFi} variables for a factor i. M_{PSF} maximum subordinate factors, and I_{RFi} is a factor's intensity of i's significance rating. T_{NF} total amount of variables considered, and M_{SR} maximum scale rating. C is the constant, $b = T_{NF}$ is the fraction of variations, and M_{SR} greatest promising rating on the scale.

4.2.3.3 Weight normalization

The normalization was carried out using the following steps:

1. Grouping of ratings to form a matrix for each of the eighteen factors, as shown in **Table 4.1**.
2. The *nth* root of each rating was determined, with n being the total number of variables investigated.
3. The results of step 2 were added together to arrive at a total.
4. The nth root of each element was used to divide the total in step 2.

In Eq. (5), these steps are merged to give the following model:

$$N_{wi} = \frac{x_i^{1/n}}{\sum_{i=1}^{n} x_i^{1/n}} \tag{5}$$

where N_{wi} is the factor's normalized weight i, N number of variables, and x_i is the original rate of factor i before normalization.

4.2.3.4 Model for allocating resource

It is vital to have a model that is capable of effectively distributing resources based on the priority of the various factors to reduce the negative impacts that are being caused by the aforementioned problems that are impeding the transition to renewables. The simplified model for allocating resources that follows takes into consideration, for the purpose of providing the best possible distribution of resources, the weight that each component carries. This indicates that factors with a high priority have a high probability of being the primary cause or initiating factor, and thus, they call for a greater investment of resources. In this paradigm, rather than concentrating on the symptoms of a problem, the emphasis is placed on finding and addressing its underlying causes. The generalized model for determining the optimal approach for resource distribution is represented in Eq. (6).

$$C_i = \frac{N_{wi}}{\sum_{i=1}^{n} N_{wi}} x\, C_T \tag{6}$$

$$C_T = \sum_{i=1}^{n} C_i \, N_{wi} = C_i N_{wi} + C_{i+1} N_{wi+1} + C_{i+2} N_{wi+2} + \cdots + C_{i+n-1s} N_{wi+n-1} + C_{i+n} N_{wi+n} \tag{7}$$

C_T represents available resources, N_{wi} represents the normalized weights of factor i and C_i the number of resources available to each factor. On the other hand, the model implies that the components are easily identifiable. One disadvantage of the method is that its objectivity cannot be guaranteed.

4.2.3.5 Identified factors affecting the transition to renewable energy resource allocation

The identified factors' normalized weights are then entered into the resource allocation model. As previously stated, values for each factor. To be equivalent in criticality, factors with the same priority level are allocated the resource Eq. (8).

$$\begin{aligned} C_T = \sum_{i=1}^{18} C_i \, N_{wi} = {} & C_1 N_{w1} + C_2 N_{w2} + C_3 N_{w3} + C_4 N_{w4} + C_5 N_{w5} + C_6 N_{w6} + C_7 N_{w7} + C_8 N_{w8} \\ & + C_9 N_{w9} + C_{10} N_{w10} + C_{11} N_{w11} + C_{12} N_{w12} + C_{13} N_{w13} + C_{14} N_{w14} + C_{15} N_{w15} \\ & + C_{16} N_{w16} + C_{17} N_{w17} \\ & + C_{18} N_{w18} \, , \end{aligned} \tag{8}$$

4.3 Results

The HSIM of the factors that were identified as barriers to renewable energy transition are highlighted in **Table 4.1** with the HTSD being represented in **Fig. 4.2**.

Table 4.1. HSIM pair-wise connection between factors affecting the transition to renewables in developing nations

i	***j***																	
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**
1	0	1	1	1	1	1	0	1	1	1	1	0	1	0	1	1	0	0
2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
4	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0
5	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0
6	0	1	1	0	0	0	0	0	0	0	0	0	0	1	1	0	1	0
7	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0
8	0	1	1	0	0	1	0	0	0	0	0	0	1	0	1	0	0	0
9	0	1	1	0	0	1	0	1	0	0	0	0	1	0	1	0	0	0
10	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
11	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0
12	0	0	0	0	0	0	0	1	1	0	0	0	1	0	0	0	0	0
13	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
14	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
15	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0
16	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0
17	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	1	0	0
18	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0

Table 4.2. The HTSD subordination table

Number of elements	Number of subordinate factors	Element number	Number of subordinate factors
1	0	10	5
2	4	11	1
3	4	12	0
4	1	13	4
5	1	14	5
6	3	15	4
7	0	16	2
8	2	17	1
9	4	18	0

In the HTSD framework, the variables and the significant rating weights of the factors are shown in **Tables 4.2 and 4.3**, respectively.

As shown in **Table 4.3**, factors **1** (competing against fossil fuels), **7** (Poor attitude towards operation and maintenance), **12** (Loss of other/impact on other), and **18** (standards and certifications are lacking) are the least important when it comes to barriers for the transition to renewable energy in developing nations. The most important factors are **10** (barriers to public awareness and information) and **14** (ineffective government policies), followed by **2** (subsidies and government grants), **3** (non or few renewables financing institutions), **9** (technology complexity), **13** (experienced professionals are scarce), and **15** (inadequate financial incentives). The least important factors are **1** (competing against fossil fuels) and **7** (poor attitude towards operation and maintenance). **Table 4** presents the normalized factor weights for the barriers of renewable energy transition.

Table 4.3. Significance rating of factors

Element number	Rating	Element number	Rating
1	0.028	10	2.667
2	2.139	11	0.556
3	2.139	12	0.028
4	0.556	13	2.139
5	0.556	14	2.667
6	1.611	15	2.139
7	0.028	16	1.083
8	1.083	17	0.556
9	2.139	18	0.028

Table 4.4. Normalized weights for renewable energy transition barriers

Number of elements	C	***IRFi***	$\frac{1}{n}/x_i$	N_{wi}
1	8.5	0.028	0.843	0.048
2	8.5	2.139	1.037	0.059
3	8.5	2.139	1.037	0.059
4	8.5	0.556	0.972	0.055
5	8.5	0.556	0.972	0.055
6	8.5	1.611	1.023	0.058
7	8.5	0.028	0.843	0.048
8	8.5	1.083	1.004	0.057
9	8.5	2.139	1.037	0.059
10	8.5	2.667	1.048	0.060
11	8.5	0.556	0.972	0.055
12	8.5	0.028	0.843	0.048
13	8.5	2.139	1.037	0.059
14	8.5	2.667	1.048	0.060
15	8.5	2.139	1.037	0.059
16	8.5	1.083	1.004	0.057
17	8.5	0.556	0.972	0.055
18	8.5	0.028	0.843	0.048
		Total	**17.573**	**1.000**

The decision-maker is given some insight into the interconnection that exists among the many aspects that were taken into consideration by the hierarchical order that has been exhibited so far. In addition, it displays the sequence in which actions are carried out according to the subordination order.

A factor's "weight" or "intensity of relevance" is directly proportional to the number of factors that it subordinates to. The intensity rating will be increased according to the amount of subordinating factors present. Because of this, the importance of a factor increases in proportion to the number of other factors that it subordinates. It is possible that the priority rating or hierarchical position of a factor is not the ideal metric to use when attempting to determine the degree to which a factor is important. This inference is based on the observation that a component that has a sizeable number of subordinating factors may, in turn, be subordinated to a factor that has a smaller number of subordinates. As a result, the aspect that is the most significant could not necessarily express itself in the position that is highest up in the hierarchy.

On the other hand, the hierarchical structure in this study has adhered to the weight magnitude of the components, which indicates the relevance of the factors. The HTSD is generally used to represent the sequence in which a group of factors, components, objectives, actions, etc. that are all part of the same system and are working toward the same goal are put into effect.

With Eq. (9), the normalized weights of the identified factors were determined:

$$C_T = \sum_{i=1}^{18} C_i\, N_{wi} = 0.05C_1 + 0.05C_2 + 0.05C_3 + 0.05C_4 + 0.05C_5 + 0.05C_6 + 0.05C_7 + 0.05C_8 + 0.05C_9 + 0.05C_{10} + 0.04C_{11} + 0.05C_{12} + 0.05C_{13} + 0.04C_{14} + 0.05C_{15} + 0.05C_{16} + 0.05C_{17} + 0.05C_{18}, \quad (9)$$

Despite computing the factors' normalization weights with a constant value of C, dissimilar n_{th} roots of x_i and normalized weights for the factors were obtained. Factors **10** (barriers to public awareness and information) and **14** (ineffective government policies) have the highest ratings and normalized weight for the identified factors N_{wi}.

4.4 Discussion

This study has presented barriers to renewable energy transition in developing countries. Factors **2** (subsidies and government grants), **3** (non or few renewables financing institutions), **13** (experienced professionals are scarce), **10** (barriers to public awareness and information), and **14** (ineffective government policies) were assigned higher priority order on the hierarchy, as indicated in **Fig. 2**. These are the barriers for renewable energy transition in developing countries. Factors **5** (intangible expenses), **11** (not in my backyard syndrome), **7** (poor attitude towards operation and maintenance), **16** (administrative and bureaucratic complexities), **18** (standards and certifications are lacking), and **15** (inadequate financial incentives) make up the second degree of significance. The top-level factors have a direct effect on the second-level factors while the second-level factors also have a direct relationship with the third, fourth, and fifth hierarchy-level factors, etc., as presented in **Fig. 4.2**.

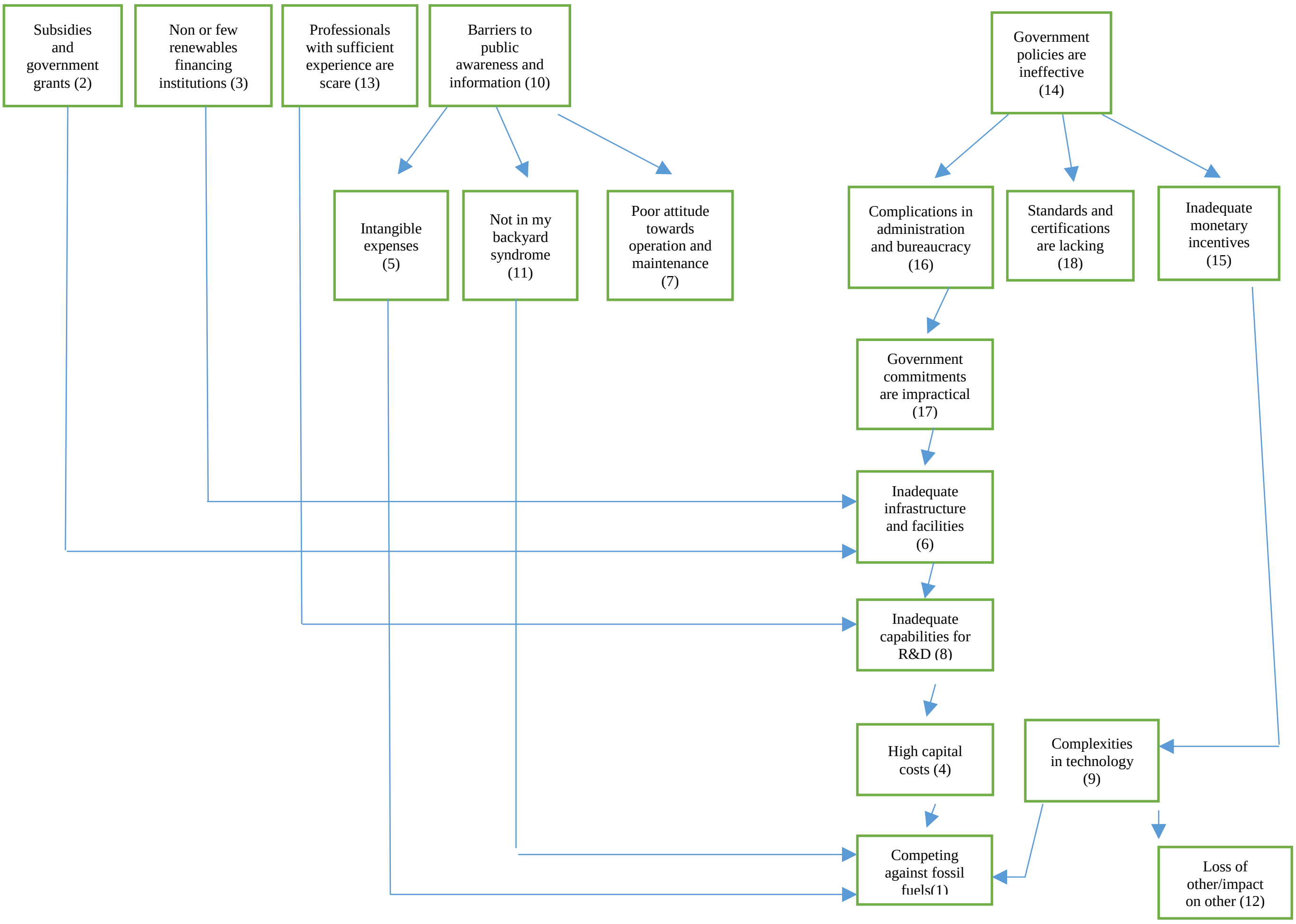

Fig. 4.3. HTSD for factors affecting the transition to renewables in developing nations

Table 4.3 displays the relative relevance of each factor and other variables analyzed, as well as the intensity of the multiple barriers impacting the transition to renewables in developing countries. The scale rating was between 0 which is the minimum and 9 the maximum. Subordinate factors weighting is determined by the number of subordinate factors available to a factor. This will make the numerical analysis of prioritized factors simplified. The number of subordinate factors that are accessible to a factor is a primary consideration in the application of the weighting principle, which determines how intensely important a component is. The rationale behind this is to facilitate further numerical examination of issues that have been prioritized.

In addition to this, the factors' weights after being normalized were calculated. In most cases, the total of the normalized weights assigned to the various factors under consideration will amount to one. Because of this, expressing the ratio of proportionality between the various components was made much simpler.

As can be seen in the model for resource allocation, the normalized weight served as the foundation for the distribution of resources among the various criteria. This method demonstrates that a component i may have an identical weight value as another factor j but be lower than it in the hierarchical position. This is because this methodology considers weight values. The evidence for this may be found in factors **10** (barriers to public awareness and information) and **14** (ineffective government policies). Factors **10** and **14** have a larger weight value, and both are put in the same hierarchy because they have been identified as a possible root cause of the slow transition to renewable energy in developing countries. The number of subordinates tied to a factor reflects the extent to which it is important or its weight value, while the ordering of factors in the hierarchy shows the order of preference for the execution of solutions to handle renewable energy transition issues. One of the most fundamental benefits of activity prioritization is that it acts as a guide to the transition of renewables in developing countries. This is accomplished by assisting the decision-maker in determining which set of systemic factors are to be given preference and to what extent at various points in time. It is obvious that knowing the order in which the components are ranked is one thing but knowing the relative weight of significance of each aspect in order to assist in making decisions is another.

4.5 Conclusion

A strategy for optimal planning and sustainable policy formulation towards accelerating the integration of renewable energy sources in developing countries has been explored and presented in this paper. The study identified the barriers responsible for the slow transition to a renewable energy-dependent economy in developing economies. The HSIM approach was used to analyze and rank the identified barriers ensuring that resources are dispersed in a prioritized order in a bid to address these barriers. A long-term strategy to meet rising energy demand while reducing GHG emissions would be particularly beneficial to developing nations. Owing to reasons such as financial investments, power purchase agreements, regulatory and legislative frameworks, politics, policy and strategies, technology and innovation, environmental programs, public awareness, etc., the transition to renewable energy has remained an exceedingly sluggish act that requires a holistic intervention to ensure sustainable renewable power supply in the affected low-income nations. The study found out that the factors that are immensely responsible for the slow transition to renewable energy in developing countries are absence of subsidies and government grants, non or few renewables financing institutions, experienced professionals are scarce, barriers to public awareness and information, and ineffective government policies. A significant benefit of the weighted factors prioritization approach as presented herein is that it is capable of aiding stakeholders such as the government, legislators, members of the academia, research students, etc., to identify system drivers requiring the most significant to the least attention in all ramifications. Understanding the components' relative importance for improved management decision-making is a critical activity that is premised on the hierarchical order.

Chapter References

[1] Ouedraogo, N. (2017). Modeling sustainable long-term electricity supply-demand in Africa. *Applied Energy*, *190*, 1047-1067. doi: 10.1016/j.apenergy.2016.12.162

[2] IEA, India Energy Outlook, (2015). Paris, https://www.iea.org/publications/ free publications/publication/africa- energy-outlook.html.

[3] Ouedraogo, N. (2013). Energy consumption and human development: Evidence from a panel cointegration and error correction model. *Energy*, *63*, 28-41. doi: 10.1016/j.energy.2013.09.067.

[4] Ouedraogo, N. (2013). Energy consumption and economic growth: Evidence from the economic community of West African States (ECOWAS). *Energy Economics*, *36*, 637-647. doi:10.1016/j.eneco.2012.11.011

[5] NERC (2018). Annual Report & Accounts (NERC: Nigerian Electricity Regulatory Commission), Abuja.

[6] H. A. Ibrahim and M. K. Ayomoh, "Identification and Prioritisation of Electricity Driving Factors for Power Supply Sustainability: A Case of Developing and Underdeveloped Nations," 2021 IEEE Asia-Pacific Conference on Computer Science and Data Engineering (CSDE), 2021, pp. 1-6, doi: 10.1109/CSDE53843.2021.9718450.

[7] G. Aquila, E. de Oliveira Pamplona, A.R. de Queiroz, P.R. Junior, M.N. Fonseca, (2017). An overview of incentive policies for the expansion of renewable energy generation in electricity power systems and the Brazilian experience, Renewable and Sustainable Energy Reviews 70 (2017) 1090–1098.

[8] IRENA (2021). Retrieved 9 October 2021, from https://www.irena.org/IRENADocuments/Statistical_Profiles/Asia/Malaysia_Asia_RE_SP.pdf.

[9] Pakistan - Renewable Energy. (2021). Retrieved 9 October 2021, from https://www.trade.gov/country-commercial-guides/pakistan- renewable-energy.

[10] News, L. (2021). Iran Falls Drastically Short Of Renewable Energy Target | OilPrice.com. Retrieved 9 October 2021, from https://oilprice.com/Latest-Energy-News/World-News/Iran-Falls- Drastically-Short-Of-Renewable-Energy-Target.html.

[11] IEA, World Bank, Sustainable Energy for All 2015-Progress toward Sustainable Energy, World Bank, (2015), https://doi.org/10.1596/978- 1-4648-0690-2. Washington, DC.

[12] Hyde, K.M., Maier, H.R., Colby, C.B., (2005). A distance-based uncertainty analysis approach to multi-criteria decision analysis for water resource decision making. Journal of Environmental Management 77 (4), 278–290.

[13] kasingh, B., Ngamsomsuke, K., Letcher, R.A., Spate, J., (2005). A data mining approach to simulating farmers' crop choices for integrated water resources management. Journal of Environmental Management 77 (4), 315–325.

[14] Xevi, E., Khan, S., (2005). A multi-objective optimisation approach to water management. Journal of Environmental Management 77 (4), 269–277.

[15] Oke, S.A., Ayomoh, M.K.O., (2005). The hybrid structural interaction matrix (HSIM): a new prioritizing tool for maintenance. International Journal of Quality and Reliability Management 22 (6), 607–625.

[16] Ayomoh, M.K.O., Oke, S.A., (2006). A framework for measuring safety levels for production environments. Safety Science 44, 221–239.

[17] Ansari, M., Kharb, R., Luthra, S., Shimmi, S., & Chatterji, S. (2013). Analysis of barriers to implementing solar power installations in India using interpretive structural modeling technique. *Renewable And Sustainable Energy Reviews*, *27*, 163-174. doi: 10.1016/j.rser.2013.07.002.

[18] Ohunakin, O., Adaramola, M., Oyewola, O., & Fagbenle, R. (2014). Solar energy applications and development in Nigeria: Drivers and barriers. *Renewable And Sustainable Energy Reviews*, *32*, 294-301. doi: 10.1016/j.rser.2014.01.014.

[19] Arnold, U., & Yildiz, Ö. (2015). Economic risk analysis of decentralized renewable energy infrastructures – A Monte Carlo Simulation approach. *Renewable Energy*, *77*, 227-239. doi: 10.1016/j.renene.2014.11.059.

[20] Dulal, H., Shah, K., Sapkota, C., Uma, G., & Kandel, B. (2013). Renewable energy diffusion in Asia: Can it happen without government support?. *Energy Policy*, *59*, 301-311. doi: 10.1016/j.enpol.2013.03.040.

[21] Sen, R., & Bhattacharyya, S. (2014). Off-grid electricity generation with renewable energy technologies in India: An application of HOMER. *Renewable Energy*, *62*, 388-398. doi: 10.1016/j.renene.2013.07.028.

[22] Cho C., Yang L., Chu Y., Yang H. C, C., L., Y., Y., C., & H., Y. (2013). Renewable energy and renewable R&D in EU countries. *Integrate. Anal*, *2*(1), 10-16.

[23] Nasirov, S., Silva, C., & Agostini, C. (2015). Investors' Perspectives on Barriers to the Deployment of Renewable Energy Sources in Chile. *Energies*, *8*(5), 3794-3814. doi: 10.3390/en8053794.

[24] Guo, X., Liu, H., Mao, X., Jin, J., Chen, D., & Cheng, S. (2014). Willingness to pay for renewable electricity: A contingent valuation study in Beijing, China. *Energy Policy*, *68*, 340-347. doi: 10.1016/j.enpol.2013.11.032.

[25] Chauhan, A., & Saini, R. (2015). Renewable energy-based off-grid rural electrification in the Uttarakhand state of India: Technology options, modelling method, barriers, and recommendations. *Renewable And Sustainable Energy Reviews*, *51*, 662-681.doi: 10.1016/j.rser.2015.06.043.

[26] Zhang, H., Li, L., Zhou, D., & Zhou, P. (2014). Political connections, government subsidies and firm financial performance: Evidence from renewable energy manufacturing in China. *Renewable Energy*, *63*, 330-336. doi: 10.1016/j.renene.2013.09.029.

[27] Sun, P., & Nie, P. (2015). A comparative study of the feed-in tariff and renewable portfolio standard policy in the renewable energy industry. *Renewable Energy*, *74*, 255-262. doi: 10.1016/j.renene.2014.08.027.

[28] Ahlborg, H., & Hammar, L. (2014). Drivers and barriers to rural electrification in Tanzania and Mozambique – Grid-extension, off-grid, and renewable energy technologies. *Renewable Energy*, *61*, 117-124. doi: 10.1016/j.renene.2012.09.057.

[29] Goldsmiths K.R. (2015). Barriers and solutions to the development of renewable energy technologies in the Caribbean. (April).

[30] Emodi, V., Yusuf, S., & Boo, K. (2014). The Necessity of the Development of Standards for Renewable Energy Technologies in Nigeria. *Smart Grid And Renewable Energy*, *05*(11), 259-274. https://doi.org/10.4236/sgre.2014.511024.

[31] Oke, S., Ayomoh, M., Akanbi, O., & Oyawale, F. (2008). Application of hybrid structural interaction matrix to quality management. *International Journal of Productivity And Quality Management*, *3*(3), 275. doi: 10.1504/ijpqm.2008.017499.

Chapter 5

Optimum predictive modelling for a sustainable power supply mix: A case of the Nigerian power system

5.0 Chapter Overview

The chapter discusses the use of multi-objective optimization for developing an optimum predictive model for a sustainable power supply mix in Nigeria. The chapter highlights the ever-increasing demand for electricity in Nigeria and its impact on the environment, which necessitates the expansion of the power generation mix to include sustainable energy sources. The chapter specifically focuses on the case of the Nigerian power system.

The chapter emphasizes that sustainable and efficient power generation planning must consider multiple conflicting objectives, such as reducing costs, reducing CO_2 emissions, and increasing jobs. To address this, the chapter proposes the use of multi-objective optimization techniques to develop a predictive model for Nigeria's power supply architecture.

The chapter describes the methodology used, including the utilization of the Hybrid Structural Interaction Matrix to compute weights for the conflicting objectives, which are then incorporated into a single-objective model. The chapter also provides details on the indigenous energy sources considered in the model, such as large hydropower plants, solar PV, solar thermal, incinerator, nuclear, gas plant, combined plant, and diesel engine.

The chapter presents the findings from the simulations conducted using the predictive model. The results suggest that Nigeria has the potential to generate up to 2,100 TWh of power by 2050, with large hydropower plants and solar PV being the leading options. The chapter also discusses the expected job creation from the construction and operation of power generation plants, as well as the projected CO_2 emissions and cost of power generation.

The chapter concludes that Nigeria can meet its power supply obligations by harnessing indigenous energy sources and developing an optimal power supply mix. The findings of the study contribute to the understanding of how multi-objective optimization can be used for sustainable power generation planning in the context of the Nigerian power system.

5.1 Introduction

A sustainable power supply mix entails meeting today's power requirements while not risking future generations' capacity to achieve theirs [1]. Since its inception and implementation, sustainable development has been the subject of a plethora of research on various themes, levels, and viewpoints [2]. Nigeria must solve its problem of inadequate power supply to stay competitive and relevant among nations, especially as the COVID-19 pandemic has wreaked havoc on the economy [3]. Nigeria, fortunately, has a diverse abundant range of energy sources from which to draw and establish a sustainable power supply mix that would satisfy the growing power demand, conserve the environment, and reduce greenhouse gas (GHG) emissions [4]. Despite its abundance of power-generating sources, Nigeria is struggling to fulfill its rapidly increasing power demand and is plagued by rolling blackouts in most parts of the country [5]. Electricity is available to just 55.4% of the population, with electrification rates lower in the east and rural areas [6].

The utilization of RE (renewable energy) sources is regarded as a crucial component of sustainable energy systems [7]. The major challenges confronting Nigeria such as unemployment and security threats will all be addressed through industrialization, and this can only be achieved by steady, economical, and environment-friendly power supply [6].

Policymakers and researchers who want to develop an environmentally friendly power supply system need to use energy modelling and optimization techniques to ensure that different objectives such as cost, emissions, jobs, etc., are met [8]. Modelers have been developing optimization models of energy systems since the 1990s [9-13]. Costs or emissions are optimized to develop optimal power supply mixes for regions, cities, and nations [14-22].

Power planning has become a complicated issue involving several factors due to the relationship between electricity consumption, protection of the environment, economic growth, and civic responsibility [23]. As a result, approaches for energy modelling and optimization that can integrate numerous objectives to develop a power policy are of great importance. Determining the optimal power generation mix that will fulfill electricity demand whilst fulfilling numerous limitations is the fundamental modelling concept behind long-term energy planning. Some important outputs of such techniques include the kind of power technology used, the quantity of installed power capacity, time to develop and operate the technology, and necessary fuel sources. Numerous studies looking at the socio-economic optimality of power planning have focused on using cost optimization models like MESSAGE, MARKAL, TIMES, etc. (see, for example, Refs. [24-33]). The strategic planning of power planning systems, on the other hand, inevitably incorporates several competing objectives [34-36]. Previous studies on multi-objective optimization addressed environmental or social objectives by transforming them into cost-equivalent objectives [37] or by viewing them as constraints with lower and higher bounds [38]. However, multi-objective optimization is more realistic because it can explicitly assign an objective function to each sustainability (cost, emissions, jobs, land, social opposition, etc.) criterion without the need for complicated equations. Prior multi-objective studies mostly concentrated on costs and emissions while ignoring the social factors. Ren et al. [39] investigated the operation strategy of a decentralized energy source while balancing energy cost minimization with environmental effect minimizing. Zhang et al. [40] examined the Japanese power generation system from an economic and environmental standpoint. In Taiwan, Ko et al. [41] used a multi-objective optimization to reduce power generating costs and CO_2 emissions. Purwanto et al. [42] created a conceptual framework for a long-term power generating mix in Indonesia that incorporated two goals: lowest generation cost and lowest CO_2 emissions. Mahbub et al. [43] discovered optimal scenarios for addressing the constraints of lowering energy costs and CO_2 emissions in Italy. Pratama et al. [44] assessed different development scenarios for Indonesian electricity production based on economic and environmental trade-offs. Tekiner et al. [45], on the other hand, investigated three goal functions; nevertheless, both non-cost criteria addressed air emissions such as CO_2 and NO_x. There is still the need to develop a multi-objective optimization model for determining trade-offs between several conflicting factors of sustainability. In this study, multi-objective optimization was used to integrate indigenous energy sources to develop a sustainable power generation mix by minimizing power generating costs, minimizing CO_2 emissions, and maximizing the number of jobs created from the construction and operation of power plants.

The Hybrid Structural Interaction Matrix (HSIM), a weighted technique that is ideally suited to dealing with energy decision-making issues, was utilized in this study to calculate the weights of the three objectives to solve the multi-objective power optimization model [46]. The same approach was utilized to analyze the factors contributing to Nigeria's rising demand for electricity.

Nigeria, as one of the top producers of oil and gas all over the world, has an urgent need to develop a long-term plan for its increasing electricity needs [47]. Nigeria also has substantial RE sources. When compared to the 28 TWh produced in 2016 [48], Nigeria's power production in 2021 increased to 36.4 TWh [48]. The industrial sector consumes 94.2% of the nation's electricity, trailed by the residential and commercial sectors, which each consume 4.04 and 1.8% [49].

RE sources such as sun, wind, biomass, and hydro are abundant in Nigeria. Every area of Nigeria receives a lot of solar radiation, with a range of 5,500–6,500 Wh/m^2 [50]. According to some studies [51–52], solar PV power generation is feasible throughout Nigeria. In the northern regions of the nation, the wind can achieve speeds of up to 7.5 m/s [53]. In terms of biomass production, Nigeria generates 144 million tonnes annually [54]. A total of 277 scattered locations in the nation can produce minor amounts of hydropower [55], and numerous rivers can be dammed to produce huge amounts of hydropower [56]. Despite this, Nigeria's RE resources have not yet been fully exploited.

Nigeria's carbon footprint cannot be underestimated given that they make up about 0.37% of the world's CO_2 emissions in 2020 [57]. In Nigeria's energy sector, CO_2 emissions from power production systems made up around 10.2% of total emissions [58]. Nigerian policymakers are very concerned about reducing GHG emissions from the power industry. Nigeria plans to achieve net zero carbon emissions by 2060 by the President's pronouncement [59]. The power industry can unavoidably be a significant contributor to future carbon emission reduction efforts.

Nigeria now has an unemployment rate of over 33% [60], which is substantially higher than the world average. Due to these alarming numbers, the administration has decided to concentrate on labor indices in any national development programs. One-way power supply systems may be able to meet some of the increasing labor demand is by being able to employ numerous people from the design, development, and operation to decommissioning of Nigeria's power infrastructure.

Studies on sustainable power supply mix in Nigeria are hard to come by, according to the literature review that was conducted. Olusola et al. [61] provided a strategy to electrify Nigeria completely by 2030 that was sustainable, renewable, and economical. In Nigeria, Bello et al. [62] used carbon emission pinch analysis, which includes sector-level macro-planning for energy. Blechinger et al. [63] used energy system simulations and geographic information system tools to develop a least-cost electrification strategy for five states in Nigeria. Ibrahim and Kirkil [64] estimated Nigeria's long-term power supply from 2010 to 2040. Sambo A. [65] used MAED to forecast energy consumption. Audu et al. [66] determined the long-term energy consumption in Nigeria. Amlabu et al. [67] explored four Nigerian regional power supply scenarios. Ezennaya et al. [68] utilized Time Series Analysis to anticipate Nigerian power consumption from 2013 to 2030. Oyelami and Adewumi [69] utilized the Harvey logistic model to forecast Nigerian power investment value from 2005 to 2026. Using LEAP, Emodi et al. [70] evaluated Nigeria's energy circumstance in the following scenarios: baseline, LCM (Low carbon moderate), LCA (Low carbon advanced), and GO (Green Optimistic). Adedokun [71] predicted electricity consumption in Nigeria using the ARIMA model to see how likely it was that Nigeria would be in the top 20 by 2020. To the best of our knowledge, there are no other studies paying attention to Nigeria's electricity generation outlook by addressing economic, environmental, and social objectives.

5.1.1 Nigerian power sector

Nigeria's growing electricity demand is 80% lower than it should be based on population and income levels [72]. Having a per capita electricity consumption rate that ranks among the world's poorest, there is little or no development in all sectors of the economy; industries are struggling to survive, agriculture is still not commercial, and education and employment are all impacted by the low electricity supply. In developing countries with fewer people, such as Tunisia and South Africa, electricity consumption is 10 to 30 times Nigeria's. With the COVID-19 pandemic causing major economic setbacks worldwide, Nigeria must urgently address the issue of low electricity supply to compete with its peer countries. **Fig. 5.1** depicts various African countries' per capita power consumption, with Nigeria having the lowest at 137 kWh and South Africa having the highest at 4,944 kWh, Botswana at 1,435 kWh, Zimbabwe at 898 kWh, Namibia at 1,541 kWh, and Libya at 3,871 kWh [73].

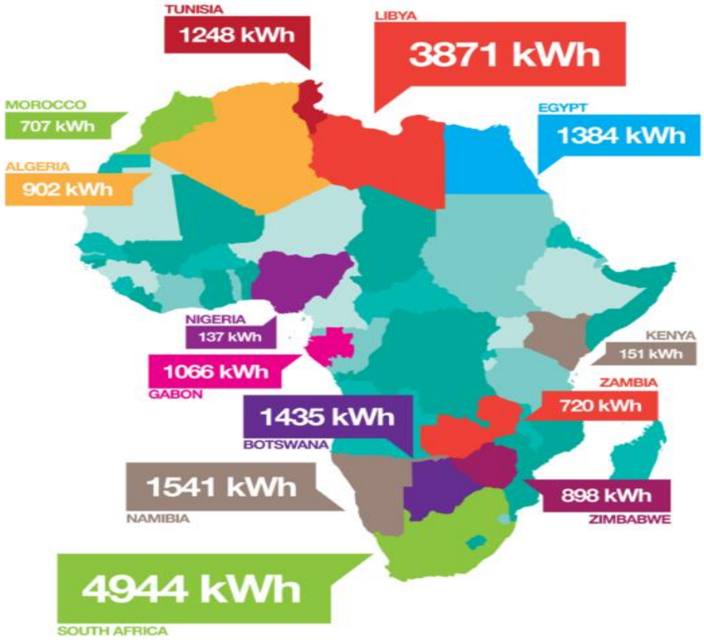

Fig. 5.1. Selected African countries' per capita power consumption (kWh) [73].

With a growing population, rising income, industrialization, and increased agricultural activity, Nigeria’s electricity demand will increase, putting additional pressure on the country’s already inadequate electricity supply. Managing the increasing electricity demand is necessary to achieve equilibrium with the power supply.

History of the Nigerian power system dated back to when the Lagos Colony was served by two power plants completed in 1886. The Nigerian Electricity Supply Company (NESCO) was created in 1929, making it the country’s first utility corporation [74]. Afterward, in 1951, the Energy Corporation of Nigeria (ECN) was established to supervise electricity transmission and distribution [74], and in 1962, the Niger Dams Authority (NDA) was established [75]. Electricity generation fell under the purview of the NDA, with transmission and distribution falling under the purview of the ECN. It was in 1972 that the ECN and the NDA amalgamated to become the National Electric Power Authority (NEPA), which was later converted into the Power Holding Company of Nigeria (PHCN) in 2005. The distribution section of Nigeria’s power supply system has now been completely privatized, resulting in the establishment of Kano, Kaduna, Jos, Eko, Benin, Abuja, Enugu, Port-Harcourt, Yola, Ikeja, and Ibadan Electricity Distribution companies, as depicted in **Fig. 5.2** [76]. Despite the country’s lengthy history of electricity reforms, the power industry has developed slowly at most. The on-grid electricity generation in Nigeria is dominated by gas and hydropower, which account for 81% and 19% respectively, of total installed capacity [77]. **Fig. 5.2** depicts the organization of Nigeria’s power sector, which is divided into generation, transmission, and distribution [78]. The Nigerian Electricity Supply Industry (NESI) has 22 gas and three hydroelectric on-grid units that can produce 12,522 MW, but the available capacity is only 7,141 MW [79]. Presently, Manitoba (Canada) Hydro International manages the Nigerian Transmission Company. The national grid transmission lines are 330 kV and are about 5,524 km long [80]. **Fig. 5.2** also indicates Nigeria’s power distribution system which comprises of 11 power distribution companies. Over 24,000 km of the distribution grid, operating at 33 kV and 11 kV, are in operation [74, 78].

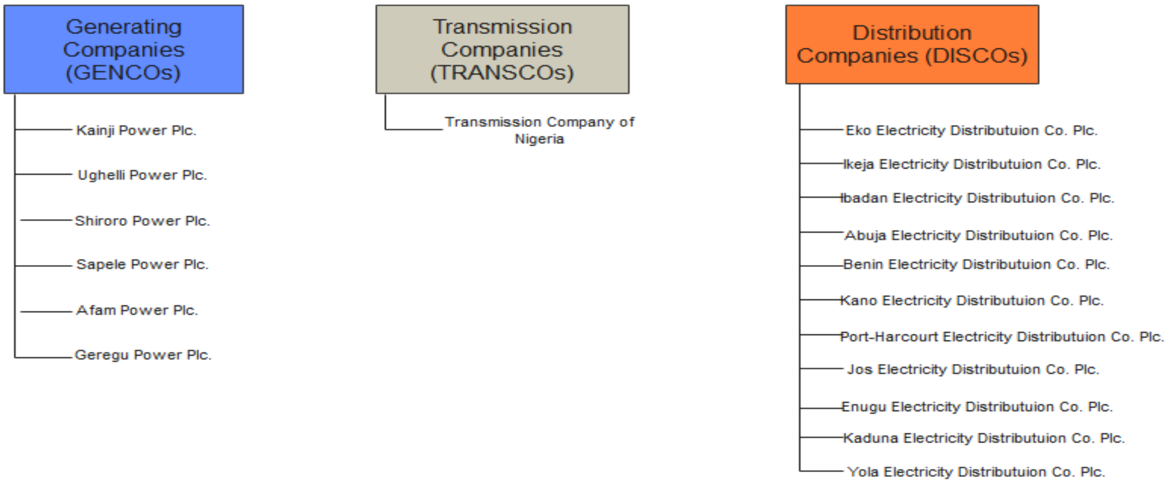

Fig. 5.2. Overview of the power system chain [88]

The amount of power that can be generated and transmitted is limited by problems associated with the power plants, such as maintenance and repairs. There are also insufficient water supplies, demand imbalances, not enough gas, and line restrictions because of the poor grid infrastructure [81]. Among other things, the mismatch between the growing power demand and supply has resulted to over-reliance on backup diesel generators. Because of these issues, huge sums of money are pumped into the power sector daily.

For a long time, the government ran and controlled the power sector. There was never enough electricity for the state-owned company, NEPA [82]. Since the democratization of Nigeria in 1999, the Federal Government has invested massively in the power industry, but with little success [82]. Privatization of electricity assets was one of the government's primary reform initiatives [78]. Various policy initiatives were implemented to achieve this goal [74]. The Electric Power Industry Reform Act (ESPR) of 2005 allowed private players into the formerly monopolized sector. Nigeria has a lot of potential for RE. Still, it doesn't have RE-based power plants that generate electricity for the country's grid right now apart from hydropower. "Nigeria's solar and wind resources are in abundance based on data from NASA [83], reprocessed by the German Aerospace Center [84], and converted to total load hours by Bogdanov and Breyer [85, 86]. However, the Nigerian government's deliberate and supportive policy direction towards a progressive RE master plan is essential [87]. It is anticipated that such a regulatory, legal, and institutional framework would support RE development in Nigeria [78]. The Nigerian government adopted the National Renewable Energy and Efficiency Policy (NREEEP) in 2015. It is the country's first policy for renewable energy and describes how it will be used in the future. By 2030, the government wants to double its on-grid power [80]. In NREEEP 2015, it says that this goal was set when the NREAP and NEEAP were made. In the NREEEP 2015 report, on-grid RE supply is expected to grow from 1.3 % to 16 % in 2030, a significant change. In 2016, the goal was changed to 30% by 2030, all of which have not been achieved" [80].

5.1.2 Energy sources

Nigeria is deficient when it comes to energy supply, even though it has a lot of fossil fuels and RE sources of its own. Fossil fuels are the country's most utilized source of energy. While RE is unavailable in the power mix of the nation apart from hydropower as already stated. The power supply mix comprises 10,142 MW of natural gas (81%). The remainder is hydropower, which accounts for 2,380 MW, or 19% of the total installed capacity [89].

It has been projected that Nigeria's RE potential (hydro, wind, solar, biomass, and geothermal) is above 68,000 MW. The government may have considered this when developing laws to promote RE. In 2005, the government unveiled the Renewable Energy Master Plan (REMP), which aimed to double the country's overall energy production by 2025 through growing renewable energy usage. Short-term: In 2005-2007, the REMP aimed to contribute 13%-23% in the medium term (2008-2015), and 36% in the long term (2016 - 2025) [89].

On the current assessment, Nigeria's recoverable oil reserves are 28.5 billion barrels, with an average daily output of roughly 2.5 million barrels, including condensates. As exploration and appraisal drilling and deep offshore exploration have continued to accumulate reserves, the average oil depletion rate is just 15%. Over 166 trillion cubic feet (TCF) of Nigeria's gas reserves include associated and non-associated gas. Nigeria is one of the ten nations with the world's largest proven gas reserves.

The Niger Delta has roughly 500 oil fields. The remainder is found on land. In all, 193 of these fields produce oil, while 23 have been shut down [90].

5.2 Methodology

A sustainable power supply model for Nigeria was developed using multi-objective optimization and is deliberated in this section. This model optimized three competing objectives by minimizing power generating costs, minimizing CO_2 emissions, and maximizing job creation for the developed optimal power supply mix. While the constraints are power demand-supply, power supply resource availability, generation constraint of power plants, budget, and targets of CO_2 emissions. From the base year (2010) to our projected target year (2050), a five-year interval was used to run the optimization model. A summary of the six-step methodology was summarized below with **Fig. 5.3** being a schematic representation of the steps that were successively followed for the development of the sustainable power supply mix for Nigeria.

- Step 1: Power system

The Power Energy System (PES) is created in step 1 for modeling purposes which highlights the power supply chain from energy sources to electricity end-users. Nigeria's available energy sources such as diesel, hydro, wind, solar, nuclear, natural gas, etc., are used in different technologies. Concerning power transmission and distribution, distributed technologies generate electricity near load centers, while centralized technologies generate electricity and then being transmitted through power grids.

- Step 2: Power model development

Based on the PES, a long-term power planning model is developed in step 2. To address power supply and sustainability concerns in Nigeria, three objectives were developed: (1) minimization of cost; (2) minimization of CO_2 emissions; (3) and maximization of jobs. Constraints to the optimization model include supply-demand, generation limitations, resource availability, budgetary restrictions, and an emissions target.

- Step 3: Data and assumptions

When running the model, it is necessary to collect the required data, which was done in step 3. For a nation to develop an energy plan, data and assumptions regarding the techno-economic, environment, power demand projection, cost of energy resources, job creation, and statistics on CO_2 emissions used were collected.

- Stage 4: Multi-Criteria Decision Making

This step involves employing the MCDM approach to the three objectives: converting the objectives into a single objective by using a weighted approach to allocate weights to each objective function in the model. The Hybrid Structural Interaction Matrix (HSIM) method was utilized in this step.

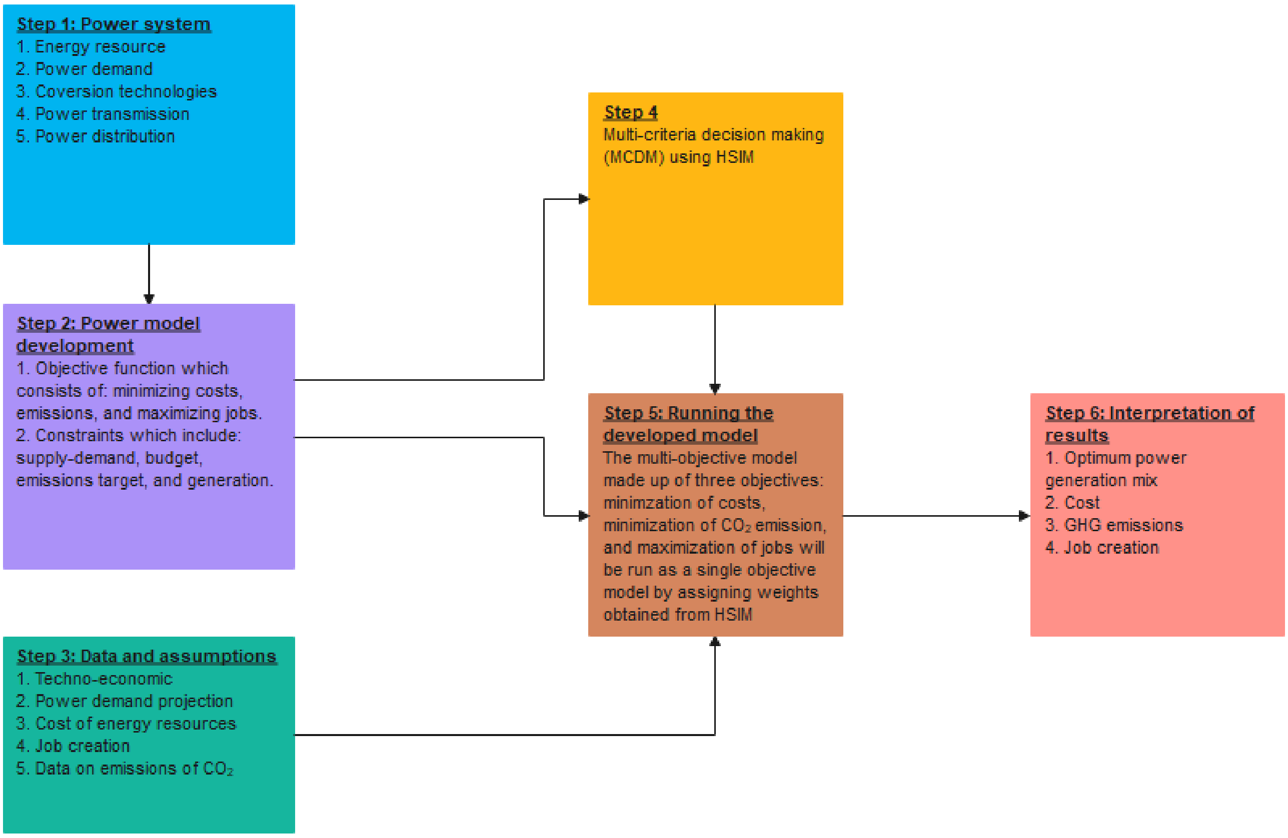

Fig. 5.3. Schematic representation of the methodology

- Step 5: Running the developed model

This involves testing the model that was developed using the data obtained in step 3.

- Step 6: Interpretation of results

The optimal power generation mix, CO_2 emissions, cost, and the jobs created from the construction and operation of power plants were then interpreted and analyzed.

5.2.1 Minimization of power generation costs for the model

The primary priority is to cut electricity generation costs as much as possible (*f1*). In the model, it uses *sLCOE* in Eq. (2) & Eq. (3) to determine *f1* in Eq. (1). *sLCOE* considers the costs of building new power plants (*C*), the payback period for old power plants (*O*), the price of fuel (*F*), and other factors. For the cost objective function, the equations look like this:

$$f1 = \sum_{t=1}^{T}\sum_{i=1}^{I}(1 + r^{-t})(G_{it}^{new}sLCOE_{it}^{new} + G_{it}^{ext}sLCOE_{it}^{ext}) \tag{2}$$

$$sLCOE_{it}^{new} = \left(\frac{[C_{it}^{new}CRF_i] + O_{fix,it}}{8760C_{f,it}}\right) + O_{var,i} + F_{it}\varepsilon_{it} \tag{3}$$

$$sLCOE_{it}^{ext} = \frac{O_{fixed,it}}{8760C_{f,it}} + O_{var,it} + F_{it}\varepsilon_{it} \tag{4}$$

$$CRF_i = \frac{r(1 + r)^n}{(1 + r)^n - 1} \tag{5}$$

The decision variables in the model are *CRF* for cost recovery factor in Eq. (4), C_f for capacity factor, ε for efficiency of transforming heat into electricity, *r* for the discounted rate, and *t* for year. The relationship between installed capacity and capital expenditures for a certain year horizon is an input parameter to a learning curve model. According to a cumulative installed capacity prediction, the amount of capital investment may be estimated:

$$C_t = C_o \cdot N_t^{\emptyset} \tag{6}$$

$$1 - 2^{\emptyset} \tag{7}$$

Eq. (6), which signifies the rate of technical learning, C_t in Eq. (5) is the decrease in future capital expenditures as a percentage that occurs with each capacity doubling up (N_t). How quickly individuals learn is determined by the progress ratio. The capital expenditure in the base year is denoted by the symbol C_o (2010).

5.2.2 The reduction of CO_2 emissions from power production facilities

It is also an objective to reduce CO_2 emissions (*f2*) represented by Eq. (7) during the lifecycle of the energy-generating technology. The CO_2 life cycle emissions of each power plant are determined by the CO_2 emission factor (E) being multiplied by the quantity of energy that is produced by the power plant:

$$f2 = \sum_{t=1}^{T}\sum_{i=1}^{I} CO_2 emissionfactor_{it} \cdot G_{it} \tag{8}$$

5.2.3 Maximization of job opportunities

The job objective function (*f3*) maximizes total job years, as it's socially more acceptable to have higher employment rates than lower rates. Eq. (8) represents the whole job objective function. The job creation objective function *f3* was obtained by multiplying the amount of power produced by the construction and operation job creation factors of each technology.

$$f3 = \sum_{t=1}^{T}\sum_{i=1}^{I}(b_i + h_i)\, G_{it}^{new} + \sum_{t=1}^{T}\sum_{i=1}^{I} h_i\, G_{it}^{ext} \tag{8}$$

5.2.4 Multi-objective function

The optimal power generation mix was obtained as a result of optimizing the three objectives considered in this study as represented by the multi-objective model in Eq. (9) [91]. The objective function is expressed as follows:

$$f4 = w1 \cdot f1 + w2 \cdot f2 + w3 \cdot f3 \tag{9}$$

Where $w1, w2,$ and $w3$ are the weighted factors of $f1, f2,$ and $f3$. The optimization model in this situation is constrained by five constraints, which are mentioned in the next section.

5.2.5 Constraints for the developed model

This section summarizes the restrictions taken into consideration in the model. In the following section, the model's resilience needs are met by constraints.

5.2.5.1 *Power demand-supply constraint*

The overall amount of energy produced by all kinds of power plants should be sufficient to fulfill the whole amount of electricity required in a given year horizon. This is represented by Eq. (10):

$$\sum_{i=1}^{I}\left(G_{it}^{new} + G_{it}^{ext}\right) \geq D_t \tag{10}$$

where D_t denotes the demand for electricity in the year *t*.

5.2.5.2 *Power supply resource availability*

For year *t*, the amounts of fossil fuel used by power generation systems must not exceed the maximum amount of fossil fuel generated by the relevant fuel type and allotted to power generation technologies for the same year which is depicted in Eq. (11).

$$\sum_{i=1}^{I} G_{it}^{new}\cdot\varepsilon_{it} + \sum_{i=1}^{I} G_{it}^{ext}\cdot\varepsilon_{it} \leq F_{sit} \tag{11}$$

It was decided to add the RE penetration constraint into the model to guarantee that the RE objectives are met on a period-by-period basis. By the study, the RE objectives were established at 20, 35, and 50% for the years 2030, 2040, and 2050.

$$\frac{\sum_{i=2}^{9}\left(G_{it}^{ext} + G_{it}^{new}\right)\cdot 8760C_{fi}}{\sum_{i=1}^{I}\left(G_{it}^{ext} + G_{it}^{new}\right)\cdot 8760C_{fi}} \geq RENTargets \tag{12}$$

5.2.5.3 *Generation* constraint *of power plants*

Restrictions on electricity generation are related to the use of current and additional capacity and the proportion of various technologies in an overall power generation system.

$$X_{it}^{new} = 8760(1-\rho)C_{fi}G_{it}^{new} \tag{13}$$

$$X_{it}^{ext} \leq 8760(1-\rho)C_{fi}G_{it}^{ext} \tag{14}$$

$$X \leq \omega_{it}\left(X_{it}^{new} + X_{it}^{ext}\right) \tag{15}$$

Each newly installed technology's annual net power generation is estimated using Eq. (13). Eq. (14) determines the maximum amount of power that may be produced from the current capacity each year. To avoid the excessive generation of any power technology, Eq. (15) mandates that each technology may only generate a specified fraction of the total yearly power generation.

5.2.5.4 *Budget constraint*

Budget constraints are imposed on capital expenditures because the capital expenses of constructing new infrastructures are relatively high.

$$\sum_{i=1}^{I} \frac{r(1+r)^{CT_i}}{(1+r)^{CT_i}-1} \cdot INVC_{it} \cdot NAC_{it} \leq bgC \tag{16}$$

In Eq. (16), the annual investment cost of developing power plants is restricted to a specific upper limit.

5.2.5.5 *Targets of CO2 emissions*

The carbon emissions reduction objective also served as a constraint, with the total quantity of CO_{2eq} emissions being limited to a maximum as highlighted in Eq. (17):

$$\sum_{i=1}^{I} \left((G_{it}^{ext} + G_{it}^{new}) \cdot 8760 C_{fi} \cdot CO_2 emission factor_i \right) \leq CO_2 emission\ target \tag{17}$$

5.3 Study and data assumptions

Existing techno-economic, environmental, power demand projection, cost of energy sources, job creation, and CO_2 emissions data for the Nigerian power system was obtained from various literature to demonstrate the multi-objective model's application. The base year is 2010 and the forecast period is for 40 years, the projection started from 2011 to 2050 with an interval of 5 years.

The assessment of power demand in on-grid and off-grid systems can either be done as a combined demand or as separate demands, depending on the methodology that is used. Examples include a study conducted by the (Energy Commission of Nigeria) ECN on the energy implications of Nigeria's Vision 2020. Such that the Model for Analysis of Energy Demand (MAED) was used to project that Nigeria's total electricity demand (combined on-grid and off-grid) by 2030 will be approximately 668.75, 1138.20, 1,343.22, and 1,821.80 TWh depending on the reference, high growth, optimistic I, and optimistic II scenarios, respectively [92]. In a separate piece of study, the multi-tier framework for electricity access that was developed by the World Bank was utilized to estimate that Nigeria's on-grid electricity demand by 2030 will be approximately 59.3, 64.3, and 74.2 TWh, respectively, for business-as-usual, moderate, and green transition scenarios. This estimate was made using the multi-tier framework for electricity access. According to the findings of the study, the power consumption off-grid in the year 2030 would be around 143.4, 135.6, and 130.8 TWh for the three similar scenarios [93], with the maximum demand being approximately 143.4 TWh.

5.3.1 Power conversion data

Nuclear power plants, gas turbines, biomass, large and small hydropower plants, wind turbines, geothermal, solar thermal, and solar photovoltaic power plants, etc., are among the power conversion technologies considered in this study. The features of each technology are summarized in **Table 5.1**, which includes cost variables, technical information, and capacity limits. For most technologies, the techno-economic characteristics are considered to remain constant across the whole analytical horizon. When the learning rate is taken into account, however, it is expected that the investment cost for certain renewable technologies would fall. While **Table 5.2** shows the CO_2 emission factors resulting from fossil fuel combustion, the growing capacity limitation for each phase is partly alleviated as the planning horizon approaches its end. The total number of direct, indirect, and induced full-time-equivalent (FTE) employment produced by each technology in each phase is shown in **Table 5.3**.

Table 5.1: Power generation systems' technical and economic characteristics [95-106]

Technology	Construction time (year)	Lifetime (year)	Capacity factor (%)	Self-consumption (%)	power capacity (GW)	Efficiency (%)	Capital cost ($/kW)	Fixed O & M cost ($/kW)	Variable O & M cost ($/kW)
Steam PP	5	30	70	6.8	3750	38	900	9500	0.48
Combined Con	5	35	70	1.9	-	32	700	4400	0.42
Combined Adv	5	35	80	1.9	-	47	1140	21000	2.6
Gas Turbine Conv	2	12	60	0.8	5000	34	550	4500	0.6
Gas Turbine Adv	3	15	60	0.8	846	40	780	24000	4.3
Coal Conv	3	30	75	5.5	-	35	1600	64000	-
Coal Adv	4	50	80	6.5	-	34	2200	88000	-
IGCC	4	40	80	10	-	45	3700	92000	6.5
Diesel engine	1	14	70	6.5	25000	40	550	3800	0.75
Nuclear Conv	7	45	80	10	-	32	4000	74000	0.7
Nuclear Adv	8	60	85	8	-	33	4200	69000	0.5
Hydro Large	7	45	18	0.5	1940	100	1200	10800	-
Hydro Small	4	40	35	0.5	64	100	2000	14000	-
Fuel Cell	0	5	60	-	-	47	4460	40000	-
Wind Turbine	2	25	30	1.4	-	100	1400	48000	-
Solar PV	1	30	18	-	400	100	1200	24000	-
Solar thermal	2	35	38	-	-	100	4300	64000	-
Geothermal PP	7	30	8o	8	-	100	5800	84000	1.1
Landfill	2	20	70	3	-	30	3300	2000	1.7
Incinerator	3	30	75	5	-	31	6400	64000	-
Solar PV (DG)	0	30	17	-	-	100	1500	37000	-
Gas Engine	1	3	90	0.7	5500	26	770	8000	5.1

Table 5.2: Factors affecting CO_2 emissions and fuel costs [108-109]

Technology	Fuel price (Cent/MJ)	CO2 emission (kg/GJ)
Gas	0.41	56.2
Coal	0.22	95.6
Oil	0.53	77.6
Diesel	0.92	74.4

Table 5.3: Effective factors in the development of jobs in the power generating industry [107]

Power technology	Technology construction stage (GWh)	Technology operation stage (GWh)
Steam PP	0.82	0.15
Combined Con	0.16	0.32
Combined Adv	0.31	0.35
Gas Turbine Conv	0.83	0.64
Gas Turbine Adv	1.07	1.07
Coal Conv	0.73	1.31
Coal Adv	0.08	0.26
IGCC	0.26	0.20
Diesel engine	0.16	0.32
Nuclear Conv	0.26	0.20
Nuclear Adv	0.20	0.26
Hydro Large	0.20	0.82
Hydro Small	0.20	0.82
Fuel Cell	0.10	0.11
Wind Turbine	0.3	0.08
Solar PV	0.06	0.83
Solar thermal	1.10	1.70
Geothermal PP	0.05	0.51
Landfill	0.13	0.73
Incinerator	0.13	0.73
Solar PV (DG)	0.60	0.83
Gas Engine	0,03	0.16

5.3.2 HSIM ranking

The HSIM approach is one of the strategies that may be used for making decisions with many objectives and doing analyses. Within the context of this study, HSIM was utilized to ascertain the relative importance of factors such as cost, CO_2 emissions, and job creation. According to HSIM, a particular element pair may interact with one another in several distinct ways. On the other hand, only an interaction that is founded on a particular contextual relationship applies to the situation that is currently taking place. In most cases, consideration is given to the orientations of the components that affect a system while making contextual linkages.

As a consequence of this, the HSIM model is intrinsically intertwined with the concept of orientation and direction. As a result of this, if $e_{ij} = 1$, then $e_{ji} = 0$, which indicates that transitivity exists. Because of this, it will be impossible for components *i* and *j* to successfully interact with one another if elements *j* and *i* interact effectively [94]. This is mathematically stated in Eq. (18) as:

$$e_{ij} = \begin{cases} 1 & \text{if } i \text{ depends on activity } j, \\ 0 & \text{if } i \text{ does not depend on activity } j, \end{cases} \quad (18)$$

The technique for establishing the HSIM for a given set of variables is represented in **Fig. 5.4** in a step-by-step manner and HSIM in **Table 5.4**.

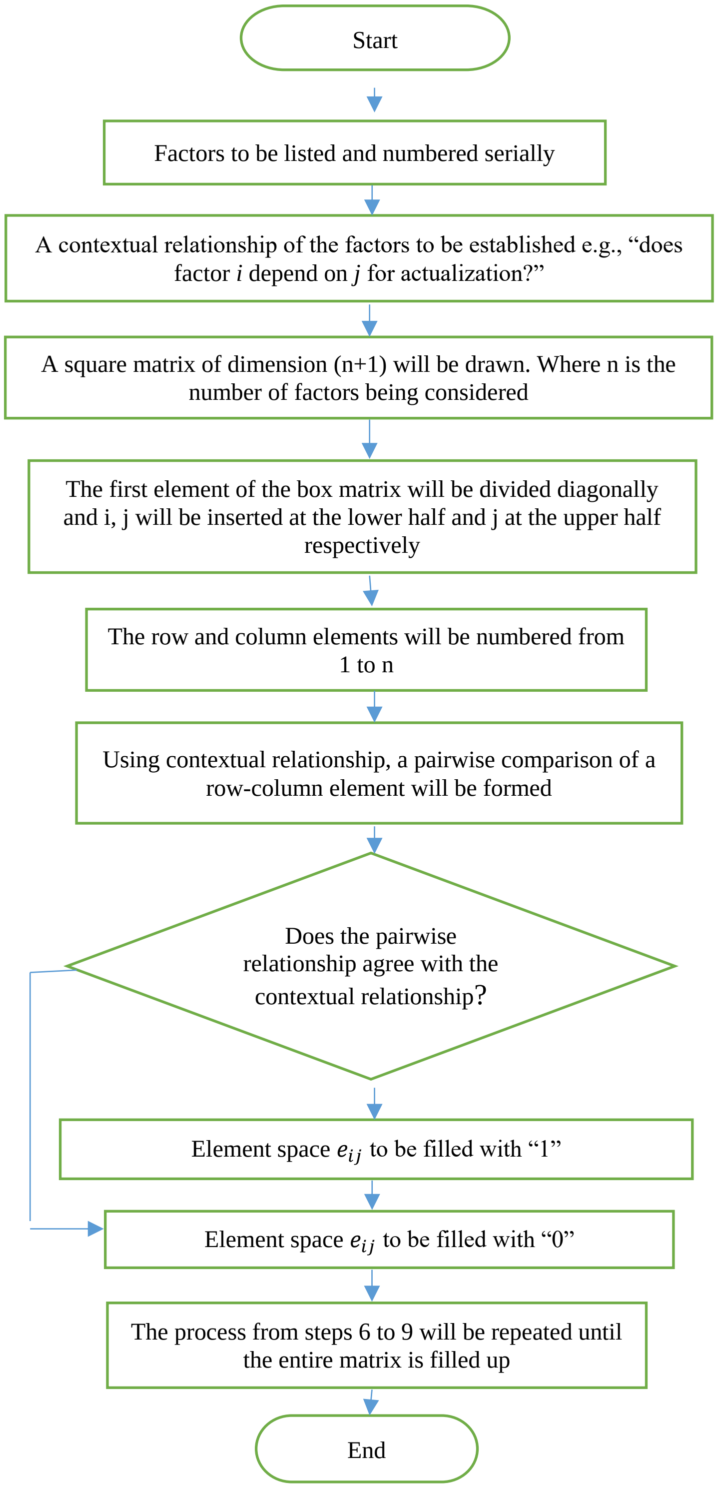

Fig. 5.4. HSIM development process [31]

Table 5.4: HSIM demonstrating the pair-wise connection between cost, CO_2, emissions, and jobs

i	*j*		
	Cost	***CO_2***	***Jobs***
Cost	0	1	0
CO_2	0	0	0
Jobs	1	1	0

The models used for calculating the weights of the objectives are highlighted in Eq. (19), Eq. (20), Eq. (21), and Eq. (22):

$$I_{RFi} = \left\{\frac{N_{SFi}}{T_{NF}} x M_{SR}\right\} + \left\{\frac{b}{T_{NF}}(M_{SR} - C)\right\}, \tag{19}$$

$$c = \frac{M_{PSF}}{T_{NF}} x M_{SR}, \tag{20}$$

$$b = N_{SFi} + 1, \tag{21}$$

$$N_{wi} = \frac{x_i^{1/n}}{\sum_{i=1}^{n} x_i^{1/n}} \tag{22}$$

“where I_{RFi} is the intensity of factor i's significance rating, N_{SFi} is the number of subordinate factors to particular factor *i*, M_{PSF} is the most number of subordinate elements that can be considered, C constant, *b*=T_{NF} the proportion of variations, T_{NF} is the number of variables in total, M_{SR} the highest possible scale rating, N_{wi} is the factor's normalized weight *i*, N number of variables, and x_i is the original rate of factor *i* before normalization.” [46]

Table 5.5: Normalized weights of cost, CO_2, emissions, and jobs

Element number	**C**	I_{RFi}	$\frac{1}{n}x_i$	N_{wi}
Cost	6	5.000	1.080	0.330
CO_2	6	9.000	1.110	0.340
Jobs	6	5.000	1.080	0.330
		Total	3.270	1.000

Table 5.5 displays the weights of each of the objectives considered in this study and their degree of importance. The scale rating was between 0 and 9, with 0 being the lowest possible score and 9 representing the greatest possible score [110]. The number of subordinate factors that may be accessed by a component is what ultimately decides the principle that will be used to weigh or give a degree of importance to those elements. As a result, the values were found to be appropriate for the weights of cost, CO_2, and job's objective functions which are 0.330, 0.340, and 0.330, respectively.

5.4 Results and discussion

The planning for Nigeria's sustainable power supply was carried out with consideration given to the following three objectives: reducing costs, reducing CO_2 emissions, and increasing jobs. The model was solved by utilizing a modelling program called GAMS (General Algebraic Modeling System).

5.4.1 Demand for electricity in Nigeria

Electricity demand in Nigeria from the household, service, industrial, transportation, and agricultural sectors in the base year is 187 TWh which is projected to be 299 TWh in 2020 [111]. **Fig. 5.5** depicts how the electricity demand will attain 2,003 TWh by 2050. Among the electricity demand sectors, the household sector has the highest demand which will increase from 71 TWh in 2010 to 1,218 TWh by 2050. This is followed by the service, industrial, and transportation sectors.

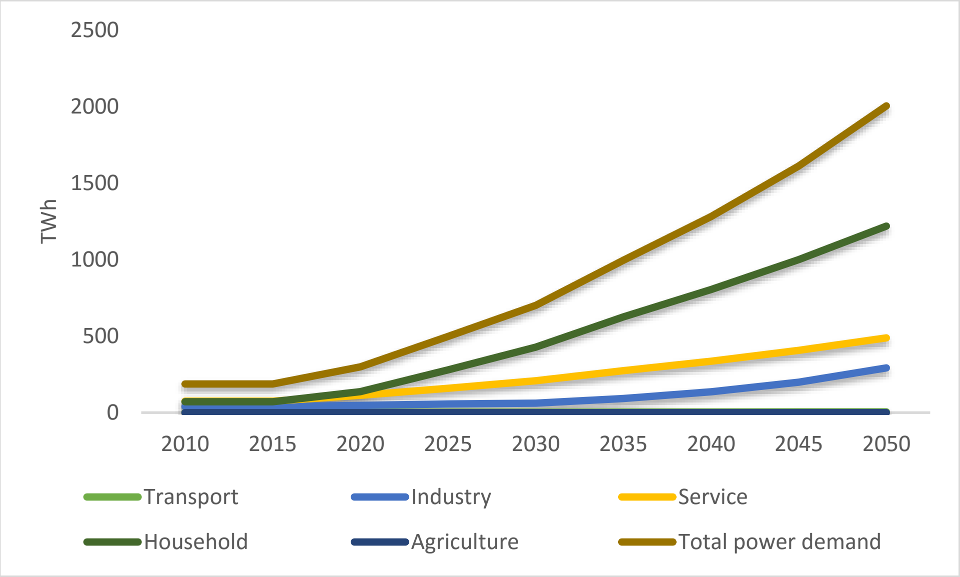

Fig. 5.5. Nigeria's electricity demand from 2010-to 2050 [111]

5.4.2 Results obtained from the simulation

5.4.2.1 Power generation by technologies

The optimum trajectory of Nigeria's overall power generation is represented in **Fig 5.6**. From the base year to 2050, the projected power supply increased from around 218 TWh to about 2,100 TWh. The Hydropower large power plant and solar PV aggressively penetrated the power supply mix over the projected period.

The base year of 2010 in the power supply mix is made up of 10% Gas Turbine Conventional, 5% Diesel engine, 6% Hydropower large, and 79% Gas engine. Fossil fuels dominate the power generation mix in the base year which accounts for 94% and renewable energy is 6%. By the year 2050, renewable energy will largely be integrated into the power supply mix which will be made up of 23% Combined advanced, 11% Gas turbine conventional, 3% Gas Turbine advanced, 8% Nuclear advanced, 12% Hydropower large, 1% Hydropower small, 2% Wind turbine, 15% solar PV, 12% Solar thermal, 7% Incinerator, and 6% Gas engine. Renewable energy sources will make up at least 49% of the power supply mix, nuclear energy which is mostly classified as an alternative energy source is 8%, and the remaining 48% is for fossil fuels. Renewable energy sources massively increased by about 716% in the power generation mix from the base year to the projected period (2050). Gas power plants remain heavily in the power supply mix because of the low price of natural gas. Considering the environmental impact of coal which is often at times referred to as the dirtiest form of fossil fuels and the need to adhere to emission regulations, coal power plants are unavailable in the power supply mix. In addition, steam power plants have been eliminated during the planning period. While gas power plants have been considerably present during the planning period because of the low cost of gas but have still been significantly reduced during the planning horizon.

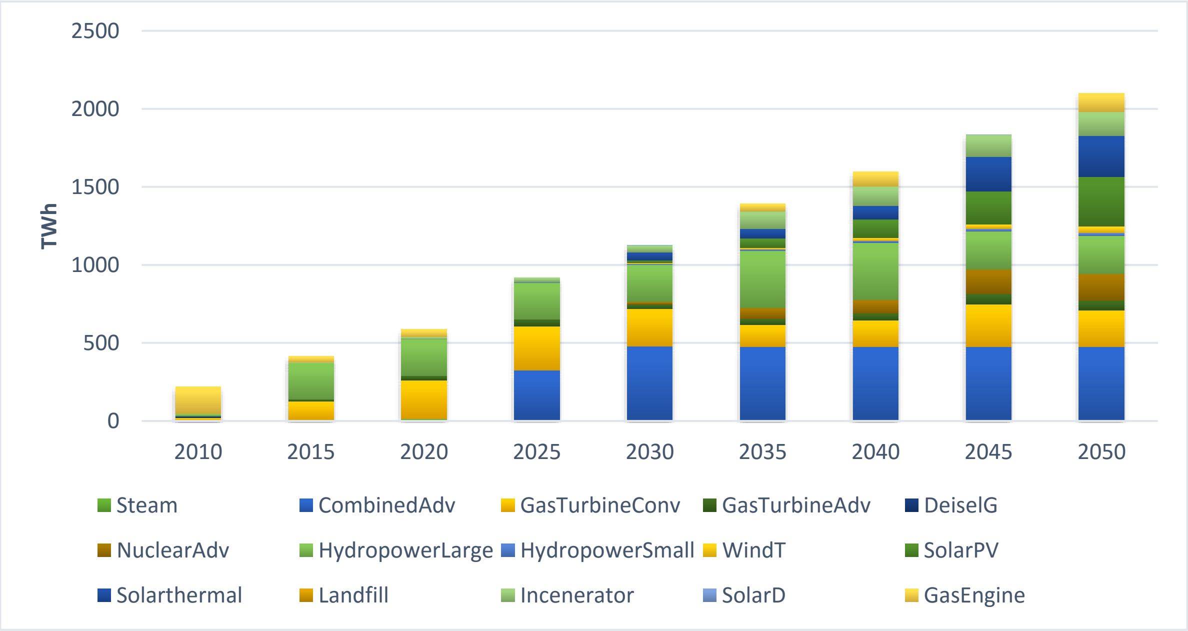

Fig. 5.6. Nigeria's electricity supply projection from 2010-2050

5.4.2.2 Emissions from the power supply mix

The sole GHG that was taken into consideration in this study was CO_2 emissions since it is the most prevalent GHG in the energy sector. The pattern of emissions that are expected to take place between the base year and 2050 is shown graphically in **Fig. 5.7**. According to the study, there has been an ongoing increase in CO_2 emissions of varying magnitudes. The emissions of CO_2 will increase from 111 million tonnes of CO_2 (M_tCO_2) in the base year to about 266 M_tCO_2 in the year 2050. The result shows significant dependency on technologies that rely on fossil fuels for the generation of electricity, this is mostly attributable to the cheaper cost of natural gas; this dependence has led to the development and rise of CO_2 emissions. The CO_2 emissions rapidly increased at first, but then leveled off and remained constant from 2030 to 2045, and then gradually reached the peak level of 266 M_tCO_2 in 2050.

A more aggressive penetration of renewable energy sources will go a long way toward helping Nigeria decrease its national GHG emissions inventory and supporting the country's efforts toward reaching a variety of international climate commitments. There is an urgent requirement for concerted efforts to accelerate the deployment of renewable energy technology across the nation. Therefore, obstacles that are responsible for the slow transition to renewable energy sources such as the absence of incentives, subsidies, grants, scarcity of renewable energy technologies experts, inadequate research and development capabilities, government bureaucracy, etc., need to be minimized or even eliminated for the transition to occur.

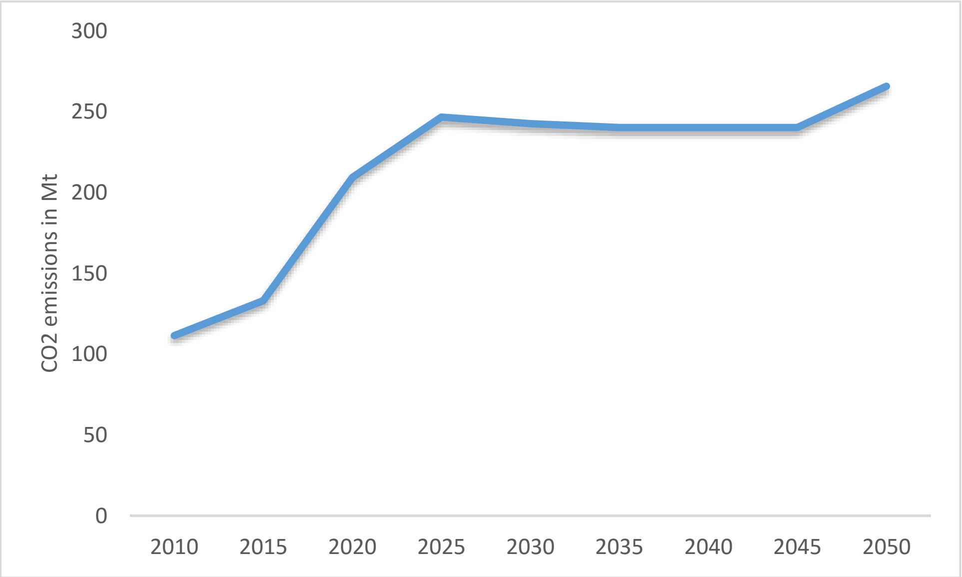

Fig. 5.7. Nigeria's CO_2 emissions from power generation

5.4.2.3 Jobs created

The employment impact of the power generation planning is displayed in **Fig. 5.8**. The capacity to generate power expanded by around 865% throughout the planned period, and the number of jobs that were created increased by more than 3,068%. This indicates that a 1% increase in power generation will result in a 3.54% rise in the number of jobs created. The overall number of jobs in the base year was approximately 66 thousand, but that number is projected to rise to 963 thousand by 2030 and peaked at almost 2.05 million jobs by 2050. This implies that there is great potential for job creation if power generation is expanded to harness all the available energy sources in Nigeria including fossil fuels, renewable energy, and alternative energy. Even though this study only considered jobs that will be created from the construction and operation of power generation technologies, there is much more room for job creation if the manufacturing of parts for the power plants is considered together with decommissioning jobs. Because of this, the potential for employment in Nigeria will increase significantly if these are included. The preceding information indicates that a shift in strategy toward the incorporation of renewable energy sources into the power generating process has the ability not only to industrialize the economy but also to bring down the extremely high unemployment rate that exists in the country.

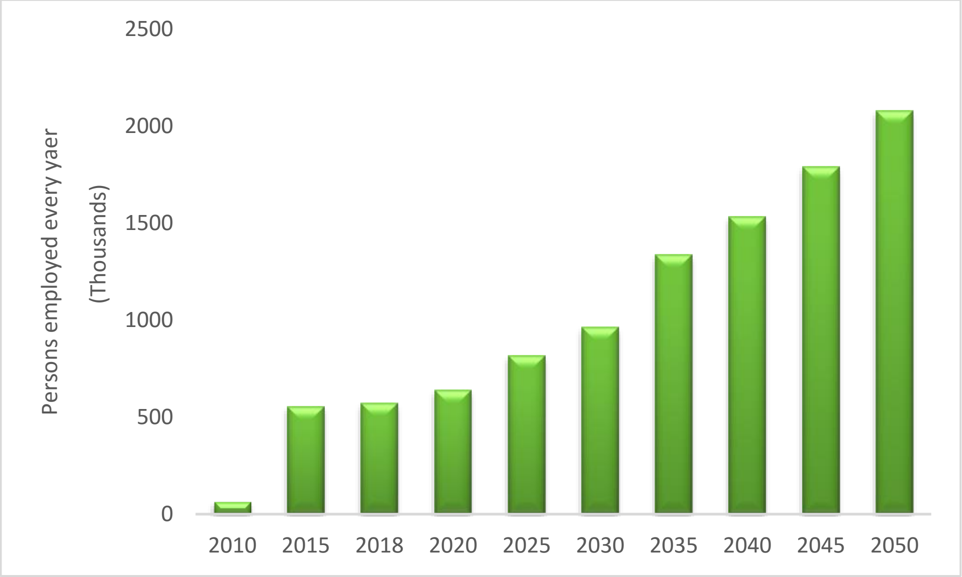

Fig. 5.8. Persons employed from PP construction and operation 2010-2050

5.4.2.4 Power generation fuel consumption

As can be seen in **Fig.5.9**, the total amount of fuel that was used to generate electricity in the base year was 13,814 PJ. The fuel consumption as projected from the base year increased and stabilized at 34,074 PJ from 2035 until 2045 when consumption of fuel remained constant. The fuel consumed for power generation during the study period peaked at 37,694 PJ in 2050 which might be ascribed to the rapid integration of various sources of energy to satisfy the growing electricity demand. The amount of fuel used had increased by a staggering 146% between the years 2011 and 2035, and by 11% between 2035 and 2050. As highlighted earlier, there is an aggressive integration of energy sources throughout the power planning horizon, this is because of the growing electricity demand. As Nigeria is a developing nation factors such as industrialization, GDP growth, income growth, population growth, literacy, urbanization, etc., are driving factors for the increment of electricity demand [63].

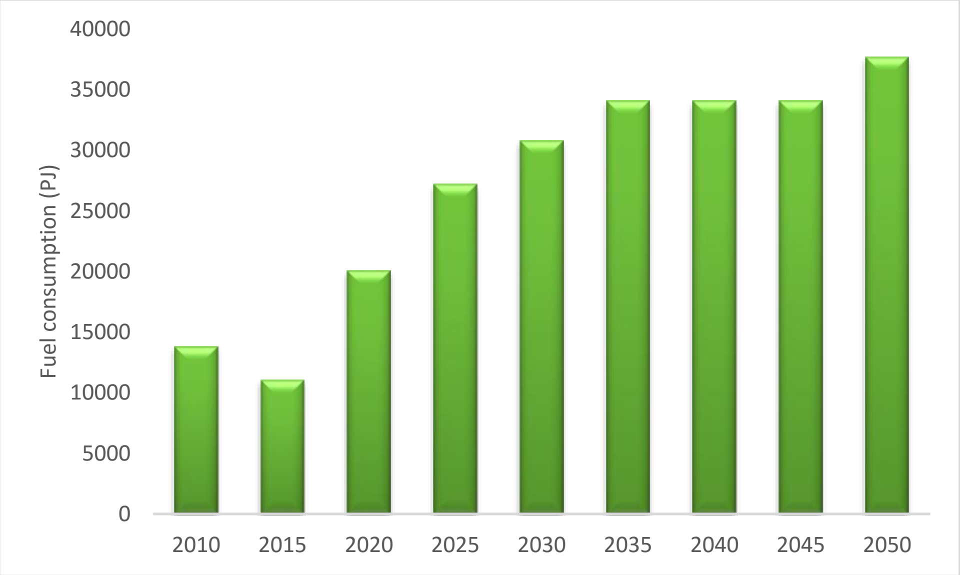

Fig. 5.9. Fuel consumed for power generation

5.4.2.5 Costs of implementing the power supply system

Fig. 5.10 displays the costs of power generation throughout the planning period. These costs are comprised of constant O&M expenses, variable O&M costs, and capital costs. The results demonstrate a rising expansion of annual investments throughout the energy planning horizon. The costs of generating in the base year are as follows: fixed O&M costs amount to 24.5 billion US$; variable O&M costs amount to 7.2 billion US$; and capital costs total 900 million US$. The whole cost of producing electricity is projected to drop to roughly 27.1 billion US$ by the year 2050. The enormous expenditures made on new power production facilities led to the power generation capital cost reaching its all-time high of 45 billion US$ in the year 2020. The rapid rise in capital costs can be attributed to the investments made in expanding hydropower large plants, incinerator power plants, and gas turbine conversion facilities. In 2020, the fixed costs reached their maximum level of 36 billion US$. The cost of overall generating was at its highest in the year 2030, coming in at 13.4 billion US$. This can be attributed to the decreased costs of operation, maintenance, and fuel that have resulted from the introduction of solar power generation plants and wind turbines, as well as the expansion of hydropower plants and the construction of small hydropower plants and incinerator power plants, among other types of power plants. The significant decrease in the prices of producing electricity as a result of the widespread adoption of renewable energy technology is the most significant benefit that conventional energy sources do not offer in comparison to renewable energy sources. On the other hand, this does not necessarily imply that the initial capital investment required for renewable energy technology is less than that required for conventional technologies. It is important to make it clear that these costs are only associated with the energy system when they are considered in isolation, and that they do not represent the total net cost to the nation. When all opportunities are considered together, an energy system with a high proportion of renewable power will have the lowest overall cost. When viewed from an economic perspective, the total annual cost of an energy system that is 100% sustainable will, over time, be lower. During the transition period, there will be an increase in capital expenditures, but the cost of gasoline will continue to go down. This will result in energy independence as well as energy security for Nigeria given that the country's energy system will mostly be based on local solar, hydro, biomass, and wind resources.

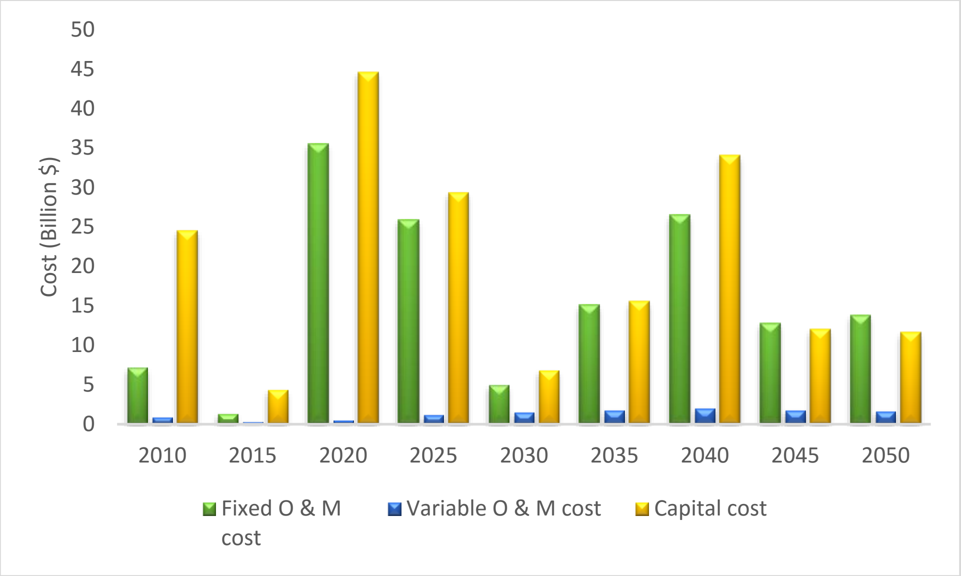

Fig. 5.10. Power generation costs

5.4.2.6 Comparison of results and outlook

In this part of the study, to obtain a more comprehensive understanding of power planning in Nigeria, relevant papers were compared with the findings of this study. An investigation was carried out to determine whether it is possible to run a power supply system entirely on renewable sources of energy in Nigeria. The findings of this study are consistent with the outcomes of the Renewable Energy Scenario (REN) 1, including the amount of CO_2 emissions, the number of jobs produced, and the power supply mix [111]. After reaching a peak of approximately 280 M_tCO_2 in 2040, the REN1 scenario's CO_2 emissions began a steady fall that eventually brought them to levels very close to zero. As a result of the fact that the REN1 scenario was built on the premise of reaching a power supply mix consisting of 100% renewable energy by the year 2050, fossil fuel power plants were fully eliminated from the power mix to accomplish this goal. On the other hand, the purpose of this study is to figure out how to get the best possible combination of sources of power while minimizing wasteful spending and emissions of greenhouse gases and boosting employment opportunities. Therefore, fossil fuel power plants continued to be a part of the mix of power supplies, which is responsible for the rise in CO_2 emissions from 240 M_tCO_2 in the year 2040 to 266 M_tCO_2 by the year 2050, instead of decreasing to zero as predicted by the research that was compared.

The LEAP energy modeling tool was utilized by Emodi et al. [70] to devise a low carbon emission energy development plan for Nigeria from the years 2010 to 2040. According to the research, the reference scenario predicts that the energy demand will rise to 3,075 PJ by 2040, with a corresponding increase in greenhouse gas emissions of 201.2 Mt CO2. In the GO scenario, more aggressive policy action by the Nigerian government would lead to a drop in both energy demand (2,249 PJ) and GHG emission (124.4 M_tCO_2) in the year 2040. The demand for energy and GHG emission substantially dropped by the year 2040 because of energy efficiency and conservation measures being implemented in the GO scenario. Emodi et al. [70] obtained that CO_2 emissions will attain 240 M_tCO_2 by the year 2040, which is obviously in line with our findings. Because of the larger participation of fossil fuel plants in the energy mix throughout the planning era, the energy demand is significantly higher in this location.

According to the results of the studies reviewed, Nigeria holds the potential to meet its energy needs and minimize its emissions of GHG by using energy sources that are available to the nation. Because of this, it is necessary to work as swiftly as possible toward the goal of integrating all these energy sources to form an optimal power supply mix. Most significantly, it was obtained that massive hydropower plants and solar PV will be the dominating technologies for power supply over the planned timeframe. Because of this, the Federal Government of Nigeria (FGN) must position solar PV, which are also known as solar cells, at the core of its policies addressing the distribution of electricity. Within a short period, the FGN must initiate policies and regulatory frameworks that can advance solar PV technologies as well as other RE technologies across the nation. Even if there have been some efforts made in this respect, such as the introduction of feed-in tariffs and the decrease of import duties on RE Technologies, the FGN must establish new policies to speed up the distribution of RE Technologies across the country. A future goal policy ought to be the adoption of a RE portfolio standard. This standard ought to make it obligatory for all power producers and distributors, respectively, to create energy from renewable sources and to acquire electricity from businesses that generate electricity using renewable sources. The nationwide shift to the use of renewable energy sources will be accelerated as a result of the execution of this initiative. The two recognized and most feasible RE Technologies (solar PV and hydropower large plants) are plagued by the variability of supply, and this will become a hindrance to the transition to total renewables if it is not addressed. As a result of this, technologies for the storage of power, such as batteries and pumped hydro, will be necessary to offer flexibility within the system and ensure that the quantity of energy demand is always equal to the amount that is supplied.

5.5 Conclusion

Energy accessibility and security as well as the mitigation of climate change at a cost that is affordable are the modern focal points of studies for economies that are still in the process of developing or underdevelopment all over the world. The three goals that were addressed in this research all have a significant connection to the use of renewable energy sources (minimization of costs, minimization of CO_2 emissions, and maximization of jobs). In the course of this study, an effort was made to investigate the best possible power supply mix by utilizing the GAMS model. This was done to reduce costs and emissions and increase job opportunities. According to the findings, Nigeria would have the capability to generate 2,100 TWh of power by the year 2050. In addition, solar PV and hydropower large would account for the majority of Nigeria's long-term energy mix during the period that was forecast. In addition, by the year 2050, the power supply mix will include the generation of electricity from solar thermal plants, incinerators, nuclear power plants, gas plants, combined plants, and diesel engines. It was found that the construction and operation of power generation plants will contribute around 2.05 million jobs to the economy by the year 2050. These positions will be created over the next three decades. By the year 2050, CO_2 emissions will have attained 266 M_tCO_2. The cost of producing electricity is projected to go down from its peak of 36 billion US dollars in 2030 to 27.1 billion US$ in 2050. It was found feasible to satisfy Nigeria's ever-increasing demand for electricity by tapping into indigenous energy sources. It was also obtained from the results that it is feasible for Nigeria's economy to keep up with the nation's growing demand for power despite the country's relatively high power system costs. Although there are many advantages to a sustainable power supply system, an active and passionate governmental intervention would be necessary to propel the development of renewable energy technology in Nigeria. This is the case even though there are many benefits to such a system. To make renewable energy sources more competitive, it is necessary to remove the obstacles that are causing the slow transition to these sources. These obstacles include fossil fuel subsidies and grants, inadequate infrastructure, inadequate training of personnel, lack of public awareness, and so on.

The lack of data and the significant assumptions that were formed during this study were the two primary obstacles that stood in the way of significant progress being accomplished. The projection of future prices of natural gas, diesel, coal, and oil will be extremely difficult to get right because of the unpredictability of a variety of factors, such as fuel prices. The nations that make up the (Organization for Economic Co-operation and Development) OECD have contributed towards the development and operation of power plants in underdeveloped and developing economies. Because of this, the results will not be precise, and one must use some degree of discretion while interpreting and analyzing the results. Despite this, it is felt that the findings provide an excellent basis for addressing the issues with Nigeria's electricity supply and reducing the emissions of GHG’s. This research will be expanded in the future to include developing several scenarios and comparing the results of those scenarios, in addition to investigating several additional competing objectives for the optimization model.

Chapter References

[1] Saeid Atabaki M, Mohammadi M, Aryanpur V. An integrated simulation-optimization modelling approach for sustainability assessment of electricity generation system. *Sustainable Energy Technologies and Assessments*. 2022;52:102010. doi:10.1016/j.seta.2022.102010.

[2] Ye N, Kueh T, Hou L, Liu Y, Yu H. A bibliometric analysis of corporate social responsibility in sustainable development. *J Clean Prod*. 2020;272:122679. doi:10.1016/j.jclepro.2020.122679.

[3] World Bank. Nigeria’s Economy Faces Worst Recession in Four Decades, says New World Bank Report. The World Bank. https://www.worldbank.org/en/news/press-release/2020/06/25/nigerias-economy-faces-worst-recession-in-four-decades-says-new-world-bank-report. Published 2020. Accessed July 29, 2022.

[4] Olujobi O, Ufua D, Olokundun M, Olujobi O. Conversion of organic wastes to electricity in Nigeria: legal perspective on the challenges and prospects. *International Journal of Environmental Science and Technology*. 2021;19(2):939-950. doi:10.1007/s13762-020-03059-3.

[5] Iroh O, Kalu I, Nteegah A. Empirical Cost of Electricity Outage on Labour and Capital Productivity in Nigeria. *Applied Journal of Economics, Management and Social Sciences*. 2022;3(1). doi:10.53790/ajmss.v3i1.23.

[6] World Bank. Access to electricity (% of the population) - Nigeria | Data. Published 2022. Available from: https://data.worldbank.org/indicator/EG.ELC.ACCS.ZS?locations=NG (accessed Mar. 28, 2022).

[7] Zhao X, Mahendru M, Ma X, Rao A, Shang Y. Impacts of environmental regulations on green economic growth in China: New guidelines regarding renewable energy and energy efficiency. *Renew Energy*. 2022;187:728-742. doi:10.1016/j.renene.2022.01.076.

[8] Walther J, Weigold M. A Systematic Review on Predicting and Forecasting the Electrical Energy Consumption in the Manufacturing Industry. *Energies (Basel)*. 2021;14(4):968. doi:10.3390/en14040968.

[9] C. Berglund and P. Söderholm, “Modeling technical change in energy system analysis: Analyzing the introduction of learning-by-doing in bottom-up energy models,” *Energy Policy*, vol. 34, no. 12, pp. 1344–1356, 2006, doi: 10.1016/j.enpol.2004.09.002.

[10] R. G. Cong, “An optimization model for renewable energy generation and its application in China: A perspective of maximum utilization,” *Renewable and Sustainable Energy Reviews*, vol. 17. pp. 94–103, Jan. 2013. doi: 10.1016/j.rser.2012.09.005.

[11] K. U. Rao and V. V. N. Kishore, “A review of technology diffusion models with special reference to renewable energy technologies,” *Renewable and Sustainable Energy Reviews*, vol. 14, no. 3. pp. 1070–1078, Apr. 2010. doi: 10.1016/j.rser.2009.11.007.

[12] P. D. Lund, “Energy policy planning near grid parity using a price-driven technology penetration model,” *Technological Forecasting and Social Change*, vol. 90, no. PB, pp. 389–399, Jan. 2015, doi: 10.1016/j.techfore.2014.05.004.

[13] P. Lund, “Market penetration rates of new energy technologies,” *Energy Policy*, vol. 34, no. 17, pp. 3317–3326, Nov. 2006, doi: 10.1016/j.enpol.2005.07.002.

[14] S. Mallah and N. K. Bansal, “Renewable energy for sustainable electrical energy system in India,” *Energy Policy*, vol. 38, no. 8, pp. 3933–3942, Aug. 2010, doi: 10.1016/j.enpol.2010.03.017.

[15] N. A. Utama, K. N. Ishihara, T. Tezuka, N. A. Utama, K. N. Ishihara, and T. Tezuka, “Power Generation Optimization in ASEAN by 2030,” *Energy and Power Engineering*, vol. 4, no. 4, pp. 226–232, Jun. 2012, doi: 10.4236/EPE.2012.44031.

[16] Q. Zhang, K. N. Ishihara, B. C. Mclellan, and T. Tezuka, “Scenario analysis on future electricity supply and demand in Japan,” *Energy*, vol. 38, no. 1, pp. 376–385, 2012, doi: 10.1016/j.energy.2011.11.046.

[17] Z. A. Muis, H. Hashim, Z. A. Manan, F. M. Taha, and P. L. Douglas, “Optimal planning of renewable energy-integrated electricity generation schemes with CO2 reduction target,” *Renewable Energy*, vol. 35, no. 11, pp. 2562–2570, Nov. 2010, doi: 10.1016/j.renene.2010.03.032.

[18] Q. Zhang, K. N. Ishihara, B. C. Mclellan, and T. Tezuka, “Scenario analysis on future electricity supply and demand in Japan,” *Energy*, vol. 38, no. 1, pp. 376–385, 2012, doi: 10.1016/j.energy.2011.11.046.

[19] Q. Zhang, B. C. Mclellan, T. Tezuka, and K. N. Ishihara, “An integrated model for long-term power generation planning toward future smart electricity systems,” *Applied Energy*, vol. 112,

pp. 1424–1437, 2013, doi: 10.1016/j.apenergy.2013.03.073.

[20] T. Luz, P. Moura, and A. de Almeida, “Multi-objective power generation expansion planning with high penetration of renewables,” Renew Sustain Energy Rev, vol. 81, pp. 2637- 2643, 2018, http://doi.org/10.1016/j.rser.2017.06.069.

[21] A. Poullikkas, G. Kourtis, and I. Hadjipaschalis, “A hybrid model for the optimum integration of renewable technologies in power generation systems,” *Energy Policy*, vol. 39, no. 2, pp. 926–935, Feb. 2011, doi: 10.1016/j.enpol.2010.11.018.

[22] C. Barteczko-Hibbert, I. Bonis, M. Binns, C. Theodoropoulos, and A. Azapagic, “A multi-period mixed-integer linear optimisation of future electricity supply considering life cycle costs and environmental impacts,” *Applied Energy*, vol. 133, pp. 317–334, Nov. 2014, doi: 10.1016/j.apenergy.2014.07.066.

[23] Purwanto WW, Pratama YW, Nugroho YS, Hertono GF, Hartono D, Tezuka T. Multi-objective optimization model for sustainable Indonesian electricity system: analysis of economic, environment, and adequacy of energy sources. Renew Energy 2015;81:308e18.

[24] Amorim F, Pina A, Gerbelov a H, da Silva PP, Vasconcelos J, Martins V. Electricity decarbonisation pathways for 2050 in Portugal: a TIMES (The Integrated MARKAL-EFOM System) based approach in closed versus open systems modelling. Energy 2014;69:104e12.

[25] Dountio EG, Meukam P, Tchaptchet DLP, Ango LEO, Simo A. Electricity generation technology options under the greenhouse gases mitigation scenario: case study of Cameroon. Energy Strat Rev 2016;13:191e211.

[26] Hainoun A, Aldin MS, Almoustafa S. Formulating an optimal long-term energy supply strategy for Syria using MESSAGE model. Energy Pol 2010;38(4): 1701e14.

[27] Jaskolski M. Modelling long-term technological transition of Polish power system using MARKAL: emission trade impact. Energy Pol 2016;97:365e77.

[28] Komusanac I, Cosic B, Duic N. Impact of high penetration of wind and solar PV generation on the country power system load: the case study of Croatia. Appl Energy 2016;184:1470e82.

[29] McPherson M, Karney B. Long-term scenario alternatives and their implications: LEAP model application of Panamaʹ s electricity sector. Energy Pol 2014;68:146e57.

[30] Merkel E, Fehrenbach D, McKenna R, Fichtner W. Modelling decentralised heat supply: an application and methodological extension in TIMES. Energy 2014;73:592e605.

[31] Park NB, Yun S, Eui CJ. An analysis of long-term scenarios for the transition to renewable energy in the Korean electricity sector. Energy Pol 2013;52: 288e96.

[32] Tomaschek J, Kober R, Fahl U, Lozynskyy Y. Energy system modelling and GIS to build an integrated climate protection concept for Gauteng Province, South Africa. Energy Pol 2016;88:445e55.

[33] Welsch M, Deane P, Howells M, Gallachoir BO, Rogan F, Bazilian M, et al. Incorporating flexibility requirements into long-term energy system modelseA case study on high levels of renewable electricity penetration in Ireland. Appl Energy 2014;135:600e15).

[34] Heinricha G, Bassonc L, Cohena B, Howellsd M, Petrie J. Ranking and selection of power expansion alternatives for multiple objectives under uncertainty. Energy 2007;32:2350e69.

[35] Ren HB, Zhou WS, Nakagami K, Gao WJ, Wu Q. Multi-objective optimization for the operation of distributed energy systems considering economic and environmental aspects. Appl Energy 2010;87:3642e51.

[36] Antunes CH, Martins GA, Brito IS. A multiple objective mixed integer linear programming

model for power generation expansion planning. Energy 2004;29:613e27.

[37] Aryanpur V, Shafiei E. Optimal deployment of renewable electricity technologies in Iran and implications for emissions reductions. Energy 2015;91: 882e93.

[38] Dhakouani A, Gardumi F, Znouda E, Bouden C, Howells M. Long-term optimisation model of the Tunisian power system. Energy 2017;141:550e62.

[39] Ren et al. Ren HB, Zhou WS, Nakagami K, Gao WJ, Wu Q. Multi-objective optimization for the operation of distributed energy systems considering economic and environmental aspects. Appl Energy 2010;87:3642e51.

[40] Zhang Q, Mclellan BC, Tezuka T, Ishihara KN. Economic and environmental analysis of power generation expansion in Japan considering Fukushima nuclear accident using a multi-objective optimization model. Energy 2012;44(1):986e95.

[41] Ko L, Chen CY, Seow VC. Electrical power planning and scheduling in Taiwan based on the simulation results of multi-objective planning model. Int J Elect prower Energy Syst 2014;55(1):331e40.

[42] Purwanto WW, Pratama YW, Nugroho YS, Hertono GF, Hartono D, Tezuka T. Multi-objective optimization model for sustainable Indonesian electricity system: analysis of economic, environment, and adequacy of energy sources. Renew Energy 2015;81:308e18.

[43] Mahbub MS, Viesi D, Crema L. Designing optimized energy scenarios for an Italian Alpine valley: the case of Giudicarie Esteriori. Energy 2016;116(1): 236e49].

[44] Pratama YW, Purwanto WW, Tezuka T, McLellan BC, Hartono D, Hidayatno A, Daud Y. Multi-objective optimization of a multiregional electricity system in an archipelagic state: the role of renewable energy in energy system sustainability. Renew Sustain Energy Rev 2017;77(1):423e39.

[45] Tekiner H, Coit DW, Felder FA. Multi-period multi-objective electricity generation expansion planning problem with Monte-Carlo simulation. Elec Power Syst Res 2010;80(12):1394e405.

[46] H. A. Ibrahim and M. K. Ayomoh, "Identification and Prioritisation of Electricity Driving Factors for Power Supply Sustainability: A Case of Developing and Underdeveloped Nations," 2021 IEEE Asia-Pacific Conference on Computer Science and Data Engineering (CSDE), 2021, pp. 1-6, doi: 10.1109/CSDE53843.2021.9718450.

[47] Adeniyi A, Ighalo J, Adeyanju C. Materials-to-product potentials for sustainable development in Nigeria. *International Journal of Sustainable Engineering*. 2021;14(4):664-671. doi:10.1080/19397038.2021.1896591.

[48] Statista. Nigeria: annual electricity generation 2020-2021 | Statista. Statista. https://www.statista.com/statistics/1294835/annual-electrical-energy-generation-in-nigeria/. Published 2022. Accessed July 28, 2022.

[49] Umunna Nwachukwu M, Flora Ezedinma N, Jiburum U. Comparative Analysis of Electricity Consumption among Residential, Commercial and Industrial Sectors of the Nigeria's Economy. *Journal of Energy Technologies and Policies*. 2014;4(3):7-13. https://www.iiste.org/Journals/index.php/JETP/article/view/11660/12005. Accessed July 28, 2022.

[50] M.F. Akorede, O. Ibrahim, S.A. Amuda, A.O. Otuoze, B.J. Olufeagba, Current status and outlook of renewable energy development in Nigeria, Niger. J. Technol. 36 (2017) 196–212, doi:10.4314/njt.v36i1.25.

[51] T.C. Chineke, U.K. Okoro, Application of Sayigh ‘“Universal Formula”’ for global solar

radiation estimation in the Niger Delta region of Nigeria, Renew. Energy 35 (2010) 734–739.

[52] M. Shaaban, J. Petinrin, Renewable energy potentials in Nigeria: meeting rural energy needs, Renew Sustain Energy Rev 29 (2014) 72–84.

[53] M.O. Dioha, I.J. Dioha, O.A. Olugboji, An assessment of Nigeria wind energy potential based on technical and financial analyses, J. Sustain. Energy 7 (2016) 53–57.

[54] M. Shaaban, J. Petinrin, Renewable energy potentials in Nigeria: meeting rural energy needs, Renew Sustain Energy Rev 29 (2014) 72–84.

[55] R. Kela, K.M. Usman, A. Tijjani, Potentials of small hydro power in Nigeria: the current status and investment opportunities, Int. J. Sci. Eng. Res. 3 (2012) 1–5.

[56] J.U. Abaka, T.B. Ibraheem, H. Salmanu, O. Olokede, Hydropower potential of Nigeria, Int. J. Mod. Eng. Res. 7 (2017) 52–58.

[57] Ritchie H, Roser M, Rosado P. CO_2 and Greenhouse Gas Emissions. Our World in Data. https://ourworldindata.org/co2-emissions. Published 2022. Accessed July 28, 2022.

[58] Dokua Sasu D. Carbon emissions from electricity generation in Nigeria 2000-2020. Statista. https://www.statista.com/statistics/1307126/power-sector-carbon-emissions-in-nigeria/#:~:text=As%20of%202020%2C%20carbon%20emissions%20from%20the%20power,equivalent.%20This%20kept%20stable%20from%20the%20previous%20year. Published 2022. Accessed July 28, 2022.

[59] Olurounbi R. Bloomberg - Are you a robot?. Bloomberg.com. https://www.bloomberg.com/news/articles/2021-11-02/nigeria-targets-to-reach-net-zero-emissions-by-2060-buhari-says. Published 2022. Accessed July 28, 2022.

[60] Olurounbi R. Nigeria Unemployment Rate Rises to 33%, Second Highest on Global List. Bloomberg.com. https://www.bloomberg.com/news/articles/2021-03-15/nigeria-unemployment-rate-rises-to-second-highest-on-global-list. Published 2022. Accessed July 28, 2022.

[61] Bamisile O, Huang Q, Xu X et al. An approach for sustainable energy planning towards 100 % electrification of Nigeria by 2030. Energy. 2020;197:117172. doi:10.1016/j.energy.2020.117172.

[62] Salman B, Nomanbhay S, Foo D. Carbon emissions pinch analysis (CEPA) for energy sector planning in Nigeria. *Clean Technol Environ Policy*. 2018;21(1):93-108. doi:10.1007/s10098-018-1620-5.

[63] Blechinger P, Cader C, Bertheau P. Least-Cost Electrification Modeling and Planning—A Case Study for Five Nigerian Federal States. *Proceedings of the IEEE*. 2019;107(9):1923-1940. doi:10.1109/jproc.2019.2924644.

[64] Ibrahim H, Ye G. Electricity Demand and Supply Scenario Analysis for Nigeria Using Long Range Energy Alternatives Planning (LEAP). *J Sci Res Rep*. 2018;19(2):1-12. doi:10.9734/jsrr/2018/39719.

[65] A. S. Sambo, “Matching Electricity Supply with Demand in Nigeria,” *32 | Fourth Quarter*, 2008.

[66] Nathan Pelesai A, O. Thank God A. The Dynamics of Demand and Supply of Electricity in Nigeria. The *International Institute for Science, Technology and Education (IISTE)*. 2013;3(2225-0565):25-36. Available from: https://www.iiste.org/Journals/index.php/DCS/article/view/4663/4742. Accessed April 11, 2022.

[67] C. Amlabu, J. Agber, C. Onah and S. Mohammed, "Electric Load Forecasting: A Case Study of the Nigerian Power Sector", *International Journal of Engineering and Innovative Technology (IJEIT)*, vol. 2, no. 13, 2013. [Accessed 31 March 2022].

[68] E. O. S and I. O. E, "Analysis Of Nigeria's National Electricity Demand Forecast (2013-2030)," *International Journal of Scientific & Technology Research*, vol. 3, 2014, [Online]. Available: www.ijstr.org.

[69] Oyediran Oyelami B and adedoyin Adewumi A. Models for Forecasting the Demand and Supply of Electricity in Nigeria. *American Journal of Modeling and Optimization*. 2014;2(1):25-33. doi:10.12691/ajmo-2-1-4. http://pubs.sciepub.com/ajmo/2/1/4.

[70] N. V. Emodi, C. C. Emodi, G. P. Murthy, and A. S. A. Emodi, "Energy policy for low carbon development in Nigeria: A LEAP model application," *Renewable and Sustainable Energy Reviews*, vol. 68. Elsevier Ltd, pp. 247–261, Feb. 01, 2017. doi: 10.1016/j.rser.2016.09.118.

[71] A. Adedokun, "Nigeria electricity forecast and vision 20: 2020: Evidence from ARIMA model," *http://dx.doi.org/10.1080/15567249.2014.912697*, vol. 11, no. 11, pp. 1027–1034, Nov. 2016, doi: 10.1080/15567249.2014.912697.

[72] Moss T and Portelance G. Do African Countries Consume Less (or More) Electricity than Their Income Levels Suggest?. Center for Global Development | Ideas to Action. Published 2017. Available from: https://www.cgdev.org/blog/do-african-countries-consume-less-or-more-electricity-than-their-income-levels-suggest Accessed April 10, 2022.

[73] World Bank. Electric power consumption (kWh per capita) | Worlddataview.com. Worlddataview.com. Available: https://worlddataview.com/topics/environment/electric_power_consumption_kwh_per_capita. Published 2022. Accessed March 14, 2022.

[74] M. O. Oseni, "An analysis of the power sector performance in Nigeria," *Renewable and Sustainable Energy Reviews*, vol. 15, no. 9. Elsevier Ltd, pp. 4765–4774, 2011. doi: 10.1016/j.rser.2011.07.075.

[75] Y. S. Mohammed, M. W. Mustafa, N. Bashir, and A. S. Mokhtar, "Renewable energy resources for distributed power generation in Nigeria: A review of the potential," *Renewable and Sustainable Energy Reviews*, vol. 22. Elsevier Ltd, pp. 257–268, 2013. doi: 10.1016/j.rser.2013.01.020.

[76] Patrick N. O. Unlocking the potential of the power sector for industrialization and poverty alleviation in Nigeria | UNCTAD. Unctad.org. https://unctad.org/webflyer/unlocking-potential-power-sector-industrialization-and-poverty-alleviation-nigeria. Published 2017. Accessed April 23, 2022.]

[77] Yetano Roche M. Comparison of Costs of Electricity Generation in Nigeria. Ng.boell.org. Published 2017. Available from: https://ng.boell.org/sites/default/files/true_cost_of_power_technical_report_final.pdf. Accessed April 17, 2022.

[78] S. O. Oyedepo, "Towards achieving energy for sustainable development in Nigeria," *Renewable and Sustainable Energy Reviews*, vol. 34. Elsevier Ltd, pp. 255–272, 2014. doi: 10.1016/j.rser.2014.03.019.

[79] Ogunbiyi D, Abiodun M. *Nigeria Power Baseline Report*. Abuja: Advisory Power Team; 2015:1-30. Available from: https://mypower.ng/wp-content/uploads/2018/01/Baseline-Report.pdf. Accessed April 15, 2022.

[80] Adebisi A, Yusuf Yabo F. Nigeria SE4ALL Action Agenda Final. Seforall.org. Published 2016. Available from: https://www.seforall.org/sites/default/files/NIGERIA_SE4ALL_ACTION_AGENDA_FINAL.pdf. Accessed May 14, 2022.

[81] C. Raffaello, D. Irina, K. Rogers and J. Allen "Assessing Low-Carbon Development in Nigeria," *Assessing Low-Carbon Development in Nigeria*, Jun. 2013, doi: 10.1596/978-0-8213-9973-6. http://documents.worldbank.org/curated/en/333931468332952975/Assessing-low-carbon-development-in-Nigeria-an-analysis-of-four-sectors.

[82] Patrick O, Tolulolope O, Sunny O, Patrick O, Tolulolope O, Sunny O. Smart Grid Technology and Its Possible Applications to the Nigeria 330 kV Power System. Smart Grid and Renewable Energy 2013;4:391–7. https://doi.org/10.4236/SGRE.2013.45045.

[83] NASA. "Surface meteorology and Solar Energy," Atmospheric Science Data Center | Projects | SSE. Asdc.larc.nasa.gov. Available from: https://asdc.larc.nasa.gov/project/SSE. Published 2018. Accessed February 23, 2022.

[84] Stetter D. "Enhancement of the REMix energy system model: global renewable energy potentials, optimized power plant siting and scenario validation." Published Dissertation 2014. https://elib.dlr.de/92150/ (accessed Mar. 29, 2022).

[85] D. Bogdanov and C. Breyer, "North-East Asian Super Grid for 100% renewable energy supply: Optimal mix of energy technologies for electricity, gas and heat supply options," *Energy Conversion and Management*, vol. 112, pp. 176–190, Mar. 2016, doi: 10.1016/j.enconman.2016.01.019.

[86] S. Afanasyeva, D. Bogdanov, and C. Breyer, "Relevance of PV with single-axis tracking for energy scenarios," *Solar Energy*, vol. 173, pp. 173–191, Oct. 2018, doi: 10.1016/j.solener.2018.07.029.

[87] U. B. Akuru, I. E. Onukwube, O. I. Okoro, and E. S. Obe, "Towards 100% renewable energy in Nigeria," *Renewable and Sustainable Energy Reviews*, vol. 71. Elsevier Ltd, pp. 943–953, 2017. doi: 10.1016/j.rser.2016.12.123.

[88] Ajayi A, Sowande S, Oyewolu N, Anyanechi C. A Guide to the Nigerian Power Sector. KPMG. https://home.kpmg/ng/en/home/insights/2016/09/a-guide-to-the-nigerian-power-sector.html. Published 2016. (accessed Apr. 21, 2022).

[89] Akuru UB, Animalu AOE, Animalu AOE. "Nigeria-Electricity-Supply". KPMG. Available from: https://home.kpmg/.../insights/2021/11/nigeria-electricity-supply-industry-highlights.html / Published 2021 (accessed Apr. 01, 2022).

[90] NNPC. Crude Oil Reserves/ Production. Napims.nnpcgroup.com. Available from: https://napims.nnpcgroup.com/Pages/Crude-Oil-Reserves-Production.aspx. Published 2022. Accessed March 16, 2022.

[91] Arnette A, Zobel C. An optimization model for regional renewable energy development. *Renewable and Sustainable Energy Reviews*. 2012;16(7):4606-4615. doi:10.1016/j.rser.2012.04.014.

[92] ECN. Energy Implications of Vision 20: 2020 And Beyond. Abuja, Abuja, 2014.

[93] M. Yetano Roche, H. Verolme, C. Agbaegbu, T. Binnington, M. Fischedick, and E. O. Oladipo, "Achieving Sustainable Development Goals in Nigeria's power sector: assessment of transition pathways," *Climate Policy*, vol. 20, no. 7, pp. 846–865, Aug. 2020, doi: 10.1080/14693062.2019.1661818/SUPPL_FILE/TCPO_A_1661818_SM9019.DOCX.

[94] Oke, S., Ayomoh, M., Akanbi, O., & Oyawale, F. (2008). Application of hybrid structural interaction matrix to quality management. *International Journal Of Productivity And Quality Management*, *3*(3), 275. doi: 10.1504/ijpqm.2008.017499.

[95] N. B. Park, S. J. Yun, and E. C. Jeon, "An analysis of long-term scenarios for the transition to renewable energy in the Korean electricity sector," *Energy Policy*, vol. 52, pp. 288–296, Jan. 2013, doi: 10.1016/J.ENPOL.2012.09.021.

[96] TAVANIR Holding Company. Electricity power industry in Iran (2015-2016). Tehran: TAVANIR; 2016. Available from: http://amar.tavanir.org.ir/pages/ report/stat94/sanatebargh/sanatebargh%20l/sanatl.pdf. (accessed Apr. 01, 2022).

[97] Renewable Energy Organization of Iran (SUNA) – Kish Solar Trading Company. 2012. Available from: http://kishsolar.com/renewable-energy-organization-of-iran-suna/?lang=en (accessed Apr. 01, 2022).

[98] IEA and NEA. Projected cost of generating electricity. Paris: IEA; 2015. Available from: https://www.oecd-nea.org/ndd/pubs/2015/7057-proj-costs-electricity-2015.pdf (accessed Apr. 01, 2022).

[99] IEA-ETSAP. Technology brief: coal-fired power. IEA-ETSAP. 2010. Available from: http://www.etsap.org/E-techDS/PDF/E01-coal-fired-power-GS-AD-gct. pdf (accessed Apr. 01, 2022).

[100] IEA. Renewable energy essentials: geothermal. Paris: IEA; 2010. Available from: https://www.iea.org/publications/freepublications/publication/ Geothermal_Essentials.pdf (accessed Apr. 01, 2022).

[101] IEA. Technology roadmap: solar thermal electricity. Paris: IEA; 2014. Available from: https://www.iea.org/media/freepublications/technologyroadmaps/ TechnologyRoadmapSolarThermalElectricity_2014edition4.pdf (accessed Apr. 01, 2022).

[102] IEA. Renewable energy essentials: hydropower. Paris: IEA; 2010. Available from: http://www.iea.org/publications/freepublications/publication/hydro power_essentials.pdf (accessed Apr. 01, 2022).

[103] Roche M.Y., Ude N., Ofoegbu D.I. True cost of electricity in Nigeria: comparison of costs of electricity generation in Nigeria. Abuja: Nigerian Economic Summit Group and Heinrich Böll Stiftung Nigeria; 2017.

[104] Roche Y.M., Verolme H., Agbaegbu C., Binnington T., Fischedick M., Oladipo E.O. Achieving sustainable development goals in Nigeria's power sector: assessment of transition pathways. Clim. Policy 2019:1–20. 10.1080/14693062.2019.1661818.

[105] IEA. Energy technology perspectives Catalysing Energy Technology Transformations: OECD/IEA; 2017. Available from: https://www.iea.org/media/freepublications/technologyroadmaps/EnergyTechnology Perspectives 2017 – Analysis - IEA2017edition4.pdf (accessed Apr. 01, 2022).

[106] M. Ram, M. Child, A. Aghahosseini, D. Bogdanov, A. Lohrmann, C. Breyer, A comparative analysis of electricity generation costs from renewable, fossil fuel and nuclear sources in G20 countries for the period 2015-2030, J. Clean. Prod. 199 (2018) 687–704, doi:10.1016/j.jclepro.2018.07.159.

[107] S. J. W. Klein and S. Whalley, "Comparing the sustainability of U.S. electricity options through multi-criteria decision analysis," *Energy Policy*, vol. 79, pp. 127–149, Apr. 2015, doi: 10.1016/J.ENPOL.2015.01.007.

[108] IPCC. Guidelines for national greenhouse gas inventories. 2006. Available from: http://www.ipcc-nggip.iges.or.jp/public/2006gl/index.html (accessed Apr. 01, 2022).

[109] EIA. “Annual Energy Outlook 2022 - U.S. Energy Information Administration (EIA).” 2022. Available from: https://www.eia.gov/outlooks/aeo/ (accessed Apr. 01, 2022).

[110] Oke S, Ayomoh M. The hybrid structural interaction matrix. *International Journal of Quality & Reliability Management*. 2005;22(6):607-625. doi:10.1108/02656710510604917.

[111] Tambari I, Dioha M, Failler P. Renewable energy scenarios for sustainable electricity supply in Nigeria. *Energy and Climate Change*. 2020;1:100017. doi:10.1016/j.egycc.2020.100017.

Chapter 6

Renewable energy's impact on power supply accessibility, affordability, and environmental sustainability: A system dynamics approach

6.0 Chapter Overview

The chapter titled "Renewable Energy's Impact on Power Supply Accessibility, Affordability, and Environmental Sustainability: A System Dynamics Approach" is focused on studying the effects of renewable energy on three key aspects: power supply accessibility, affordability, and environmental sustainability. The chapter is based on a system dynamics approach, which is a method for understanding and analyzing complex systems with feedback loops and dynamic interactions.

The dynamics and complexities of renewable energy adoption, particularly in the context of power supply accessibility, are explored in the chapter. The impacts of renewable energy sources such as solar, wind, or hydro power on the accessibility of electricity to different regions or communities, especially in developing economies, are investigated. The affordability of renewable energy in terms of its costs, pricing structures, and economic implications for consumers, governments, and other stakeholders is also analyzed. The potential benefits and challenges of incorporating renewable energy into power supply systems in terms of affordability and financial sustainability are examined.

Furthermore, the environmental sustainability aspects of renewable energy are explored in the chapter, considering its potential to reduce greenhouse gas emissions, mitigate climate change, and protect the environment. The potential environmental impacts of renewable energy sources, such as land use, water use, wildlife conservation, and waste management, are analyzed. The interactions and feedback loops between renewable energy adoption and environmental sustainability, including potential trade-offs or synergies, are also examined.

Overall, a comprehensive analysis of the impact of renewable energy on power supply accessibility, affordability, and environmental sustainability is provided in the chapter, utilizing a system dynamics approach. The chapter contributes to the existing literature on renewable energy adoption, provides insights for policymakers and practitioners, and highlights the potential benefits and challenges of transitioning to renewable energy sources for power generation.

6.1 Introduction

The World Economic Forum (WEF) first discussed the relationship between water, energy, and food in 2008 [1]. Between these three sectors, there are two different kinds of interactions: synergy, in which advancement in one area promotes the growth of another or results in a compromise in that field, and vice versa. The effectiveness of controlling food, energy, and water to prevent shortages has been the other. Every choice in these areas should thus be carefully considered because one decision in one sector will have an indirect or direct impact on the other sectors.

Considering the energy sector, burning fossil fuels is the leading cause of air pollution worldwide [2]. Consequently, the pollution from burning fossil fuels alone kills more than 8 million people per year around the world [3]. In addition, burning fossil fuels releases a lot of greenhouse gases into the atmosphere. One of these, carbon dioxide, retains heat in the atmosphere and causes climate change. The greatest threat that humanity is now facing is regarded as climate change. An estimated 11.4% of the world's energy in 2019 came from renewables, while the remaining 4.3% came from non-renewable sources like fossil fuels, which account for 84.3% of all energy production [4]. Comparatively speaking, fossil fuels provided 86.1% of the world's energy in the year 2000. Nigeria's top goal should be energy source diversification to achieve a power supply system that is accessible, affordable, and environmentally sustainable to the entire nation. In light of the current trend towards sustainable development, Nigeria shouldn't fall behind in adopting policies to address issues with power supply accessibility, affordability, and environmental sustainability [5]. The overreliance on fossil fuel sources, which strains the reserves, is the root of the problem. The policy framework that is reliant on fossil fuels to provide the majority of its energy needs is another issue. By introducing other options [6] such biomass, solar, and hydro, geothermal, tidal, etc., it is feasible to eliminate this burden.

Utilizing the System Dynamics software Vensim, indicators are collected for each variable of power supply availability, affordability, and environmental sustainability as well as the relationships between the variables. 60% of RE capacity is the goal Nigeria has set for itself by 2030 [7], with a current RE penetration in the power sources mix of roughly 23% as of 2020. Transition to a low-carbon economy to enhance environmental sustainability depends heavily on RE. The cost of renewable energy is considerable, particularly in the early phases, which reduces energy efficiency. Energy consumption is to blame for 73.2% of the world's greenhouse gas emissions in 2016 [8]. This covers the utilization of energy for the generation of heat, electricity, and energy for transportation. The main barrier to the implementation of renewables is the capital investment, however as technology evolves, the cost of RE is decreasing [9]. As a result, this study will provide a thorough analysis of Nigeria's power supply accessibility, affordability, and environmental sustainability, with a focus on the significance of renewable energy to these aspects. Certainly, reducing poverty and enhancing the standard of living in the nation depend on economic growth. Energy is critical for economic development since it is the "oxygen" of both the economy as well as the key driver behind economic growth [10]. Nigeria is one of the world's top producers of both oil and natural gas [11]. Nigeria's energy industry is therefore essential to the country's economy's development. Fossil fuels have been Nigeria's main source of energy for industry, domestic usage, transportation, and the generation of electricity. Currently, up to 77% of Nigeria's energy mix comes from natural gas, which is mostly used to create electricity [12]. An inefficient and decaying power generation, transmission, and distribution system has hampered all economic processes. The decoupling of the power industry, which comprises of 23 grid-connected power stations with a combined installed capacity of 10,396 MW and a combined available capacity of 6,056 MW [13], led to the formation of the Nigerian Electricity Supply Industry (NESI). The only component of the power production chain wholly owned by Nigeria is the Transmission Company of Nigeria (TCN), which was formed in 2005 when the National Electric Power Authority (NEPA) was decoupled. The 132kV and 330kV transmission systems are operated, maintained, and expanded by TCN [14]. There are more than 24000 km of distribution network on the grid line, which works at medium and low voltages (33kV and 11kV, respectively) in 2010 [14]. In Nigeria, the distribution of electricity is handled by 11 energy distribution companies (DISCOS). Ikeja Electricity Distribution Company has a service area of 36,585 km, whereas Kano has a service area of 7,404 km and has the greatest losses at 40%. The Ikeja network has the largest power demands of 1,400 MW due to the strong energy consumption by businesses in that specific region, whereas the Ibadan network does have the highest output of 878 MW with 812,000 consumers [15]. Nigeria therefore intends to diversify its mix of energy sources in order to minimize its use of fossil fuels, as announced at COP26 [16], and avoid becoming overly dependent on fossil fuel sources. Despite this, Nigeria's improved power supply accessibility, affordability, and environmental sustainability cannot be realized due to the country's overreliance on fossil fuels. Nigeria has a booming population of more than 200 million people with an annual growth rate of 2.55% [17]. This immediately results in a rise in energy consumption, which might provide Nigeria with further difficulties. Little or no research has been performed using a system dynamics approach to analyze the influence of renewable energy on the accessibility, affordability, and environmental sustainability of power supply in Nigeria. This directly contributes to a dearth of study on establishing a causal link between the various dimensions of accessibility, affordability, and environmental sustainability of the power supply. The ultimate purpose of this study is to examine accessibility, affordability, and environmental sustainability on Nigeria's power system, as well as the influence of RE on these aspects. To achieve this, three causal loop diagrams are created, one for each of the three dimensions of accessibility, affordability, and environmental sustainability. The next stage in the process of investigating how renewable energy impacts the availability, affordability, and environmental sustainability of power supply was the development of two stock-flow diagrams (SFD) for two distinct scenarios.

6.2 Nigeria’s energy policies and their interaction with power supply accessibility, affordability, and environmental sustainability

6.2.1 Nigeria's energy policies

Table 6.1 provides a summary of Nigeria's energy policies so that scenarios for power supply accessibility, affordability, and environmental sustainability may be developed.

The dimensions of power supply accessibility, affordability, and environmental sustainability:

The article briefly discusses the impact of renewable energy on power affordability, accessibility, and environmental sustainability. The three dimensions listed above have been determined to be the most important factors for the sustainability of Nigeria's power supply based on the study that has already been done.

6.2.2 Availability dimension

One of the more established aspects of energy security is availability which has been observed from various literatures. This relates directly to the natural origins of power sources. Nigeria has relied on fossil fuels for long years because they are easily accessible [12]. Nigeria has additionally been importing refined fossil fuels from other nations at the same time. Nigeria has been using natural gas to produce energy for some while now [18]. This situation has the potential to turn Nigeria from a major exporter to an importer. As a result, the supply of fuel reserves is dependent on both domestic and foreign providers of energy.

6.2.3 Affordability dimension

Energy access and availability at a reasonable cost are all that is meant by the term "affordable energy" [19]. Affordability, according to Sovacool and Brown [20] is characterized as ensuring access to energy resources; conversely, it suggests that people from all socioeconomic strata should have access to energy [21]. According to Kruyt et al., [22], it is the minimal energy prices for customers. Affordability is one among the aspects that has to be given importance since transitioning to RE would be costlier than using fossil fuels. This is due to the fact that using RE requires more expensive equipment than using traditional fuels for power generation. As a result, this dimension and the nation's economic situation are stable and reliable. Aside from that, there is a strong correlation between the cost of energy resources and their volatility. For a brief while, supply and demand mismatches can be used to explain the unpredictability of fossil fuels [23].

Table 6.1: An overview of Nigeria's energy policies

Year	Policy on Energy	Objective of the policy	Reference
2003	National Energy Policy (NEP)	The NEP places a strong emphasis on making the best use possible of the country's energy resources to ensure long-term economic and social development with the effective involvement of the private sector.	[24]
2014	National Renewable Energy and Energy Efficiency Policy (NREEEP)	In addition to applying energy efficiency and conservation technologies and best practices in the domestic, commercial, industrial, transportation, agricultural, and construction sectors of the nation's economy, this policy outlines the exploration, exploitation, and allocation of all renewable sources. This paper, it is believed, will offer the framework required for more effective development of energy efficiency and renewable energy for sustainable growth of the country's economy.	[25]
2007	National Energy	To create a framework for the implementation NEP.	[26].

	Masterplan (NEMP)		
2006	Renewable Energy Masterplan (REMP)	By 2030, 36% of all power will be generated from renewable sources, up from 13% in 2015, according to the REMP. By 2025, 10% of the power consumed in Nigeria would be from renewable sources.	[27]

6.2.4 *Environmental sustainability dimension*

This factor is crucial in demonstrating the enormous environmental impact that fossil fuel-related human activities may have [28]. Within this dimension, the amount of carbon dioxide emissions is crucial. Within such an aspect, the relationship between CO_2 emission and other metrics, including population, GDP, energy consumption, etc., was investigated. Since it impacts the quantity of RE used to generate electricity, which is directly tied to lowering GHG emissions, the amount of renewable energy utilized in the generation of electricity is a clear demonstration of this dimension. Diversifying the sources of electricity-generating fuels is widely employed as an indicator of power supply accessibility, affordability, and environmental sustainability, according to Kosaki & Unesaki, [29]; Zhu et al., [30]; and Alvarez-Ramos et al., [31]. This is referred to as the "environmental stewardship dimension" toward "accessibility, affordability, and environmental sustainability" in Sovacool & Brown's [20] analysis, which also notes that it emphasizes sustainability.

6.3 Methodology

Accessibility, affordability, and environmental sustainability of power generation were further investigated in this study. To investigate the link between several indicators of each dimension, causal loop diagrams were developed. A causal loop diagram was made for each of the three dimensions using the corresponding indicators. The causal loop diagram shows how several dimension indicators are related causally. This study provided two distinct situations. Studying the nation's aspiration for power supply accessibility, affordability, environmental sustainability and taking into account the difficulties the nation has faced in helping design these two scenarios. As a result, the underlying premise of the scenarios is the objective set out in the various policies that have been discussed. For each scenario the simulation of the Stock and Flow Diagram (SFD) for the next five years was performed.

6.3.1 *System dynamic approach*

A simulation technique that addresses real-world issues is termed as system dynamics approach [32]. This is accomplished by outlining how the variables interact in actual complicated systems. The link between the indicators of each dimension is generated using the Vensim software. The Causal Loop Diagrams (CLDs) will include positive (+) arrows for relationships with mutual supports and negative (-) arrows for links that are contradictory to one another. The purpose of the causal loop diagrams is to analyze the link between the variables that either directly or indirectly impact one another. In this study, two distinct cases are described, each of which includes a stockflow diagram (SFD) for simulation. Stocks are essential for generating system behavior. It establishes the system's current state [33]. Stocks can only be modified by flows into and out of the system, which can only be measured one instant at a time. Flows are measured throughout a period because they are expressed per unit of time. Energy intensity, cost, and energy consumption all rise when overall energy use rises. As a result, energy is used less efficiently. Energy stock would gradually rise as a result of this, and production rates may go up. The remaining CLDs and their loops may also be easily read and comprehended in order to comprehend the connection and causation of the indicators of each dimension. If there isn't at least one stock involved in a causal loop, the loop becomes instantaneous. Stocks are influenced by auxiliary variables but changing the system's mathematical structure by adding or eliminating auxiliary variables has no effect. Every variable and its fluxes must be defined by quantitative values and equations in order to be quantitatively modeled. According to the research of Morecroft and Sterman (1994), there are two presumptions: (1) flows inside processes are continuous, and (2) flow lacks a random component [34]. With these two presumptions in mind, the stock and flow system may be compared to a "plumbing system," with the stock serving as the tank and the flows serving as the valves that regulate the flow rate into and out of the tank. It is necessary to establish the flow equation and the beginning values for each stock. These equations enable the model to be solved in Vensim, which then produces a graphical depiction of the change over time.

6.4 CLD and SFD

6.4.1 Availability dimension CLD

As seen by the CLD in Fig. 6.1, when there are more people, there is a greater need for electricity since there are more people doing more things. The population of Nigeria has been continuously increasing, with a growth rate of 2.5% yearly [35]. The need for energy in Nigeria will rise gradually along with the country's population growth. As shown in **Fig. 6.1**, a higher birth rate increases the population, and a higher death rate decreases it. The balancing loop states that when demand for power increases, more power is generated while also using more primary source of energy. Energy intensity is directly connected to the overall use of primary energy. This is because the energy intensity is the proportion of gross domestic product to total primary energy use (GDP). As a result, the amount of primary energy consumed overall directly proportionately determines the energy intensity. Energy intensity would rise with a rise in the overall use of primary energy. Energy demand will rise as energy intensity increases, raising the cost of energy as a result. Furthering explanation is the fact that as power consumption rises, so does the requirement for generation. Energy reserves will decrease due to the growth in energy output. As a result, the ratio of the nation's energy reserves to its total production drops. The nation's power supply accessibility, affordability, and environmental sustainability is at jeopardy as a result, and energy shortages might result. When there is a shortage of energy, energy demand will rise. One of the problems Nigeria's electricity supply today faces is the accessibility, affordability, and environmental sustainability brought on by the importation of fossil fuels from other nations [36]. The country's economic growth is projected to slow down as its dependence on energy imports increases, which is bad for the accessibility, affordability, and environmental sustainability of the country's long-term power supply: As a result, the nation's principal energy source is now dependent on energy imports.

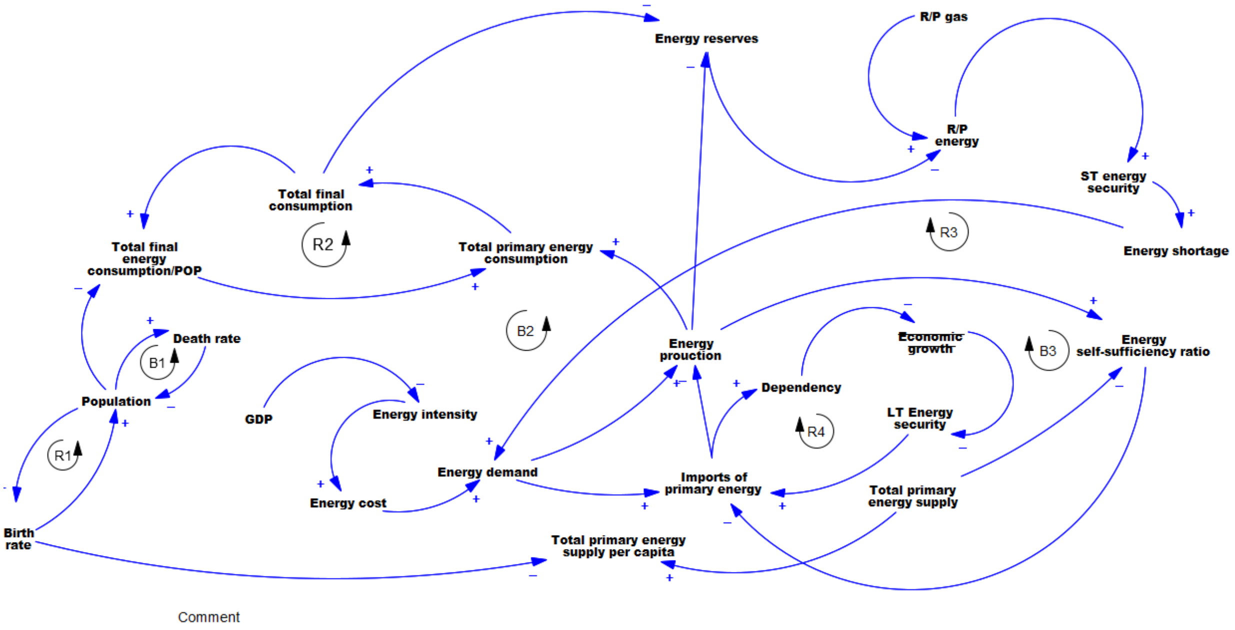

Fig. 6.1. Power supply availability CLD

6.4.2 Affordability dimension CLD

The consequences of the population's birth and death rates are addressed by the reinforcing loop and balancing loop in **Fig. 6.2**. Any population rise immediately leads to a rise in energy consumption, as seen by the balancing loop B2. Increased energy demand will probably result in higher energy costs and a decrease in energy supply. As a result, there is a reduction in the amount of power produced. As a result, fewer people would have access to power on a percentage basis. Increasing energy output in R2 is a result of higher energy consumption. Energy consumption will inevitably rise if energy output remains high. In the meanwhile, balancing loop B3 connects the production and consumption of power to its supply and demand. Higher power output would result in higher electricity demand. As a result, the demand for power would rise. Higher electricity demand would result in higher electricity prices and a reduction in the amount of electricity available. If a result, as the supply of power declines, so would the amount of electricity produced. The retail power price, sometimes referred to as supply and demand in the electricity tariff, is related to loops R3 and B4. A higher electricity tariff lowers demand whereas a higher electricity tariff reduces supply, which raises the electricity tariff in the scenario where higher demand raises the power tariff. This is because there won't be any carbon emissions at all while utilizing RE as a source of energy. As a result, there is a decrease in the environmental effect of emissions and contaminants. As a result, the nation will build additional RE capacity, which immediately raises the output of renewables. The ratio of power used to CO_2 emissions rises when CO_2 emissions increase as well. Climate change is more likely to occur if CO_2 emissions are larger than they were under energy consumed. The environmental sustainability dimension performs worse as the likelihood of climate change rises. The CO_2 emissions raise the CO_2 over GDP ratio since they are exactly proportional, which is the final explanation for loop B4. As a result, the nation's economy will expand less rapidly. The country's poverty is likely to rise as a result, which will lower the standard of living. A lower standard of living can raise CO_2 emissions once more.

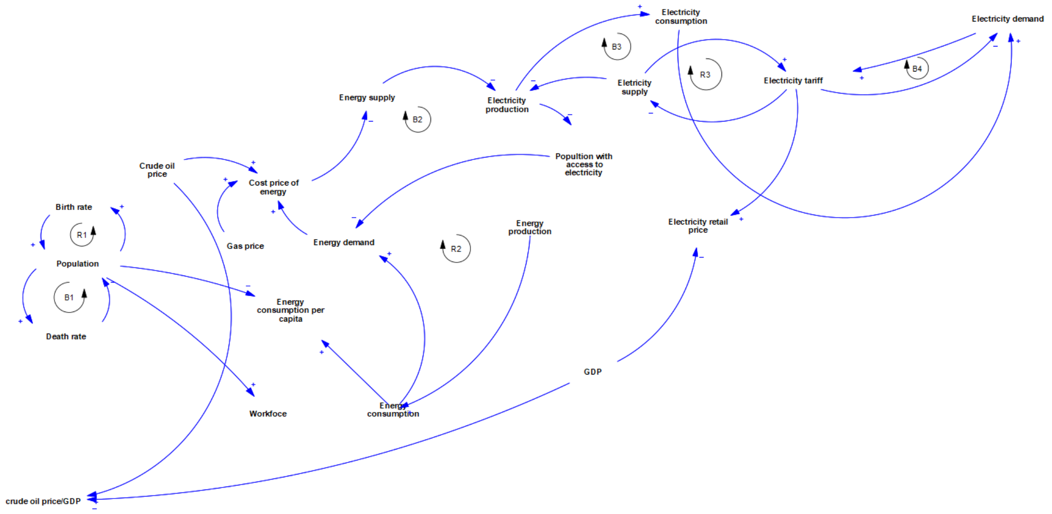

Fig. 6.2. Affordable power CLD

6.4.3 Environmental sustainability dimension causal loop diagram

According to **Fig. 6.3**. the non-carbon percentage of the power generation increases as RE production increases. This is because using renewables as an energy source will result in zero carbon emissions. Consequently, pollutants and toxins have less of an impact on the environment. As a result, the country's capability for harnessing renewable will increase, increasing the share of renewable output. The ratio of energy used to CO_2 emissions increases in R3 as greenhouse gas (CO_2) emissions grow.

Climate change is more likely to occur if CO_2 emissions are larger than they were under primary energy. The environmental sustainability factor performs worse as the likelihood of climate change rises. The CO_2 emissions raise the CO_2 over GDP ratio since they are exactly proportional, which is the final explanation for loop R4. As a result, the nation's economy will expand less rapidly. The country's poverty is likely to rise as a result, which will lower the standard of living. A lower standard of living can raise CO_2 emissions once more.

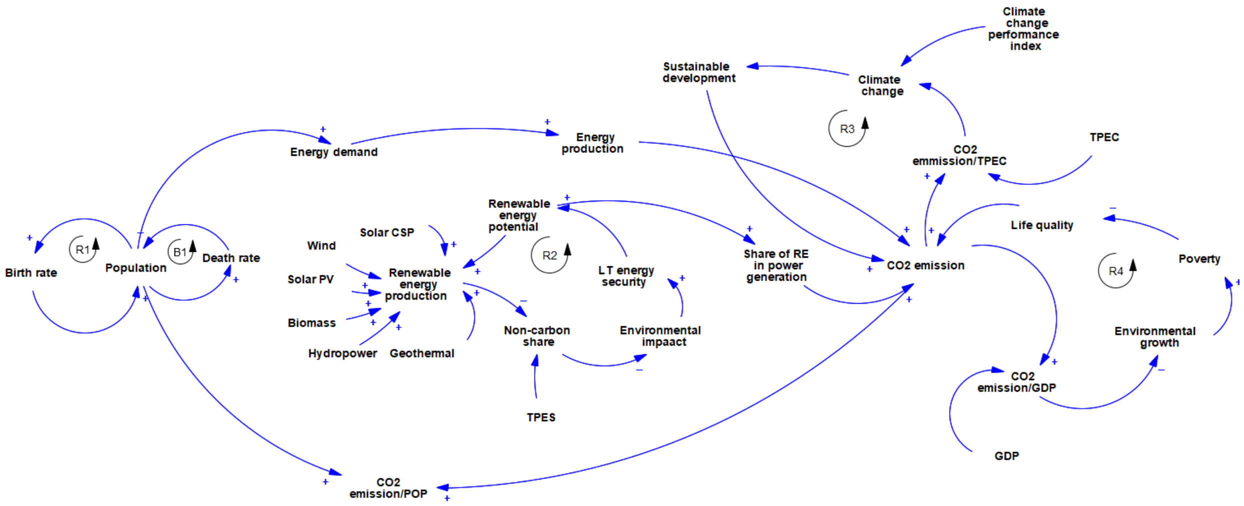

Fig.6.3. Environment Sustainability CLD

6.4.4 Stock and flow diagrams

Fig. 6.4 shows a Stock and Flow Diagram (SFD) that illustrates the direct effect of a business as usual (BAU) scenario on Nigeria's access, affordability, and environmental sustainability of its power supply. In Nigeria, natural gas and hydropower plants account for 77% and 23%, respectively, of the country's total power generating mix as of 2021 [16]. Natural gas power plants are thought to operate at an efficiency of about 45%. This immediately correlates with the remainder being lost to the environment to the tune of 55%. Gas has the benefit of having the best power efficiency of any power plant and emitting less carbon dioxide than other fossil fuels like coal. To lessen its reliance on fossil fuels, the Nigerian government has been trying to use RE sources for power generation. This is demonstrated by the REMP's 2030 capacity mix objective, which calls for 36% RE. In turn, this would result in a reduction in our reliance on fossil fuels. A forecast is given for a significant increase in electricity output and efficiency over the next five years if the reliance on fossil fuels declines (**Fig. 6.6**). In **Fig. 6.4**, as the number of energy sources becomes more plentiful, so does power generation, and so does the amount of energy that is accessible for use in power generation. With decreased reliance on fossil fuels and a larger proportion of RE in the power supply mix, it is anticipated that Nigeria would be able to ensure a better power supply that is accessible, affordable, and environmentally sustainable. Power costs rise as a result of increased power generation. Power wastage decreases when energy costs rise in an indirect manner. Thus, power supply efficiency is increased. The effect of the proportion of renewable energy on the availability, affordability, and environmental sustainability of the power supply is shown in **Fig. 6.5**. According to the REMP, renewable energy sources will produce 36% of total electricity by 2030, up from 13% in 2015. 10% of the electricity used in Nigeria by 2025 will come from renewable sources [27]. The diversification of the power supply mix, which includes the incorporation of energy sources like solar, hydro, biomass, wind, tidal, etc., has been substantially slowed down by the Covid-19 pandemic outbreak, though. The pandemic temporarily reduced the consumption of power, but it is expected that as the nation concentrates on its economic recovery, the increase in demand will level off going forward. This rise in power demand is brought on by both increased power consumption and an increasing population [37]. In accordance with the government's target of 36% renewables in the power mix by 2030, a projection is prepared on the availability, affordability, and environmental sustainability of power production and delivery. According to **Fig. 6.7**, a rise in the proportion of renewables in the power supply mix results in an explosive increase in power output. Comparable scenario-based research will assist energy policymakers in formulating policies based on greater facts and proof. As a result, individuals in charge of energy policy should develop strategies that focus on better and more sustainable developments for Nigeria's power supply in terms of accessibility, affordability, and environmental sustainability.

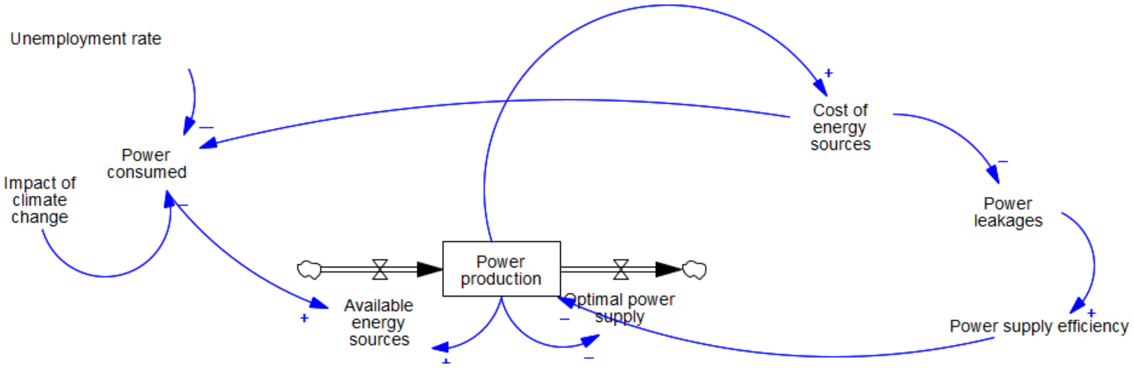

Fig. 6.4. The BAU SFD

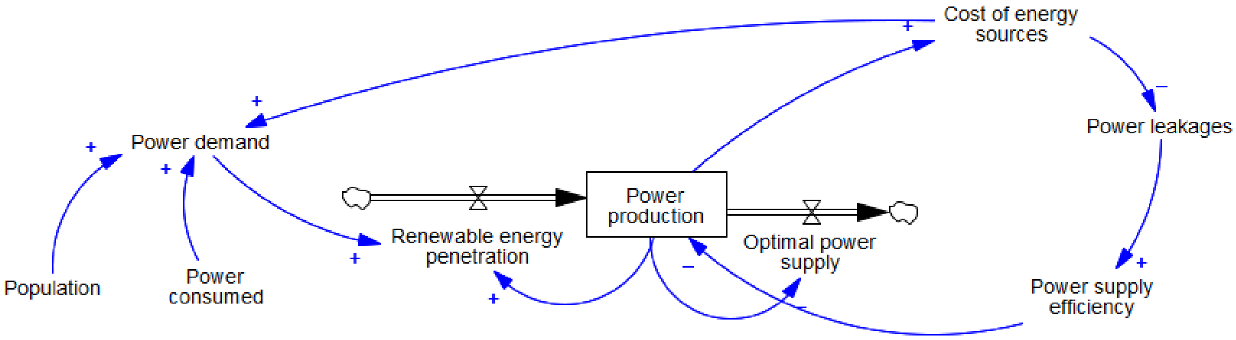

Fig. 6.5. The renewable penetration SFD

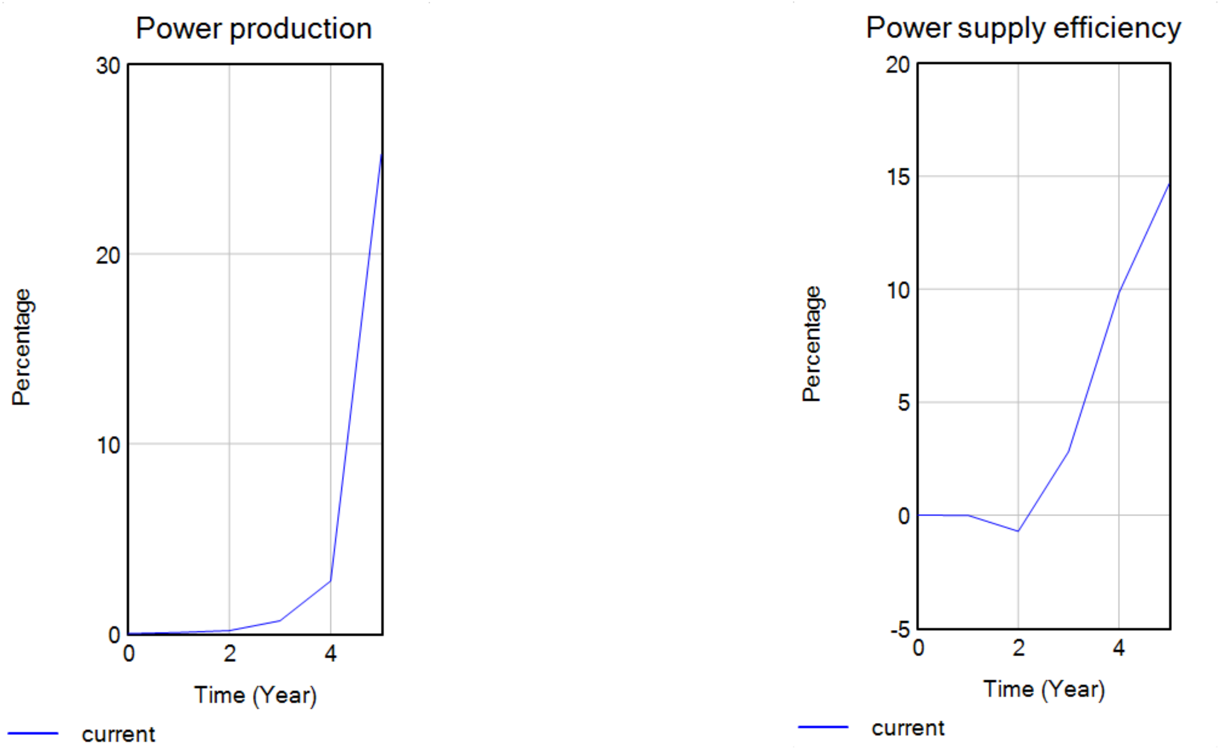

Fig. 6.6. Simulation results of the BAU SFD

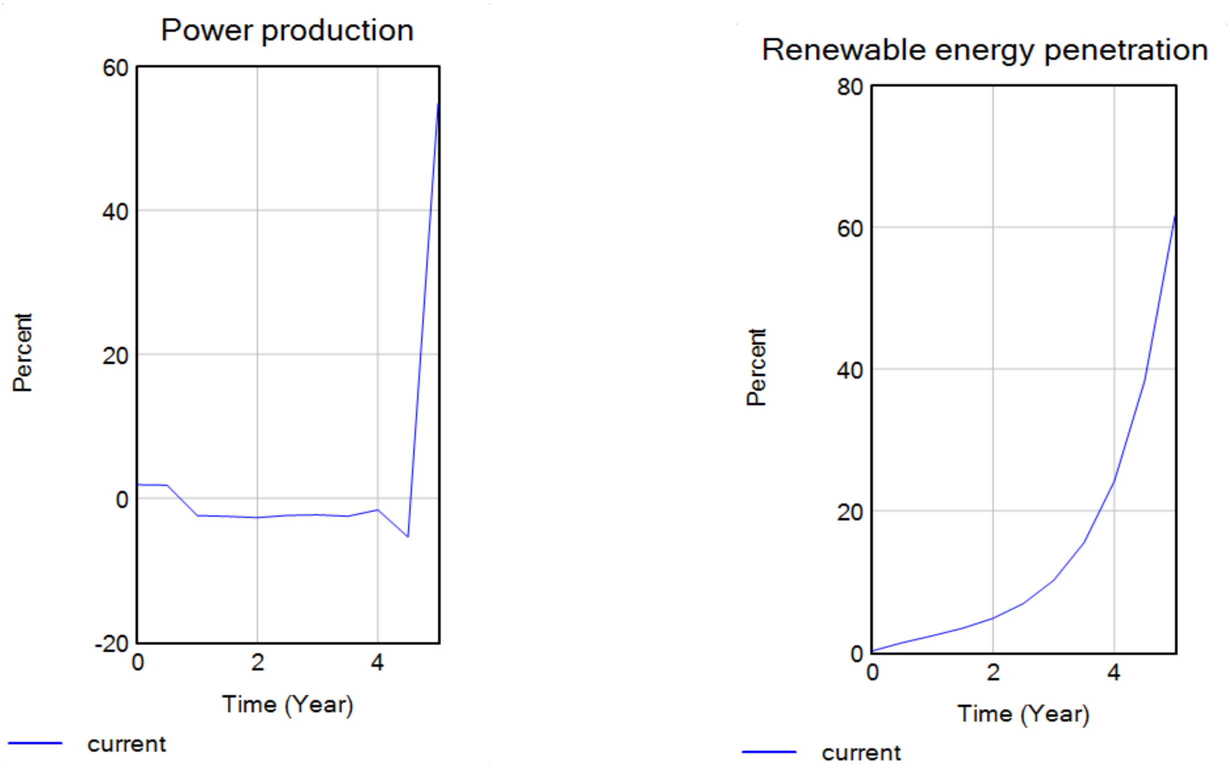

Fig. 6.7. Simulation results of the renewable penetration SFD

6.5 Conclusion

Three CLDs were developed in this study to examine the relationships among the various indicators of power supply accessibility, affordability, and environmental sustainability dimensions. In order to examine the effects of an increased percentage of RE in power generation on Nigeria's power supply accessibility, affordability, and environmental sustainability, two distinct scenarios were developed. Accessibility, affordability, and environmental sustainability of the electricity supply are thought to be enhanced if indeed the country's plan of using 36% renewables in the mix of power sources is to be met. By making investments in RE, reducing the usage of fossil fuels for the power generation is also feasible [55]. The only barrier the nation will encounter is the cost of investing in RE technology, which is greater than that of fossil fuels. RE must ultimately take over as the main energy source since it is a more sustainable option compared to other sources of energy with no or extremely low greenhouse gas emissions. These objectives would be threatened by the RE's intermittent nature, however with improved financing and energy storage technologies, these can be overcome. Nigeria has to make progress in implementing the policies necessary to increase the country's accessibility, affordability, and environmental sustainability. The model must be validated and verified with the necessary parties from the Ministry of Power, Ministry of Science and Technology, Ministry of Agriculture, Ministry of Petroleum, Ministry of Environment, NNPC (Nigerian National Petroleum Company) Limited, ECN (Energy Commission of Nigeria), REA (Rural Electrification Agency), and other NGOs working within the energy sector. This will guarantee that the model appropriately represents the current energy policies in Nigeria. This might be a chance to broaden the present research, which would be beneficial.

Chapter References

[1] Nair K, Shadman S, Chin CM, Sakundarini N, Yap EH, Koyande A. Developing a system dynamics model to study the impact of renewable energy in the short-and long-term energy security. Materials Science for Energy Technologies. 2021 Jan 1;4:391-7.

[2] A. Pareek, R. Dom, J. Gupta, J. Chandran, V. Adepu, P.H. Borse, Insights into renewable hydrogen energy: Recent advances and prospects, Mater. Sci. Energy Technol. 3 (2020) 319–327, https://doi.org/10.1016/j.mset.2019.12.002.

[3] I. Kottasová, A. Dewan, Fossil fuel air pollution causes almost 1 in 5 deaths globally each year, CNN (2021).

[4] H. Ritchie, Energy mix, Our World Data. (2019).

[5] S. Shadman, C.M.M. Chin. The role of current and future renewable energy policies in fortifying Malaysia’s energy security : PESTLE and SWOT analysis through stakeholder engagement, Progress in Energy and Environment, 16 (2021), pp. 1-17. https://www.akademiabaru.com/submit/index.php/progee/ article/view/2395/2430.

[6] E.R. Bandala, M. Berli, Engineered nanomaterials (ENMs) and their role at the nexus of Food, Energy, and Water, Mater. Sci. Energy Technol. 2 (2019) 29–40, https://doi.org/10.1016/j.mset.2018.09.004.

[7] Ibrahim HA, Ayomoh MK. Identification and prioritization of factors affecting the transition to renewables in developing economies. Energy Reports. 2022 Nov 1;8:94-104.

[8] H. Ritchie, Sector by sector: where do global greenhouse gas emissions come from?, Our, World Data. (2020).

[9] C.J. Randall, Renewable Vs Nonrenewable Energy Resources, Sciencing. Com, 2018.

[10] M. Azam, Energy and economic growth in developing Asian economies, J. Asia Pacific Econ. 25 (2020) 447–471, https://doi.org/10.1080/ 13547860.2019.1665328.

[11] Ibrahim HA, Kirkil G. Electricity demand and supply scenario analysis for Nigeria using long range energy alternatives planning (LEAP). J. Sci. Res. Rep. 2018 May;19(2):1-2.

[12] S.S. Ahmad, C. Yap, S. Mokhtar, Z. Mali, S. Mansor, M.S.A.A. Rahim, Energy Malaysia 12 (2017) 12.

[13] Vincent, E.N. and Yusuf, S.D., (2014). Integrating Renewable Energy and Smart Grid Technology into the Nigerian Electricity Grid System. Smart Grid and Renewable Energy, 5, 220-238. http://dx.doi.org/10.4236/sgre.2014.59021.

[14] NERC, (2011). Presentation at the Electric Power Investor's Forum (February 2011).

[15] S. O. Adams, R. O. Akano ,O. J. Asemota, (2011). 'Forecasting Electricity Generation in Nigeria using Univariate Time Series Models ', European Journal of Scientific Research, Vol.58 No.1 (2011), (1450-216X), pp. 30-37.

[16] Ibrahim HA, Ayomoh MK. Optimum predictive modelling for a sustainable power supply mix: A case of the Nigerian power system. Energy Strategy Reviews. 2022 Nov 1;44:100962.

[17] M. Yetano Roche, H. Verolme, C. Agbaegbu, T. Binnington, M. Fischedick, and E. O. Oladipo, “Achieving Sustainable Development Goals in Nigeria’s power sector: assessment of transition pathways,” Climate Policy, vol. 20, no. 7, pp. 846–865, Aug. 2020, doi: 10.1080/14693062.2019.1661818/SUPPL_FILE/TCPO_A_1661818_SM9019.DOC X.

[18] M. Raman, Malaysia is burning more coal now than it did 20 years ago, Star Media Gr, Berhad, 2020.

[19] S. Tongsopit, N. Kittner, Y. Chang, A. Aksornkij, W. Wangjiraniran, Energy security in ASEAN: A quantitative approach for sustainable energy policy, Energy Policy 90 (2016) 60–72, https://doi.org/10.1016/j. enpol.2015.11.019.

[20] B.K. Sovacool, M.A. Brown, Competing dimensions of energy security: An international perspective, 2010. https://doi.org/10.1146/annurev-environ 042509-143035.

[21] Sadia Malik, Maha Qasim, Hasan Saeed, Youngho Chang, Farhad Taghizadeh Hesary, Energy security in Pakistan: perspectives and policy implications from a quantitative analysis, Energy Policy 144 (2020) 111552, https://doi.org/ 10.1016/j.enpol.2020.111552.

[22] Bert Kruyt, D.P. van Vuuren, H.J.M. de Vries, H. Groenenberg, Indicators for energy security, Energy Policy 37 (6) (2009) 2166–2181, https://doi.org/ 10.1016/j.enpol.2009.02.006.

[23] Ibrahim HA, Ayomoh MK. Identification and Prioritisation of Electricity Driving Factors for Power Supply Sustainability: A Case of Developing and Underdeveloped Nations. In 2021 IEEE Asia-Pacific Conference on Computer Science and Data Engineering (CSDE) 2021 Dec 8 (pp. 1-6). IEEE.

[24] Energy Commission of Nigeria. https://www.energy.gov.ng/Energy_Policies_Plan/APPROVED_REVISED_NEP_2022.pdf. Accessed October 21, 2022.

[25] Draft national renewable energy and energy efficiency policy (NREEEP). https://energy.gov.ng/Energy_Policies_Plan/natonal_renewable_energy_and_energy_efficiency_policy.pdf. Accessed October 21, 2022.

[26] Energy efficiency policies and programs. Energy.gov. https://www.energy.gov/eere/slsc/energy-efficiency-policies-and-programs. Accessed October 21, 2022.

[27] Iea. Nigeria renewable energy master plan – policies. IEA. https://www.iea.org/policies/4974-nigeria-renewable-energy-master-plan. Accessed October 21, 2022.

[28] Xu Gong, You Wang, Boqiang Lin, Assessing dynamic China's energy security: Based on functional data analysis, Energy 217 (2021) 119324, https://doi.org/ 10.1016/j.energy.2020.119324.

[29] Shoki Kosai, Hironobu Unesaki, Short-term vs long-term reliance: Development of a novel approach for diversity of fuels for electricity in energy security, Appl. Energy 262 (2020) 114520, https://doi.org/10.1016/j. apenergy.2020.114520.

[30] D. Zhu, S.M. Mortazavi, A. Maleki, A. Aslani, H. Yousefi, Analysis of the robustness of energy supply in Japan: Role of renewable energy, Energy Rep. 6 (2020) 378–391, https://doi.org/10.1016/j.egyr.2020.01.011.

[31] C. Álvarez-Ramos, A.M. Diez-Suárez, M. de Simón-Martín, A. González-Martínez, E. Rosales-Asensio, A brief systematic review of the literature on the economic, social and environmental impacts of shale gas exploitation in the United Kingdom, Energy Rep. 6 (2020) 11–17, https://doi.org/10.1016/j.egyr.2020.10.014.

[32] A. Maryani, S. Wignjosoebroto, S.G. Partiwi, A system dynamics approach for modeling construction accidents, Procedia Manuf. 4 (2015) 392–401, https:// doi.org/10.1016/j.promfg.2015.11.055.

[33] N. Osgood, Introduction to Stocks & Flows State of the System : Stocks (‘‘ Levels ”, ‘‘ State Variables ”, ‘‘ Compartments ”), (n.d.).

[34] System Analysis I Compendium for students, (2009).

[35] Population growth (annual %) - nigeria. Data. https://data.worldbank.org/indicator/SP.POP.GROW?locations=NG. Accessed October 20, 2022.

[36] E.J.M. Sahid, C.C. Siang, L.Y. Peng, Enhancing energy security in Malaysia: The challenges towards sustainable environment, IOP Conf. Ser. Earth Environ. Sci. 16 (2013) 012120, https://doi.org/10.1088/1755-1315/16/1/012120.

[37] A. Kumar, T. Bhattacharya, S.M. Mozammil Hasnain, A. Kumar Nayak, M.S. Hasnain, Applications of biomass-derived materials for energy production, conversion, and storage, Mater. Sci. Energy Technol. 3 (2020) 905–920, https:// doi.org/10.1016/j.mset.2020.10.012.

[38] N. V. Emodi, C. C. Emodi, G. P. Murthy, and A. S. A. Emodi, "Energy policy for low carbon development in Nigeria: A LEAP model application," Renewable and Sustainable Energy Reviews, vol. 68. Elsevier Ltd, pp. 247–261, Feb. 01, 2017. doi: 10.1016/j.rser.2016.09.118.

Chapter 7

Conclusion and recommendations

7.1 Conclusion

In this thesis, holistic thinking revolving around energy mix for a sustainable power generation in the Nigerian power system has been developed using a multi-objective optimization approach to integrate indigenous energy sources into the existing power generation mix. The model has three conflicting objectives: reducing power generating costs, reducing CO_2 emissions, and increasing jobs. Hybrid Structural Interaction Matrix was utilized to compute the weights of the three objectives for the multi-objective model to be modified into a single objective model. This will help in addressing Nigeria's rising power demand and mitigate GHG emissions. To ensure that factors responsible for the rising power demand and slow transition to renewables are properly managed to lay the basis for the sustainable power supply mix, the Hybrid Structural Interaction Matrix (HSIM) was utilized to prioritize the identified factors which guaranteed optimal resource allocation. The impact of renewable energy on power accessibility, affordability, and environmental sustainability was also investigated using system dynamics approach.

It was inferred that Nigeria would have the capability to generate 2,100 TWh of power by the year 2050. In addition, solar PV and hydropower large would account for the majority of Nigeria's long-term energy mix during the period that was forecast. In addition, by the year 2050, the power supply mix will include the generation of electricity from solar thermal plants, incinerators, nuclear power plants, gas plants, combined plants, and diesel engines. It was found that the construction and operation of power generation plants will contribute around 2.05 million jobs to the economy by the year 2050. These positions will be created over the next three decades. By the year 2050, CO_2 emissions will have attained 266 M_tCO_2. The cost of producing electricity is projected to go down from its peak of 36 billion US dollars in 2030 to 27.1 billion US$ in 2050. It was found feasible to satisfy Nigeria's ever-increasing demand for electricity by tapping into indigenous energy sources. It was also inferred that from the results, it is feasible for Nigeria's economy to keep up with the nation's growing demand for power despite the country's relatively high-power system costs. Although there are many advantages to a sustainable power supply system, an active and passionate governmental intervention would be necessary to propel the development of renewable energy technology in Nigeria. This is the case even though there are many benefits to such a system. To make renewable energy sources more competitive, it is necessary to remove the obstacles that are causing the slow transition to these sources. These obstacles include fossil fuel subsidies and grants, inadequate infrastructure, inadequate training of personnel, lack of public awareness, and so on.

The direct factors responsible for the slow transition to renewables were found to be the absence of subsidies and government grants, none or few renewable financing institutions, experienced professionals are scarce, barriers to public awareness and information, and ineffective government policies. In the case of rising power demand, the impact of urbanization, industrialization, agriculture, commercial/services growth rates, and pollution were identified to be directly responsible for the rising power demand. The outcome from the system dynamics approach on accessibility, affordability, and environmental sustainability of the electricity supply are thought to be enhanced if indeed the country's plan of using 36% renewables in the mix of power sources is to be met.

7.1.1 Research findings

The findings of this PhD research, in accordance with the research questions, comprise:

1. The research has identified that the current power sources mix in developing economies, including Nigeria, presents challenges in terms of cost, reliability, environmental impact, and accessibility to electricity. For example, the reliance on conventional sources of power, such as fossil fuels, may result in lower upfront costs but can be unreliable and have negative environmental impacts. In contrast, renewable energy sources, such as solar and wind, may have higher upfront costs but offer greater reliability and lower environmental impact in the long run. These findings contribute to the existing body of knowledge by providing specific insights into the advantages and disadvantages of the current power sources mix in the context of developing economies.

2. The research has identified key factors that drive electricity sustainability in developing economies, including Nigeria, such as resource availability, technological innovation, policy and regulatory frameworks, economic considerations, and social and cultural factors. These factors have been systematically identified and prioritized to inform policy interventions and actions towards sustainable power supply. For instance, understanding the importance of resource availability, such as renewable energy resources, can inform policymakers in promoting renewable energy development as a sustainable solution. This contributes to the literature by providing a comprehensive understanding of the multifaceted factors that influence electricity sustainability in developing economies.

3. The research has identified factors that influence the transition to renewable energy sources in developing economies, including Nigeria, such as technological maturity, policy and regulatory frameworks, investment and financing mechanisms, and social acceptance. These factors have been systematically analyzed and prioritized to facilitate the adoption and integration of renewables in the power mix of developing countries. This contributes to the existing knowledge by providing insights into the specific factors that hinder or enable the transition to renewable energy sources in the context of developing economies.

4. The research has developed an optimal predictive model that considers factors such as energy demand, resource availability, and environmental sustainability to determine a sustainable power supply mix for the Nigerian power system. This model has been used

to inform policy and planning decisions for a sustainable energy future in Nigeria and other developing economies. This contributes to the literature by providing a novel approach to developing predictive models for sustainable power supply mix optimization, considering specific factors relevant to developing economies.

5. The research has utilized a system dynamics approach to model and analyze the impact of renewable energy on power supply accessibility, affordability, and environmental sustainability in developing economies, including Nigeria. The insights gained from this analysis contribute to the literature by providing a nuanced understanding of the complex interactions and feedback loops between different variables and stakeholders in the energy system, and how policy interventions can influence the outcomes in terms of power supply accessibility, affordability, and environmental sustainability.

Some findings as affirmed by outputs from this research in conjunction with the literature include:

6. Sustainable Development Goal (SDG 7- affordable and clean energy) is sustainably achievable only in an energy mix scenario. Also, a sustainable energy policy in line with SDG 7, is achievable in a holistic and integrated thinking space where the modelling of energy systems drivers is deployed fusion-wise.

7. A few notable factors directly responsible for the slow transition to renewables include: the absence of subsidies and government grants, none or few renewable financing institutions, scarcity of experienced professionals, existence of barriers to public awareness, misinformation, and ineffective government policies amongst others.

8. The dynamical impact of renewables on accessibility, affordability and environmental sustainability from mixed energy sources is positive with a transient behavioral growth over time and an asymptotic-like outlook as the transient behavior decays over time.

9. The environmental sustainability factor was observed to perform poorly as the likelihood of climate change rises. Herein, CO_2 emission rises over the planned output which negates the GDP ratio since they are exactly proportional. As a result, the nation's economy will expand less rapidly. The level of poverty is likely to rise hence, lowering the standard of living. A lower standard of living can raise CO_2 emissions once more.

In summary, the research has generated findings that addressed the research questions outlined in the PhD thesis. These findings contribute to the existing knowledge by providing specific insights into the advantages and disadvantages of the current power sources mix, key factors driving electricity sustainability, factors influencing the transition to renewable energy sources, development of an optimal predictive model for sustainable power supply mix, and application of a system dynamics approach for analyzing the impact of renewable energy in developing economies.

7.1.2 Contribution to knowledge

The contribution to knowledge of this research include:

Generalized understanding of power system availability, affordability, and sustainability driving factors: The research identifies and analyzes a diverse range of qualitative and quantitative factors that influence the availability, affordability, and sustainability of power systems. By considering multiple constraints and objectives, and adopting a systems thinking approach, the study provides a comprehensive understanding of the complex dynamics that affect power system performance. This contributes to the knowledge by presenting a holistic view of the factors that impact power systems, which can be valuable for policymakers, practitioners, and researchers working in the field of energy systems.

Development of a robust prioritization and optimization model: The research presented a prioritization and optimization model for energy mix optimization, which can be applied to the specific case of the Nigerian power system. The model integrates various factors such as technical, economic, environmental, and social considerations, and provides a systematic approach to selecting the optimal mix of power sources. The robustness of the model is highlighted by its ability to handle multi-constraints and multi-objectives, which can be complex in real-world energy planning scenarios. This contributes to the knowledge by presenting a novel and practical approach to addressing the challenge of optimizing power source mix, especially in developing economies.

Customizability and adaptability of the model: This research has highlighted that the developed prioritization and optimization model can be customized and adapted to different energy mix problem scenarios beyond the Nigerian power system. This implies that the findings and methodology presented in the study can be applied to other developing economies or regions facing similar challenges in power system optimization. The customizability and adaptability of the model contribute to the knowledge by providing a flexible and transferable approach that can be applied in different contexts to support decision-making and planning related to power system development.

Practical implications for policy and practice: This research has practical implications for policymakers and practitioners involved in energy planning and policy-making. The findings and methodology can inform decision-making related to power system development, energy mix optimization, and sustainable energy planning. The research has provided insights into the factors that need to be considered for optimal power source mix selection, and the development of a robust prioritization and optimization model can aid in making informed decisions based on technical, economic, environmental, and social considerations. This has contributed to the knowledge by providing practical recommendations that can be applied in real-world scenarios to support sustainable power system development.

In conclusion, the research has made significant contributions to the knowledge by providing a generalized understanding of power system availability, affordability, and sustainability driving factors, developing a robust prioritization and optimization model, highlighting the customizability and adaptability of the model, and providing practical implications for policy and practice. The findings and methodology presented in the study can be valuable to researchers, policymakers, and practitioners working in the field of energy systems, particularly in the context of developing economies.

7.2 Recommendations

For further implementation of this research, especially for the interest of addressing Nigeria's poor power supply and GHG mitigation, developing several scenarios and comparing the results of those scenarios for the power generation mix should be of utmost priority including the need to investigate several additional competing objectives for the multi-objective optimization model. Finally, all the developed models of the multi-objective optimization, HSIM, and system dynamics can be validated and verified with the necessary parties from the Ministry of Power, Ministry of Science and Technology, Ministry of Agriculture, Ministry of Petroleum, Ministry of Environment, NNPC (Nigerian National Petroleum Company) Limited, ECN (Energy Commission of Nigeria), REA (Rural Electrification Agency), and other NGOs working within the energy sector. This will guarantee that the models appropriately represent the current energy policies in Nigeria. The above mentioned would definitely aid with the broadening of the current research with a view of energy sustainable in place within the Nigerian system.