Optimization-based modeling of Kenya’s energy system for pathways towards access to secure, affordable, and sustainable energy services

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Optimization-based modeling of Kenya's energy system for pathways towards access to secure, affordable, and sustainable energy services

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Abstract

Global climate change is one of the most significant challenges that need urgent action in this century. Energy production and consumption, particularly for heat and electricity generation, account for the highest GHG emissions from anthropogenic activities. The world energy demand is projected to increase as the population grows and efforts double to bridge the demand-supply gap in countries yet to achieve universal access to modern energy services. Currently, out of the 770 million people who lack access to electricity worldwide, 580 million live in Africa, predominantly in the Sub-Saharan Africa region. Using advanced energy planning tools to guide national energy objectives and decisions will be critical in addressing energy poverty while shifting to low-carbon fuels in Sub-Saharan Africa. Advanced energy planning tools have a detailed technological representation, account for greenhouse gas (GHG) emissions and cost, and assess low-carbon policies optimally. This work aims to develop a quantitative energy system planning model for Kenya to evaluate pathways towards access to secure, affordable, and sustainable energy services for the 2020 to 2050 period. This thesis is composed of three journal articles that describe the outcome of this work. The first article reviews the existing integrated energy modeling studies done for the Sub-Saharan Africa region at a country or regional level. The reviewed studies show that the models, based on different mathematical approaches and assumptions, inadequately addressed some fundamental energy themes, such as low-carbon policies and energy cost. It is recommended that the SSA countries develop national-scale energy planning models using advanced planning tools, which could be expanded into a regional model. The second article develops a national-scale energy model for Kenya using the advanced bottom-up energy optimization Integrated MARAKAL-EFOM (TIMES) framework. Using the developed Kenya-TIMES model, the study assesses the environmental and techno-economic assessment of power system expansion for three projected demand levels for Kenya for the 2020 to 2045 period. The results indicate that the government will not meet its nationally determined contribution (NDC) GHG reduction targets in the vision demand scenario without implementing low-carbon policies. The third article develops the Kenya-TIMES model further to assess the low-carbon development strategies for Sub-Saharan Africa, using the case of Kenya. This study evaluates the implication of the carbon tax, renewable energy subsidy, renewable portfolio standards, and a hybrid of renewable subsidy and carbon tax policy instruments on Kenya's power generation expansion for 2020 to 2050 under vision demand level. The GHG emissions are evaluated against Kenya's NDC emission reduction targets. The results indicate the evaluated low-carbon policy instruments could help achieve emission cuts below the government's NDC targets. Overall, this work sets a benchmark for developing a national-scale energy planning model using advanced energy planning tools and using it to guide the national energy objectives and decisions that Sub-Saharan Africa countries could adopt.

The undersigned hereby certify that they recommend to the School of Technology at Reykjavík University for the acceptance of this Dissertation entitled **Optimization-based modeling of Kenya's energy system for pathways towards access to secure, affordable, and sustainable energy services** submitted by **Xavier Shioya Musonye** in partial fulfillment of the requirements for the degree of **Doctor of Philosophy (Ph.D.) in Applied Sciences.**

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I dedicate this work to my children, Lucille, Milan, Rolan and Aurelle Isendi.

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Preface

This dissertation is an original and independent work by Xavier Shioya Musonye. It comprises three published articles. The main supervisor was Hlynur Stefánsson while Brynhildur Davíðsdóttir, Eyjólfur I. Ásgeirsson, and Ragnar Kristjánsson were members of the thesis committee. The author of this thesis was responsible for conceptualizing the research idea, data collection, treatment, model development and running, model result analysis and interpretation, manuscript drafting, and implementing corrections. Brynhildur Davíðsdottir, Ragnar Kristjansson, and Eyjolfur I. Asgeirsson reviewed the research idea and the draft manuscripts. Hlynur Stefansson reviewed the research idea, data analysis and interpretation, and the draft manuscripts.

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1. Introduction

1.1 Climate change, energy and energy planning

Global climate change poses one of the most significant challenges facing humanity this century. Global climate change results from anthropogenic and natural causes (1). Human activity, for example, the burning of fossil fuels, aerosol releases, and land alteration from agriculture and deforestation, are responsible for anthropogenic emissions (2). Since the advent of industrialization, the acceleration of these activities has fundamentally increased the concentration of greenhouse gases (GHG) in the Earth’s atmosphere (3). Some of the climate change effects predicted in the past by scientists, including loss of sea ice, accelerated rise in sea level, increased drought frequency, intense heat waves, and changes in precipitation patterns, are already occurring (4). These effects and net damage costs are likely to increase significantly over time (5).

The global community established the United Nations Framework Convention on Climate Change (UNFCCC) under the United Nations in 1994 to address climate change (6). The ultimate goal of the Convention is to stabilize the GHG concentration at a level that would prevent dangerous anthropogenic interference with the climate system. The aim is to achieve such a level within a period sufficient to allow ecosystems to adapt naturally to climate change, ensure that food production is secured, and enable economic development to proceed sustainably. In December 1997, the Kyoto Protocol was adopted but entered into operation in February 2005 (7). It operationalized the UNFCCC by committing the industrialized countries and economies in transition to limit and reduce GHG emissions by agreed individual targets. The Kyoto Protocol aimed to reduce GHG emissions by 5.2% below the 1990 levels over five years starting 2008 to 2012. In 2012, the parties agreed upon the second commitment period under the Kyoto protocol, CP2. It began operating in 2013 and contained revised commitments from parties. Later on, the Paris Agreement was established under UNFCCC in December 2015 and came into force in November 2016, replacing the Kyoto Protocol. This Agreement is a legally binding international treaty on climate change adopted by 196 countries at inception. Its goal is to limit global warming below 2 degrees and as close to 1.5 degrees as possible compared to pre-industrial levels (8). The GHG emissions should be reduced to reach global net-zero by the mid-21st century. Net-zero is a state of carbon neutrality in which carbon dioxide (and other GHG gases) emission is equal to its removal from the atmosphere.

Unlike the Kyoto Protocol, the Paris Agreement commits all nations, developed and developing, into a common cause to undertake ambitious efforts to combat climate change and adapt to its effects (8). Under the Kyoto Protocol, developing nations did not have mitigation commitments. Implementation of the Paris Agreement requires economic and social transformation and works on a five-year cycle of increasingly ambitious climate action by countries. Countries are required to submit their updated “nationally determined contributions” (NDCs) every five years to the UNFCCC secretariat. The NDC reports detail the GHG emission projections for the different economic sectors, reduction targets, policies, and planned measures for reducing national emissions and adapting to climate change (9). It also contains information on the need for financial aid, technologies, and capacity building for these actions. Each successive NDC represents a progression beyond the previous one and reflects the highest possible ambition. The first GHG reduction commitments, termed the intended nationally determined contributions (INDCs), were submitted in 2015 and became the first NDCs upon ratification by the parties after the Paris Agreement entered into force in 2016. Updated NDCs reports were later submitted in 2020, detailing parties' post-2020 climate action plans (8).

Energy production and consumption accounts for the highest percentage of the total anthropogenic GHG emissions. Energy-related activities, such as electricity generation from fossil fuels, oil and gas production, and heating and cooling of buildings account for 25% of the GHG emissions resulting from anthropogenic activities (10). Nevertheless, energy is central to addressing the sustainable development goals (SDGs) challenges, including poverty eradication, gender equality, climate change-related risks, food security, quality health services, quality education, and jobs (11), thus; the sustainable development goal (SDG) number seven of universal access to affordable, reliable, sustainable, and modern energy services by 2030 (12). Further, the world energy outlook 2021 report indicates that the global energy demand will grow significantly in the coming decades (13). It has been amply demonstrated over the last two decades by many advanced economies that the process of constructing the infrastructure needed in a modern and rapidly developing economy up until now has been very energy- and emission-intensive (13). Hence, a significant proportion of the projected growth in energy demand will be by emerging markets and developing economies. So far, no country has shown a cost-effective way to leapfrog to low-carbon technologies in all areas of energy use, including energy intensive sectors such as steel, cement, and freight, which are instrumental to the construction and operation of modern economies.

The global community has assessed different GHG emission cut scenarios and their implication on the global energy demand trends. The International Energy Agency (IEA) has assessed the net-zero, announced pledge (NDCs), and stated policy scenarios (13). The net-zero scenario represents a pathway for the global energy sector to achieve net-zero carbon emissions by 2050. The announced pledge scenario assumes that all climate commitments made by governments, including the NDCs will be met in full and on time. Stated policy scenario on the other hand reflects the current governments' policy settings. The stated policy scenario's annual total energy supply grows by 1.3% from 2020 to 2030, reaching 670 exajoules (EJ) by 2030. The announced pledges scenario trim the annual growth rate to 1.0%, reaching 650 EJ in 2030. On the contrary, energy demand in the net-zero scenario declines by an average 0.7% annually to 550 EJ by 2030.

Over the years, global energy stakeholders have taken various measures to address the growing energy demand and bridge the demand-supply deficit. For instance, over the last 50 years, energy stakeholders in developed economies have developed and improved energy planning modeling tools to address energy planning challenges (14). Energy planning is an intricate task where multiple parameters need to be evaluated over a complex interconnected system and a solution that represents the best combination of the parameters being assessed selected. Therefore, the developed computer-based tools have considerably simplified energy planning and, over time, have significantly improved energy access, efficiency, and effectiveness of energy decisions at the global, regional, and national scales. More recently, high-income economies have used these advanced tools to evaluate and align their energy policies towards sustainable energy development and achieve low-carbon power development pathways, in line with their submitted NDCs, at affordable costs. The policies are implemented using economic incentives and command and control policy instruments (15). These policies aim to increase the share of renewable energy sources in the global power mix (16), reduce energy demand for the end-use demand services (17), and improve the efficiency of power generation technologies (18). So far, these policies have motivated the global renewable electricity net capacity additions' growth from 125 GW in 2012 to 198 GW in 2019 (19). Cumulatively, the share of low-carbon energy sources in the global power generation mix grew from 27.5% in 2012 to 32.2% in 2019, while fossil fuel-based generation dropped from 71.5% to 66.5% in the same period. At the same time, end-use efficiency, particularly in the European Union (EU) region, has improved by an average of 1.2% per year between 2000 and 2019. In 2019, an estimated 270 million tons of oil equivalent (Mtoe), representing 25% of the final energy consumption, was saved in the EU due to end-use efficiency improvements (20). However, rebound effects present a barrier to the effectiveness of energy efficiency measures (21). The rebound effect is a phenomenon where an increase in the efficiency of end-use energy devices increases, rather than decreases, energy consumption. Improved efficiency makes an energy-consuming technology less expensive to use, and therefore, people tend to use it more often, thus consuming more energy. Studies indicate that there has been a rebound effect resulting from efficiency improvement in the different sectors of the economy in the EU (21) (22) (23).

The measures taken by the global community have resulted in a tremendous improvement in bridging the global demand-supply deficit, curbing energy-related GHG emissions while addressing the growing energy needs sustainably. Regardless, energy statistics indicate that 770 million people had no access to electricity in 2019 (24). At the same time, 2.6 billion people lacked access to clean and safe cooking fuels and technologies. A bulk of these people are in Africa and others in Asia's middle-income economies. Asia has recorded a substantial improvement in electricity access, achieving a 96% access rate in 2019 compared to the 67% in 2000 (24). Resultantly, out of the 770 million who lack access to electricity, 580 million are from Africa, predominantly the Sub-Saharan Africa (SSA) region. In 2018, an average of only 17% of the SSA's population had access to clean cooking fuels and technologies compared to the global average of 65% in the same year. About 900 million of the approximately 1.14 billion people of the SSA's population lacked access to clean cooking fuels and technologies in 2018 (25).

The SSA countries' energy demand is projected to increase significantly, resulting from the forecasted rapid population growth (26), economic development, and accelerated urbanization (27). Africa's population is projected to grow by half a billion between 2020 and 2040, with most of this growth happening in the SSA region (28). The profound demographic changes are set to drive economic growth, infrastructure development, and, in turn, energy demand. Bridging the current demand-supply deficit and meeting the forecasted demand sustainably and affordably will require deliberate and concerted efforts by the local governments and the international community in addressing the existing energy access challenges. Various researchers have assessed the challenges that derail achieving universal energy access in the SSA region. Bazilian et al. indicate the lack of integration of the poverty dimension into the mainstream analysis of energy governance by the global energy stakeholders (29). Musonye et al. stipulate the inadequate local capacity for energy planning and the inapplication of advanced energy modeling tools to guide energy investment decisions (30). Other researchers point to corruption and the tendency by decision-makers to ignore the existing generation expansion models (31), improper planning by the SSA governments (32), and the resulting high electricity prices, which hinders connection and consumption by consumers (33). Other challenges include the intrinsic structural and administrative weaknesses of power utilities caused by political patronage (34), inadequate investment in generation expansion outpaced by the growing demand, unreliable and inefficient data use in planning and decision making, and the aging transmission and distribution infrastructure (35). The SSA region needs to address these challenges, close the demand-supply gap, and meet the projected demand while limiting GHG emissions.

All the research mentioned above agrees in their findings that there is no one-fit-all solution to addressing energy poverty in SSA. Various researchers propose a raft of solutions, with most of them emphasizing efficient and effective energy planning based on reliable and transparent data (30) (32) (35) (36). Other proposed solutions include capacity building, increased budget allocation for expansion of energy access, and leveraging decentralized energy supply to tackle energy poverty in far-flung villages (30) (35). The researchers also suggest the modernization of the aging transmission and distribution grid infrastructure, operationalization of power trade within the regional power pools to cost-share the generation expansion costs, effective and efficient procurement laws to stem corruption and political patronage in energy utilities, and the integration of income levels in energy governance decisions at the global level (29) (30) (31) (34). With the various available energy sources and different power generation and distribution technologies, it becomes difficult to design and sustainably operate this complex system without proper planning.

Efficient and effective energy planning is a prerequisite to meet the demand-supply needs in a sustainable manner. Such planning ensures that energy-related policy and investment decisions consider all essential power supply and demand-side dynamics. Various studies emphasize this observation (30) (32) (35) (36) (37) (38) (39) (40). Resultantly, for the SSA region to achieve universal energy access while limiting GHG emissions, there is a need to adopt efficient and effective energy planning first, followed by addressing the non-planning-related challenges. Requisite to efficient and effective planning is using advanced energy planning tools to inform national energy decisions. National-scale energy planning models developed using advanced energy planning tools can test and assess the cost and benefits and optimize the different energy demand-supply expansion scenarios guided by a country's energy objectives. The objectives guiding these scenarios could include targeted supply-side and demand-side efficiency improvement, GHG emission reduction, differentiation of the central grid and decentralized generation targeted supply regions, and achieving targeted percentage share of a given energy resource in the energy mix. The feasibility of objectives, such as efficiency improvement, emission reduction, and targeted percentage share of given energy resources to reduce GHG emissions, can be assessed using policy instruments and implemented as energy policies.

Over the last decades, developed economies have researched and developed various energy planning tools to aid in efficient energy planning. Some of the tools developed include top-down simulation, bottom-up optimization, and hybrid energy modeling tools (41). The top-down simulation tools are broadly aggregated macro-economic tools, which focus on market processes rather than the technology details. The tools are descriptive and describe an energy system based on a set of rules that do not necessarily lead to a complete equilibrium (42). On the other hand, bottom-up optimization tools are technology-rich tools that focus on energy technologies and how they can be substituted based on the relative cost to provide the required energy services. The bottom-up optimization tools apply a methodology where several decision variables are used to minimize or maximize an objective function over a feasible range of variable values defined by constraints (42). The hybrid tools combine both simulation and optimization methodologies. The main difference between simulation and optimization tools is that simulation models intend to envisage the performance of a given energy system, given specific assumptions. In contrast, optimization models seek the optimal system design (43). Optimization typically aligns with quantitative-oriented risk assessment and sensitivity analysis, whereas simulation aligns better with more qualitatively oriented alternative assessment approaches.

By 2021, all the SSA countries had ratified the Paris Agreement and the SDGs (44). Therefore, as the SSA countries strive to meet their population's existing and growing energy demand needs, they must limit the GHG emissions to fulfill their submitted NDCs. The bottom-up optimization tools are the ideal energy planning tools to assess targets and action plans that will meet the two objectives while accounting for costs. The optimization model results can account for the sustainability of energy resources, energy security and supply reliability, GHG emissions, and energy costs associated with the different generation-expansion pathways. Optimization models make decisions based on a typically standardized set of restrictions, rules, and presumptions combined with a limited set of pre-defined gauges such as economic values (43). Conversely, simulation models leave the user to make all the crucial decisions based on various considerations, which cannot be rated based on one common denominator. The technology-rich nature of the bottom-up optimization tools provides detailed accounting for GHG emissions associated with the different power generation technologies (43). Further, the solutions of the different scenarios are typically the least costly pathway of reaching the defined goals, for example, meeting the projected power demand and, at the same cutting GHG emissions. Decision-makers and political leaders can make good use of expert studies based on well-established quantitative-based optimization models that end up with specific recommendations directed by their general policy. Models that seek economically optimal investment strategies under existing market conditions are generally acceptable by the political leaders and decision-makers (43). It is critical to note that optimization-based modeling tools have shortcomings, like other energy modeling tools. Some of the challenges include the assumption of perfect foresight, lack of openness and accessibility of the tools, and the limited level of engagement between tool developers and decision-makers (45), (46).

1.2 Kenya's energy system

Kenya is one of the SSA countries whose energy demand is projected to grow tremendously. Apart from the forecasted growth in demographics, the Vision 2030 economic blueprint set by the Kenyan government accounts for a significant percentage of the demand growth. In this blueprint, the government aims to transform Kenya into a newly industrializing, middle-income country, providing a high quality of life to its citizens by 2030 (47). One of the key pillars to achieving Vision 2030 is access to energy by all its citizens. Under Vision 2030, power capacity is projected to grow at an annual rate of 8.8%, from 1,917 MW in 2018 to 5,780 MW in 2030 (48). Currently, Kenya has a connectivity rate of 75% (49). The total installed grid-connected power capacity in October 2021 was 2,846 MW. Hydropower comprised 826 MW, geothermal had 865 MW, wind resource accounted for 336 MW, while solar power made up 50 MW. Thermal generation, mainly powered by heavy fuel oil, gasoil, and kerosene, had 769 MW capacity. The transmission and distribution utility's latest internal report indicates a peak demand of 1,945 MW in October 2021, 32% below the total installed capacity. Electricity generation expansion based on advanced demand-supply energy planning tools fed with reliable data could help reduce such cases of idle capacity.

So far, Kenya is faring well regarding the share of renewable sources used for electricity generation. More than 85% of the annual electricity consumption is from renewable sources (49), with geothermal generation accounting for the highest share. Kenya still has unexploited renewable energy resources' potential, including 1,500 MW of hydropower, 7,000 MW of geothermal, 70,000 MW of solar, and 4,200 MW of wind (48). Historically, hydropower has been the primary source of electricity in Kenya. Due to droughts, the government has, in the past, relied on emergency diesel generation to address power demand shortfalls. The reliance on diesel generation has resulted in the high power prices caused by the fuel charge component in the electricity bills. In the early 2000s, the government accelerated geothermal power development to address baseload power shortfalls occasioned by droughts and reduce overreliance on hydropower (48). The acceleration increased geothermal capacity from 245 MW in 2000 to 865 MW in 2022. At the same period, wind and grid-connected solar power grew from zero to 336 MW and 50 MW, respectively. Even though there is a significant solar and wind resources' potential, they are not harvested on a large scale yet. Still, they might play a role in Kenya's future energy system. Biofuels are only utilized to a minimal extent when assessing Kenya's power generation expansion pathways (48).

Despite the high share of renewable sources in its electricity generation, like many other SSA countries, Kenya remains behind in attaining SDG-7, i.e., ensuring access to affordable, reliable, sustainable, and modern energy services for all. As Kenya strives to meet this goal, it has to strike a balance between providing universal energy access to its citizens at an affordable cost and in a reliable way while limiting GHG emissions committed in its NDCs under the ratified Paris Agreement. Despite the abundance of renewable energy resources, the government's least-cost power development plan aims to meet the projected demand using both fossil fuel and renewable energy sources (48). For instance, despite the higher cost of generating a unit of electricity from coal than hydropower and geothermal in Kenya's context, the government's plan indicates new coal power plants coming online before 2025. The coal power development is proposed regardless of the unexhausted hydropower and geothermal resources potential. This move will likely increase GHG emissions significantly, jeopardize the GHG emission reduction efforts and hamper meeting the projected energy demand sustainably and affordably. The Kenyan energy decision-makers currently lack an appropriate application of modern and advanced energy planning tools (50). Various researchers have developed different energy planning models for Kenya (51) (52). However, the models developed by the researchers appraise distinct aspects of Kenya's energy system based on different assumptions using inconsistent energy planning tools.

1.3 Research focus and structure

This study seeks to develop a national-scale optimization-based energy model for Kenya's energy system to explore pathways towards access to secure, affordable, and sustainable energy services for Kenya in the 2020 to 2050 period. This study addresses the following main research questions:

i) What are the existing integrated energy modeling studies for Sub-Saharan African countries?

ii) How does Kenya's energy system's generation expansion evolve under an optimization-based energy planning tool?

iii) What are the implications of low-carbon policies on Kenya's energy system when assessed under an optimization-based model?

This thesis comprises three articles that summarize these research questions' evaluation and main findings.

The first article presents a scoping review of 30 integrated energy modeling studies done for the 46 SSA countries at the national or regional level. The review sought to address the following research questions: i) Which integrated energy systems' models have been developed to chart possible future integrated energy system pathways for SSA at regional or country-specific levels? ii) What are the model's features and structure? iii) What energy themes and policies do the models evaluate? iv) What areas of improvement in the reviewed studies have the potential to address the energy poverty challenge in SSA? v) What role does the SSA institutions play in the studies? This study's findings are presented in a peer-reviewed article titled; Integrated energy systems' modeling studies for sub-Saharan Africa: A scoping review, published in the Journal of Renewable and Sustainable Energy Reviews (30).

In the second article, the study used the Integrated MARKAL-EFOM System-VEDA (TIMES-VEDA) energy modeling framework to develop a new national-scale bottom-up, optimization-based energy system model for Kenya called the Kenya-TIMES. The developed model was used to evaluate the implication of GHG emission reduction on Kenya's power system's techno-economic and environmental evolution under three government-projected electricity demand levels covering the 2020–2045 period. The study solely focused on the power sector. The evaluation sought to answer the following research questions: i) Is energy security achievable for the three projected demand levels in the business as usual (BAU) - no new policy interventions - and the carbon emission cap (CEC) cases? ii) How will the installed power capacity and electricity generation's technology mix evolve for the three government forecasted demand levels under the BAU and CEC cases? iii) What is the GHG emission level in the three government projected energy demand levels compared to the Nationally Determined Contribution (NDC) GHG emission reduction targets? iv) What are the energy system and unit electricity costs for the three demand levels under the BAU and CEC scenarios? v) Does the Kenyan government require enacting emission reduction policies to curb GHG emissions under any of the three forecasted electricity demand levels? The study's findings are presented in a peer-reviewed article titled; Environmental and techno-economic assessment of power system expansion for projected demand levels in Kenya using TIMES modeling framework, published in the Energy for Sustainable Development Journal (50).

Finally, in the third article, the author developed the Kenya-TIMES model further and used it to evaluate low-carbon development strategies for power generation expansion in the SSA, using Kenya's case study for the 2020 to 2050 period. The third article evaluates low-carbon development strategies using three policy instruments separately, including a carbon tax, renewable portfolio standards (RPS), and renewable subsidy, and a strategy applying a hybrid of a carbon tax and renewable subsidy. The study sought to answer the following research questions: i) How do the low-carbon policy instruments affect the power capacity and electricity generation's technology mix? ii) What is the impact of evaluated policy instruments on the GHG emission reduction compared to the baseline emission and the NDC reduction targets? iii) What is the cost implication of the evaluated low-carbon policy instruments on the energy system's cost and unit electricity price? iv) What is the most feasible low-carbon policy instrument regarding Kenya's energy system? v) How does further development and refinement of the Kenya-TIMES improve the model results? The study's findings are presented in an article titled; Evaluation of low carbon development strategies for power generation expansion in Sub-Saharan Africa: The case of Kenya, currently under review in the Applied Energy Journal.

The three articles are:

Paper I

Integrated energy systems' modeling studies for sub-Saharan Africa: A scoping review.

Xavier S. Musonye a,b,c,*, Brynhildur Davíðsdottir[d], Ragnar Kristjansson[c], Eyjolfur I. Asgeirsson[c] , Hlynur Stefansson[c]

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Paper II

Environmental and techno-economic assessment of power system expansion for projected demand levels in Kenya using TIMES modeling framework.

Xavier S. Musonye a,b,c,*, Brynhildur Davíðsdottir[d], Ragnar Kristjansson[c] , Eyjolfur I. Asgeirsson[c] , Hlynur Stefansson[c]

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Paper III

Evaluation of low carbon development strategies for power generation expansion in Sub-Saharan Africa: the case of Kenya.

Xavier S. Musonye a,b,c,*, Brynhildur Davíðsdottir[d], Ragnar Kristjansson[c], Eyjolfur I. Asgeirsson[c] , Hlynur Stefansson[c]

This paper is currently under review for publication in the Applied Energy Journal.

For the three articles, the author of this thesis was responsible for conceptualizing the research idea, data collection, treatment, model development and running, model result analysis and interpretation, manuscript drafting, and implementing corrections. Brynhildur Davíðsdottir, Ragnar Kristjansson, and Eyjolfur I. Asgeirsson reviewed the research idea and the draft manuscripts. Hlynur Stefansson reviewed the research idea, data analysis and interpretation, and the draft manuscripts.

2. Paper 1

Integrated energy systems' modeling studies for Sub-Saharan Africa: A scoping review

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Abstract

Sub-Saharan Africa (SSA) experiences an energy poverty crisis, with more than 600 million of its 1.2 billion inhabitants living without access to modern energy services. Despite this, vast amounts of renewable energy resources are geographically distributed across the region. SSA needs to establish proper planning mechanisms to achieve universal access while mitigating Greenhouse Gas (GHG) emissions. This paper presents a scoping review of 30 integrated energy-modeling studies concerning SSA. The review indicates that addressing the region's energy access challenges will require decentralized generation and grid extension to be employed synergistically. Achieving high access levels while limiting GHG emissions will require energy decision makers to enact and implement climate, techno-economic, environmental, and efficiency policies. Additionally, technology learning and energy storage will improve the uptake of variable renewable resources. Operationalization of power trade will reduce the capital investment costs required to meet the current and future energy demand and tap into the potential of the abundant renewable energy resources in the SSA region. Energy planning using an integrated energy systems model will be vital in achieving these aims at the national and regional levels. Accordingly, it is necessary that national governments and energy decision makers in the region work in tandem with energy stakeholders, local academic institutions, and international energy modeling experts to build local capacities. This collaboration will then enable a synchronized framework for the development of short-to-medium-term national energy models, the results of which could then be integrated into a regional model

Keywords: Energy systems modeling; Sub-Saharan Africa; Energy planning; Universal energy access; GHG emission; Renewable energy

1. Introduction

The rapid growth in global energy consumption raises concerns about likely supply insufficiencies, the exhaustion of energy resources, and significant adverse environmental impacts [1]. Despite such concerns, the provision of secure, reliable, affordable, and environmentally benign energy services is required to address the world's challenges of sustainable development, including poor health services and quality of education, high poverty levels, climate-change associated risks, food insecurity, and gender disparities [2]. These challenges are mainly experienced in developing countries, where they are likely to escalate if the current annual increase in energy access remains unchecked. Some impediments to universal energy access among these countries include ineffective energy institutions, ineffective planning, inappropriate legal and regulatory frameworks, inadequate technical and financial mechanisms, politically driven energy decisions, and corruption [2]. Currently, about 1.1 billion people worldwide live without access to electricity [3], of whom more than 600 million live in Sub-Saharan Africa (SSA) [4]. This number comprises more than half the total population of SSA, of about 1.2 billion people.

Various countries rely on different energy sources to meet their energy consumption needs; such combinations are called an energy mix [5]. Despite the larger part of its population living without access to electricity, SSA contains a diverse and vast mix of energy resources capable of meeting the continents' present and future electricity needs. These resources include solar resource potential across almost all SSA countries; geothermal capacity in Eastern Africa; hydropower resources in Central, Western, and Eastern Africa; coal in Southern Africa; and oil and gas in Eastern, Southern, and Western Africa [6]. Wind power resource potential, a consequence of the SSA's long coastal shoreline and semi-arid conditions, is also distributed among various countries in the region.

Harnessing available energy resources to generate electricity requires considerable investment. Integrated energy markets have proven that they can substantially reduce those investment costs needed to meet a given population's energy needs and improve the quality of energy services provided by power utilities [7]. Examples of such markets include Ireland's Single Energy Market (SEM), the Energy Community of South-East Europe (ECSEE), the Nord pool, and the Pennsylvania-New Jersey-Maryland Interconnection (PJM) of the USA, among others. The diversity, vastness, and geographical distribution of energy resources in SSA provide an excellent opportunity for an integrated regional electricity market. Efforts to operationalize regional power pools within SSA have been implemented with varying levels of commitment and success. Currently, there are four power pools in SSA: the Southern African Power Pool (SAPP), Western African Power Pool (WAPP), the Central African Power Pool (CAPP), and the Eastern African Power Pools (EAPP). These power pools are in the early phase of power pool formation. SAPP and CAPP are the most and least advanced in the region, respectively [4]. Currently, only 7% of electricity is traded among the various nations of SSA, particularly in the SAPP [4].

An optimal combination of supply, transmission, storage, and demand-supply energy efficiency is vital for stimulating resource development and fueling economic growth [4]. For the optimal delivery of energy services in SSA, decision makers must invest in developing energy models for testing and assessing the cost and benefits of different energy resource expansion scenarios. Additionally, the models must be able to simulate how these expansion scenarios fit with existing and expected future transmission and demand-supply situations.

Previous efforts to meet the region's energy demands without using proper energy planning mechanisms have led to unintended consequences, as manifested in the seemingly unending list of energy supply challenges. For example, the Kenyan government has had to pay for the deemed generation costs resulting from the delayed completion of a transmission line for the evacuation of power from completed power generating units built by an Independent Power Producer [8]. Nigeria's total installed electricity generation capacity is 12,522 MW, primarily generated using fossil fuels [9]. However, only 7141 MW of this amount is operational due to the breakdown of the power plants due to poor maintenance and inadequate fuel supplies [9]. Nigeria's available electricity capacity is erratic, with an on-grid per capita consumption of 126 kWh [10]. In South Africa, the total installed capacity of 47,000 MW, 80% of which is coal-generated, cannot meet demand [11, 12]. This inability is attributed to the country's aging coal power plants and sub-standard maintenance work carried out on them. Eskom, a government-owned power utility that owns all of South Africa's coal power plants, is facing a state of insolvency after the South African government reduced subsidies for coal-generated electricity. As a result, increased tariff prices, local load shedding, and power outages have become common [12]. Lastly, the underutilization of power by newly connected customers in countries like Kenya and South Africa is proving to be a challenge for utilities [13]. Extending the grid and power supply to impoverished customers with a low consumption-ability has resulted in reduced per-customer revenue. Utilities are, therefore, forced to charge high prices for the consumed power to meet their generation and supply costs.

These examples demonstrate that the SSA suffers from significant energy underdevelopment, characterized by insufficient and unreliable energy supply, a lack of access to energy services among a large proportion of the population, the high cost of energy, and the financial difficulties experienced by utility providers, among other challenges. These problems can mainly be attributed to a lack of proper demand-supply forecasting and planning, among other issues. Besides, energy investment decisions are often political, and energy models are either not used, flawed, or non-transparent. It can also be established that the current energy planning models in use are inefficient in convincing stakeholders, resulting in systemic inefficiencies experienced among SSA energy systems. Countries in SSA need to develop and adopt a host of data-driven integrated modeling tools for systems-level planning and operation on an unprecedented scale [4]. SSA's national governments must collaborate with academic institutions and private-sector stakeholders to produce necessary qualitative and quantitative data. These data will then provide model developers with the right inputs for developing energy models [4]. These models must be transparent and take into account the technological, geographical, economic, cultural, and social dimensions of the concerned country or the overall SSA region [4].

This paper provides a scoping review of the previous modeling studies on integrated energy systems for the SSA region. This review focuses on the energy system's power sector. By "integrated energy systems modeling," this review mainly focuses on models that assess integrated power expansion pathways as defined by Trotter et al. [14]. Trotter et al. define integrated energy system planning as an integrated approach of analyzing economically, technologically, environmentally, and socially appropriate generation technologies required to meet the demand of a given energy system, using different available primary energy supply options. Therefore, the reviewed modeling studies are those that assess (economically, technically, environmentally, and socially) the various generation expansion pathways that can be used to harness the available energy resources to meet demand, either through central grid expansion, a combination of grid and off-grid supply, or power trade by extending the grid across country borders. Accordingly, this paper reviews relevant studies to highlight the institutions involved in carrying out the reviewed studies, the structure of models and modeling tools involved, map out key energy integration themes and policies modeled in previous works and identify areas for improvement among those modeling studies that have been done for SSA. This review illustrates that no published research has explicitly reviewed existing integrated energy systems modeling studies that have been conducted on SSA. The main objective is to compile a scoping review of energy modeling studies that concern SSA, which researchers and energy stakeholders can use as a reference. The two goals that concern this review are as follows: to help energy stakeholders in selecting appropriate models to investigate specific SSA's energy-related issues or questions, and to identify gaps within the modeling field that must be closed if energy challenges stifling the achievement of universal energy access in SSA are to be addressed. The remaining part of the paper is divided into three sections: Section 2 discusses the energy resource potential of the SSA region, and Section 3 presents the methodology of this scoping review. Under Section 4, the results of this review are presented. Discussions and conclusions are presented in Sections 5 and 6, respectively.

2. Energy resource potential for Sub-Saharan Africa

The SSA energy resource potential data presented in this section were obtained from research and international agencies' reports concerned with energy. Renewable energy resource potential data were obtained from various research works [4,15–20] and the World Energy Council [21]. The total installed capacity of technically feasible renewable energy resources potential was obtained from the International Renewable Agency report [22]. On the other hand, the fossil fuel resources' potential was derived from the World Energy Council [21], the International Energy Agency [23], US Energy Information Administration [24], and the Organization of Petroleum Producers (OPEC) [25], as well as other research work [26].

Vast amounts of fossil fuels and renewable energy resources are found in SSA. These resources are fairly distributed across the southern, western, central, and eastern parts [4,15]. It is estimated that the technical energy resource potential of SSA is 11 TW [16]. The geographical distribution of resources in SSA provides an excellent opportunity for the region's governments to capitalize on coordinated energy resource development and regional power trade, which are vital in reducing the cost of addressing energy-access gaps in SSA [6]. This section explores the energy resources potential in SSA.

2.1 Renewable Energy Resource Potential

SSA has a high technical renewable energy resource potential, as shown in Fig. 1. These resources can be harnessed to chart a low-carbon development pathway for the region. SSA has abundant solar energy resources, with an estimated technical potential of 525 GW for solar PV and 475 GW for concentrated solar power [16]. This solar energy resource is distributed across all countries in the region. The technical wind resource potential of SSA, which is also distributed among the SSA countries, is estimated at 109 GW [16][20]. Technical geothermal energy potential in SSA is mainly confined to East African countries, which the East African Rift Valley transects, estimated at 20 GW. 10 GW are located in the Kenyan Rift Valley [18]. The Ethiopian Rift Valley is host to an estimated potential of 7 GW. At the same time, the Tanzanian and Uganda Rift Valleys have an estimated potential of over 650 MW and 450 MW, respectively [18][19]. The remaining geothermal potential of SSA is distributed among Djibouti, Eritrea, Rwanda, Comoros, Zambia, and Burundi [18].

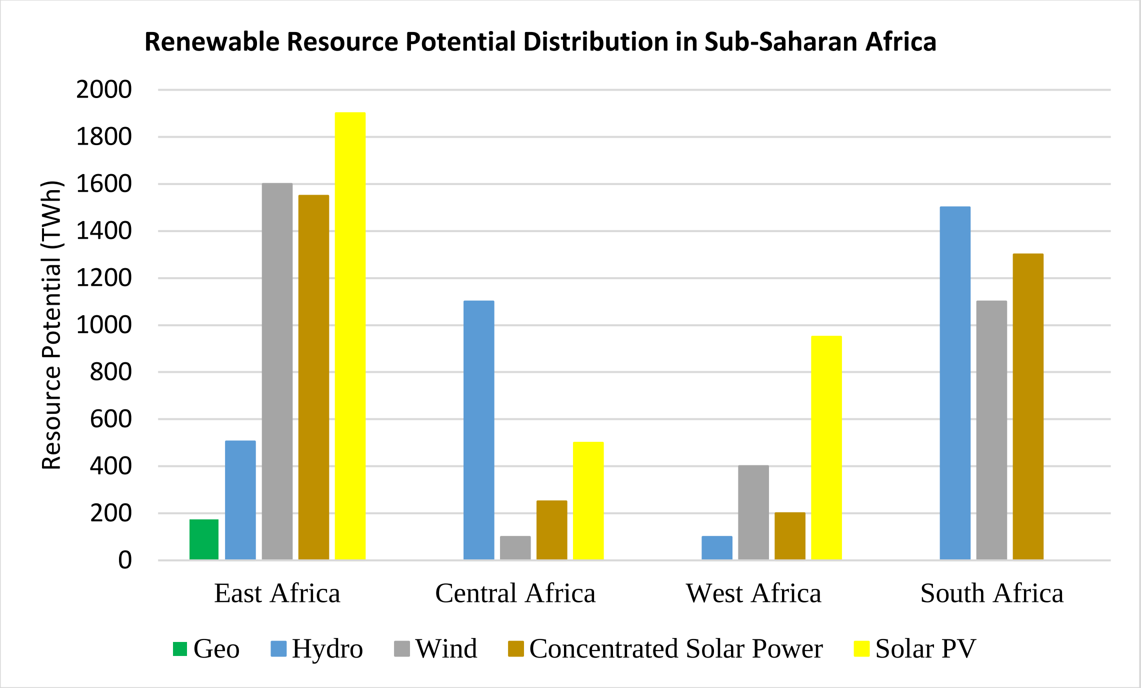

Fig. 1. The distribution of technical renewable energy resource potential in SSA. (Data from [15][16][17][18][19][20]; analysis by the author).

The technically feasible hydropower potential of SSA is estimated at 350 GW and is mainly located in Ethiopia, the Democratic Republic of Congo, Angola, Cameroon, and Gabon [16]. This energy potential is attributable to the River Nile and the Congo River, which are found in the eastern and central parts of the region, respectively. Fig 1. shows the distribution of the technical potential of renewable energy resources in SSA in terawatt hours. As of April 2019, the total installed capacity of all technically feasible renewable energy resources potential was 9% for hydro, 4% for geothermal, 4% for wind, and 0.5% for solar energy [22]. Notably, installed capacity for solar energy might be higher than the percentage mentioned above since the capacity of most installed solar stand-alone systems is undocumented.

2.2 Fossil fuels energy resource potential

Fossil fuel energy resources in the SSA consist of coal, natural gas, and oil. Major coal reserves are found in South Africa, Botswana, and Mozambique [21,22], with an estimated technical energy potential of 300 GW [16]. The technical energy potential of SSA's natural gas reserves is about 400 GW, with significant contributions coming from Mozambique, Tanzania, Nigeria, South Africa, and Mauritania, in descending order [21,23,24]. Currently, SSA's installed power generation from gas and coal is less than 2% and 17% of the region's total technical gas and coal reserve potential, respectively. Among the world's major oil producers in the region are Nigeria, Angola, and the Republic of the Congo [21]. In 2016, Nigeria was ranked as the 13th largest oil-producing country globally, with a daily production of 2.35 million barrels. In the same year, Angola's daily oil production was 1.82 million barrels, while the Republic of the Congo was 277,000 barrels [25]. The region also has a non-quantified biomass resource potential. Fig. 2 depicts the percentage of potential technical energy resources for electricity generation in SSA; oil has been excluded from the figure, as it comprises an insignificant percentage of SSA's electricity generation. Furthermore, there is a high level of disparity in the region's total estimated technical oil reserves. For example, while BP estimates these reserves at 128 billion barrels, the International Energy Agency estimates them at 200 billion barrels. The Energy Information Administration of the USA estimates these reserves at 62.6 billion barrels [24,26]. This disparity makes it difficult to determine an exact figure for this analysis.

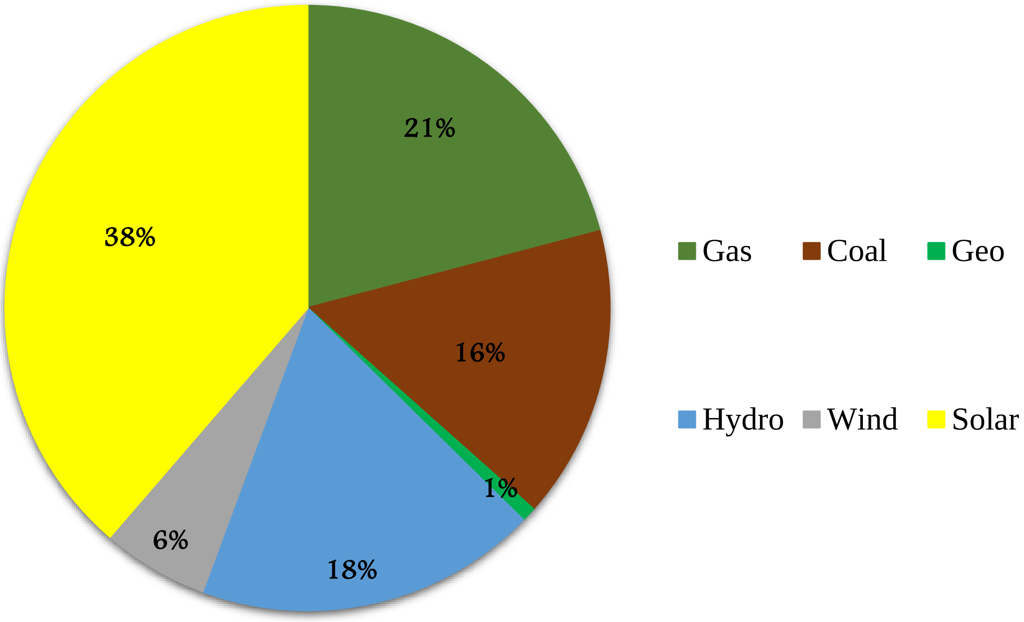

Fig.2. Distribution of potential technical energy resources in Sub-Saharan Africa.

3. Scoping review

This review uses the scoping review method. The primary purpose of scoping reviews is to map critical concepts in literature, examine the extent and range of research, identify research gaps in the knowledge base, and set a research agenda within a particular field [27]. This scoping review was undertaken by defining research questions, identifying the relevant studies, selecting studies, charting the data, and collating, summarizing, and reporting results.

3.1 Definition of the research question

Several specific research questions apply to this scoping review: Which integrated energy systems' models have been developed to chart possible future integrated energy pathways for SSA at regional or country-specific levels? What are the models' features and structures? Which policies do the models evaluate? Moreover, what are areas for improvement among existing modeling works that have the best potential to help address prevailing energy poverty in SSA?

3.2 Identification of the relevant studies

To comprehensively identify published peer-reviewed and non-peer-reviewed studies, the search was undertaken using electronic databases, reference lists, and hand-searching of critical journals. The following search engines were used: Google Scholar, Web of Science, Wikipedia, and Science Direct. The search word used for the initial search was "energy modeling for Sub-

Saharan Africa." Accordingly, the term "Sub-Saharan Africa" was replaced by each of the 46 countries found within the SSA region. This search produced 20,875 papers across three search engines, with some papers appearing across all four search engines. Most of these papers were irrelevant to the review since their studies did not concern integrated energy systems expansion for SSA or the region's various countries. The search was then further refined. The main search words were changed to "integrated energy systems modeling for Sub-Saharan Africa," with "Sub-Saharan Africa" being substituted by the names of the regions' 46 countries accordingly. This search reduced the number of papers found to 17,902. However, most of these papers were irrelevant to our review since any paper with the words "integration" and "energy" had been included in the search findings. A deliberate effort was then made to assess each title and select those papers that met the research eligibility criteria for this review. The primary criteria for this search were based on research on integrated energy systems modeling, either for the SSA region, a part of SSA, or a single country within SSA; and, published in English between 2005 and 2019. The implementation of power reforms that swept the globe beginning in the early 1990s only started in a piecemeal fashion in SSA in 2005 [28–31]. For this reason, studies included in this review were limited to those completed after 2005. This search retrieved a total of 187 papers.

3.3 Selection of relevant studies

Relevant studies were selected interactively and iteratively. The reviewers read the abstracts and introduction sections of the selected articles. At this stage, the aim was to separate those qualitative from quantitative research studies upon which this review is based. The selection of papers was strictly limited to those studies that had developed or used existing energy modeling tools to study the possible power expansion pathways by harnessing various integrated energy resources for SSA, either at a regional, sub-regional, or national scale. Consequently, those modeling studies focusing on implementing a single technology into a broader system context, and those studies limited to demand growth forecast, were exempt from this review. The snowball sampling technique was also employed to further the search for target modeling studies. Under this technique, references provided by the citations of the selected publications were pursued accordingly. Abstracts of the identified papers were read and used to refine the selected pool of papers more. After which, a complete reading of all papers in the final selected pool was undertaken. This process resulted in a database of 30 modeling studies on the "integrated energy systems modeling for Sub-Saharan Africa," drawn from academic journals, project-based research reports, and organizational reports.

3.4 Charting the data

Data extracted from each of the reviewed modeling studies included the names of the paper's authors; the year of publication; the country, sub-region, or region (SSA) modeled; the institution that carried out the modeling work; the modeling tool used and the acronym of the tool. Based on the Van Beek [32] mode of model classification, the reviewed models were classified according to methodology (simulation and/or optimization); analytical approaches (top-down, bottom-up, or hybrid); the level of the model (national or regional); their time horizon, that is, short-term (maximum of 10 years), medium-term (10–20 years) or long-term (above 20 years), and the themes and policies they tested.

3.5 Collating, summarizing, and reporting of results

A three-step qualitative synthesis was used to report the results. The first phase assessed the overview of the modeling tools, the institutions involved in developing the model, and those countries for which the energy systems were modeled. The structures and features of the various models were categorized in the second phase, and a summary of the application areas and policies covered by the reviewed models was provided in the third phase. The limitations to this literature review relate to (i) access to SSA governments' national power expansion planning models; (ii) the presentation of modeling results of the reviewed tools. Access to countries' national power expansion planning remains a challenge. Additionally, some of the national expansion planning tools reviewed are in-house commercial tools. Therefore, this review intentionally avoids judging the reliability, accuracy, and performance of the reviewed tools. The review instead identifies the lacking modeling themes in all the reviewed models and recommends the addition of these themes for improvement of the future models. Limited presentation of result comparison between different models relates to the limited availability of comparable quantitative data in the reviewed models. The models are run on different assumptions under different economic, environmental, and social setups as defined by the area covered in the model.

4. Results

This section is divided into three sub-sections: the first sub-section provides an overview of the modeling tools; the second sub-section reports on the structure and features of the reviewed models, and the third sub-section reviews the models' main policy application areas.

4.1 Overview of the modeling tools

The overview highlights the contributions (or lack thereof) made by institutions from the SSA region, Europe, Asia, and the United States to develop the SSA region's energy models. A summary of the modeling tools, institutions involved in developing the models, and the respective references of each paper are presented in Table 1.

Table 1. Overview of modeling tools used in reviewed modeling studies.

Tool Acronym	Model Name	Institution	Reference
GEMIS 4.3 & SimaPro 6	Global Emission Model for Integrated Systems & SimaPro	The University of Manchester, Manchester M13 9PL, UK; University of Surrey, Guildford GU2 7XH, UK	[33][34]
MESSAGE	Model for Energy Supply Strategy Alternatives and their General Environmental Impacts	Energy Commission of Nigeria, Nigeria	[35]
LEAP	Long-range Energy Alternative and Planning	Energy Commission of Ghana	[36]

PLOXES	PLEXOS	Department of Energy, South Africa	[37]
LIPS-OP & LIPS-XP	LIPS-OP & LIPS-XP	Energy and Petroleum Regulatory Authority, Kenya	[38]
OnSSET & OSeMOSYS	OpeN Source Spatial Electrification Toolkit; Open Source Energy Modeling SYStem	KTH Royal Institute of Technology, Sweden	[39]
GAM (GIS)	Geospatial Analysis and Mapping	KTH Royal Institute of Technology, Sweden	[40]
TIAM-ECN	TIMES Integrated Assessment Model - Energy Research Center	Energy Research Center, Netherlands	[41]
TIMER	Targets IMage Energy Regional	PBL Netherlands Environmental Assessment Agency, Netherlands	[42]
LUT-MOSEK	LUT-MOSEK	Lappeenranta University of Technology, Finland	[43]
LEAP-WEAP	Long-range Energy Alternative and Planning - Water Evaluation and Planning system	Europa-Universität Flensburg, Germany	[44]
SPLAT	System Planning Test	IRENA & KTH, Sweden	[45]
SECM	Spatial Electricity Cost Model	European Commission Joint Research Centre, Italy & United Nations Environment Programme, France	[46]
LEAP	Long-range Energy Alternative and Planning	Kadir Has University, Turkey	[47]
DLPM	Dynamic Linear Programming Model (in GAMS)	University of Bonn, Germany	[48]
PowerPlan	PowerPlan	Groupe de Recherche en Economic Therique et Applique, France; University of Gronigen, Netherlands	[49]
LEAP-OSeMOSYS	Long-range Energy Alternative and Planning - OSeMOSYS	Brunel University London, UK; University of Education, Ghana	[50][51]
TEMBA-OSeMOSYS	The Electricity Model Base for Africa-OSeMOSYS	KTH Royal Institute of Technology, Sweden; United Nations Economic Commission for Africa, Ethiopia	[52]

SATIM & SAGE	South Africa-TIMES & SAGE	United Nations University, Finland; National Treasury, South Africa; University of Cape Town, South Africa & International Food Policy Research Institute, USA	[53]
LEAP	Long-range Energy Alternative and Planning	Universiti Teknologi Malaysia, Malaysia; Nasarawa State University Keffi, Nigeria	[10]
PLEXOS	PLEXOS	Council for Scientific and Industrial Research, South Africa	[54]
MARKAL	MARKet and ALlocation	University of Cape Town, South Africa	[55]
MESSAGE & MAED	Model for Energy Supply Strategy Alternatives and their General Environmental Impacts; Model for Analysis of Energy Demand.	Nelson Mandela African Institute of Science & Technology, Arusha; the University of Dar es laam in Tanzania	[56]
LEAP	Long-range Energy Alternative and Planning	Unite Nations Economic Commission for Africa, Ethiopia	[57]
SWITCH-Kenya	Solar and Wind energy Integrated with Transmission and Conventional sources-Kenya	University of California Berkley, USA	[58]
LEAP-Kenya	Long-range Energy Alternative and Planning	Jomo Kenyatta University of Agriculture and Technology	[59]
LGE & GIS	Linear Generated Equation (in GAMS) & GIS	School of International and Public Affairs, USA; Columbia University, USA	[60]
MESSAGE	Model for Energy Supply Strategy Alternatives and their General Environmental Impacts	Prince of Songkla University, Thailand	[61]

Of the 30 modeling studies reviewed solely, SSA institutions had undertaken only eight. Non-academic institutions had completed two of these studies: the United Nations-Economic Commission for Africa in Ethiopia and the Council for Scientific and Industrial Research in South Africa. Three of the studies represent national power development plans and are done by governments' energy planning departments using local capacity, that is, for Ghana, Nigeria, and South Africa. Either the Jomo Kenyatta University of Science and Technology in Kenya, the University of Cape Town in South Africa, or collaboration between the University of Dar es Salaam and the Nelson Mandela African Institute of Science and Technology in Tanzania undertook the remaining three studies. Six of the remaining 22 studies were undertaken as collaborations between institutions in SSA and other regions. Out of these six studies, one is Kenya's national energy planning study done by a consulting firm from Germany, in collaboration with local capacity from the Ministry of Energy-Kenya, two were carried out through collaboration between institutions in Ghana and the United Kingdom, while the remaining three studies were carried out as collaborations between institutions from Nigeria and Malaysia, the USA and South Africa, and Sweden and Ethiopia. As shown in Fig. 3, European institutions have played a significant role in carrying out energy modeling studies for the SSA region. Of the remaining sixteen modeling studies, 13 were carried out by European institutions, two in the USA and one in Asia. Fig. 3 presents a percentage comparison of the contributions made by institutions from Europe, Asia, the USA, and SSA, and collaborations between institutions from SSA and other regions of the world, to the development of energy models for the SSA region.

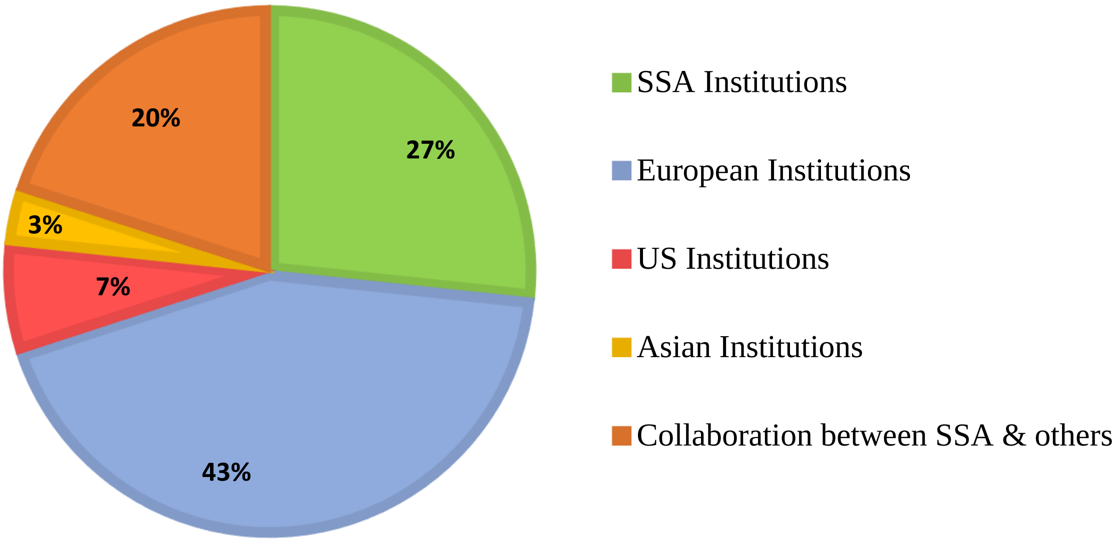

Fig. 3. Contributions made to the development of energy models for SSA by institutions from different world regions

4.2 Statistics of model structures and features

This sub-section summarizes the classification of reviewed models based on their structures and features (see Table 2). This classification criterion was based on that of Van Beek [32]. Models were classified according to geographical coverage, analytical approach, underlying methodology, and time horizon (see Table 2).

Geographical coverage is an essential factor in determining the model's scope. It reflects the level at which analysis occurs and is categorized as either global, regional, or national [31]. Overall, 22 of the 30 models were modeled at a national level, covering the following countries: Nigeria (6 models), South Africa (4), Kenya (4), and Ghana (3), Gambia (1), Tanzania (1), Ethiopia (1), Senegal (1), Rwanda (1), and Burkina Faso (1). It is important to note that the modeling study done by PowerPlan was done for both South Africa and Senegal (see Table 2). The remaining eight models were developed at a regional level. Three of these models covered the entire African continent. One model covers an interlinked power system among the EAPP countries, while the other interlinks the EAPP and SAPP power pools. The remaining 3 cover the entire SSA region, as presented in Table 2. The economic, social, and environmental processes associated with energy planning vary at different times, and time horizons frequently determine the structure and objectives of individual energy models. There is no standard definition of short-, medium-, or long-term horizons (32). However, in this review, short-term time scales are considered as having a maximum of 10 years, medium-term time scales 10-20 years, and long-term time scales more than 20 years. As summarized in Table 2, 15 of the 30 models use a long-term time scale, 12 use a medium-term time scale, and three use a short-term time scale.

The reviewed models applied three analytical approaches, top-down, bottom-up, and hybrid (see Table 2). The top-down models are broadly aggregated macro-economic models, while bottom-up models are generally technology-rich [62]. Hybrid models combine top-down and bottom-up approaches through hard or soft linking [63]. Twenty-four of the reviewed models apply a bottom-up approach, for example, MARKAL and Switch; 1 model apply a top-down approach, for instance, TIMER; and five models apply a hybrid approach, for example, SATIM and SAGE (see Table 2). The reviewed modeling studies use two modeling methodologies: optimization (e.g., MARKAL) and simulation (e.g., LEAP) (see Table 2). Optimization models endogenously optimize energy investment decisions and encompass a modeling approach whereby several decision variables are computed to minimize or maximize an objective function, subject to given constraints [64]. Conversely, simulation models are descriptive models based on logical representations of a system and evaluate a large number of alternatives under different realistic scenarios, as defined by a set of conditions. Out of the 30 reviewed models, 7 were optimization models, 17 were simulation models, while 6 applied both simulation and optimization methods (see Table 2).

Table 2. Summary of model structures applied among in reviewed modeling studies.

Modeling tool	**Region/Country Coverage**	**Analytical Approach**			**Methodology**		**Coverage**		**Time Horizon**		
		Bottom-Up	**Top-Down**	**Hybrid**	**Optimization**	**Simulation**	**National**	**Regional**	**Short**	**Medium**	**Long**
GEMIS 4.3 & SimaPro 6 (2 studies)	Nigeria	√				√	√			√	
LEAP 2013	Nigeria	√				√	√			√	
LEAP 2018	Nigeria			√		√	√				√
LUT-MOSEK	Nigeria	√			√		√				√
MESSAGE	Nigeria	√			√		√				√
TIAM-ECN	African Continent	√			√	√		√			√
TIMER	SSA Region		√			√		√		√	
LEAP–WEAP	Rwanda			√		√	√				√
PLEXOS	EAPP	√				√		√	√		
MESSAGE & MAED	Tanzania	√			√	√	√				√
LEAP	SSA Region	√				√		√			√
LEAP-OSeMOSYS (2 studies)	Ghana			√	√	√	√				√
LEAP	Ghana	√				√	√			√	
GAM (GIS)	Burkina Faso	√			√		√		√		
OnSSET & OSeMOSYS	Kenya			√	√	√	√			√	
LIPS-OP & LIPS-XP	Kenya	√				√	√				√
SWITCH-Kenya	Kenya	√			√		√			√	
LEAP-Kenya	Kenya	√				√	√			√	
SATIM & SAGE	South Africa			√	√	√	√				√
MARKAL	South Africa	√			√		√				√
PLEXOS	South Africa	√			√		√				√
SPLAT	EAPP & SAPP	√				√		√		√	
SECM	SSA Region	√				√		√	√		
TEMBA-OSeMOSYS	African Continent	√			√			√			√
MESSAGE	The Gambia	√				√	√			√	
PowerPlan	South Africa & Senegal	√				√	√			√	
LGE & GIS	African Continent	√			√	√		√		√	
DLPM	Ethiopia	√			√		√				√

4.3 Application areas of the models

The reviewed modeling studies address various themes and policy scenarios, including power trade, energy storage, renewable portfolio standards (RPS), energy efficiency measures, the environmental policy with a focus on carbon emissions, climate change with a focus on its effect on hydropower generation, universal access, transmission expansion, and decentralized generation options. Each reviewed model addresses a different number of these application areas (see Table 3). The classification of models in this sub-section, divided according to different application areas, is based on the main objectives of the study of the model concerned. To avoid redundancy, the models' application areas are divided into four main themes: climate policy, decentralized generation, and power trade and transmission, and universal access.

4.3.1 Climate policy

Some of the models discussed in this sub-section simulate climate change policy scenarios. One example is the implementation of the United Nations Framework Convention on Climate Change (UNFCCC) for capping atmospheric temperature at 2°C above pre-industrial times guidelines and the impact of climate change on SSA's future energy resource mix. Other models simulate the impact of environmental policy interventions on the penetration level of renewable and fossil fuel energy technologies in the energy mix of concerned study areas, and therefore, the GHG emissions levels impacted by these policies. Additionally, some of the environmental policy intervention models test the impact of efficiency intervention measures on power generation and carbon emission costs.

On a regional level, van der Zwaan et al. [41] use the TIAM-ECN model to investigate the effects of the UNFCCC climate guidelines on SSA's future renewable energy resource absorption. This bottom-up model applies optimization and simulation throughout the 2010-2030 period. Three scenarios are used: a reference scenario, in which Business As Usual (BAU) development is extrapolated; a policy scenario, which uses the United Nations Framework Convention on Climate target of capping atmospheric temperatures at 2°C; and a climate policy scenario, whereby there is an increase in the global CO_2 price by 4% per year, and global GHG emissions are reduced by 20% concerning 2010 levels. Ouedraogo [57] uses LEAP, which runs from 2015-2040, to simulate the various technology pathways that can be used to meet different demand scenarios for the SSA region. Using a bottom-up simulation approach, LEAP projects the impact of renewable energy and demand-supply efficiency measures on carbon emission investment and investment costs.

At the national level, Uhorakaye [44] applies a hybrid approach, using both LEAP and WEAP to assess an alternative power supply scenario for Rwanda that would be resilient to the impact of climate change between 2012-2050. Kichonge [56] links MESSAGE and MAED in a bottom-up simulation and optimization approach, intending to explore various energy supply options to meet Tanzania's electricity demand projections between 2010-2040. Based on different energy consumption levels, the two studies investigate the contribution of renewable energy sources in the power mix and the behavior of the power system at varying levels of dry climatic conditions.

Table 3. A summary of the policy application areas of the models as applied in the reviewed modeling studies

Modeling Tool	**Region/Country Covered**	**Application areas for the modeling tools**							
		Trade	**Transmission**	**RPS**	**Climate policy**	**Decentralized Generation**	**Storage**	**Efficiency**	**Universal Access**
GEMIS 4.3 and SimaPro 6 (2 studies)	Nigeria			√	√				
LEAP 2013	Nigeria				√				
LEAP 2018	Nigeria			√	√			√	
LUT & MOSEK	Nigeria			√	√				
MESSAGE	Nigeria		√	√					√
TIAM-ECN	African Continent			√	√				
TIMER	SSA Sub-regions		√		√	√			√
LEAP-WEAP	Rwanda				√				
PLEXOS	EAPP	√	√						
MESSAGE & MAED	Tanzania			√	√				√
LEAP	SSA Sub-regions			√				√	
LEAP-OSeMOSYS (2 studies)	Ghana			√	√			√	
LEAP	Ghana			√		√		√	√
GAM (GIS)	Burkina Faso		√			√			√
OnSSET & OSeMOSYS	Kenya		√	√		√			√
SWITCH-Kenya	Kenya		√	√	√		√		
LEAP-Kenya	Kenya			√	√				
LIPS-OP & LIPS-XP	Kenya		√					√	√
SATIM & SAGE	South Africa	√			√				
MARKAL	South Africa	√			√			√	
PLEXOS	South Africa		√	√	√	√		√	√
SPLAT	EAPP & SAPP	√		√	√				
SECM	SSA Region		√			√			
TEMBA-OSeMOSYS	African Continent	√	√						

MESSAGE	The Gambia	√			√	
PowerPlan	South Africa & Senegal			√	√	
LGE & GIS	African Continent	√	√		√	√
GAMS	Ethiopia			√	√	

Guta and Börner [48] use a Dynamic Linear Programming model based on GAMS to explore the least-cost investment options for Ethiopia's diversified, integrated energy sources between 2015-2110. Their study evaluates the role of public policy in promoting renewable energy investment, the implications of the impact of uncertainties relating to climate change on hydropower resource generation, and changes in land prices on future energy security.

Gujba et al. [33] use GEMIS 4.3 and SimaPro 6 to explore the environmental impact and cost regarding the Nigerian governments' defined future power sector pathways through a bottom-up simulation approach. The model evaluates carbon emissions resulting from the government's energy development plans. Gujba et al. [34] use the same model to simulate the alternative pathways and compare these outcomes with the government's plan [33]. In both cases, the two models, covering the 2010 to 2030 period, investigate government plans' economic, technological, and environmental impact against alternative pathways. Aliyu et al. [10] use a bottom-up simulation approach in LEAP to analyze Nigeria's electricity generation in 2010 and simulate a 20-year expansion plan for the country. The study evaluates the electricity generation fuels to satisfy Nigeria's electricity demand in 20 years and associated carbon emissions under projected demand scenarios. Oyewo et al. [43] use bottom-up optimization models LUT and MOSEK to explore a paradigm shift in Nigeria's energy system in becoming a fully sustainable energy system by 2050. A cost-optimal transition to a 100% renewable-based power system for Nigeria is simulated from 2015-2050 using two scenario policies. The first scenario is that no installation of fuel fossil power plants after 2015 is to be done, with only the gas turbine plants being allowed since these entail low carbon emissions and are highly efficient. The second scenario is that renewable energy capacity growth cannot exceed 4% per year. Ibrahim and Kirkil [47] use the top-down and bottom-up approaches in LEAP to project electricity demand and supply for Nigeria for the target years 2010-2040. LEAP generates BAU, Energy Conservation (EC), and Renewable Energy (REN) scenarios and simulates electricity demand and supply, environmental affects, and costs.

Winkler [55] applies the MARKAL model to analyze ways of making South Africa's future energy development more sustainable and environmentally benign. A range of policy scenarios is modeled through a bottom-up optimization approach for the 2000-2025 period. The study simulates the contributions made by both the demand and supply side of efficiency policies on sustainable energy development, the impact of increasing the amount of imported power on carbon emissions, and investment cost scenarios. Thiam and Benders [49] use PowerPlan, a bottom-up simulation model, to evaluate the contribution of renewable energy technologies towards sustainable development in developing countries. Two scenarios, BAU and hybrid renewable energy (HRE) were formulated to investigate two case studies, which apply to South Africa and Senegal from 2006-2030.

For Kenya, D. Irungu [59] uses the bottom-up approach in LEAP to determine the cost implications and associated GHG emissions for three possible development pathways: the government's Least Cost Development Plan, which was used as a reference scenario; a natural gas scenario; and a renewable energy scenario, which enforces a compulsory addition of a 5% contribution from small renewables. The model uses a bottom-up approach to simulate the pathways for the 2013-2030 period. Carvallo et al. [58] use SWITCH-Kenya, a bottom-up optimization model, to explore low carbon development pathways for Kenya from 2020-2035. Five scenarios are tested: a geothermal scenario with varying levels of geothermal capacity; a load forecast scenario, whereby the loads are varied; a coal-power scenario, whereby the government's planned coal-power generation is included in the pathway; a storage scenario whereby battery storage is included in the model; and a carbon scenario, whereby carbon emission tax is imposed.

Awopone and Zobaa [50], and Awopone et al. [51] use the top-down approach in LEAP, linked with OSeMOSYS for optimization, to analyze Ghana's energy system according to two different scenarios. The scenarios examine Ghana's optimal electricity generation scenario from 2010 to 2040 and simulate and optimize the least cost generation technology mix for Ghana's power system planned according to government energy policy and alternative pathways independent of government plans. The scenarios tested by the two models include energy emission targets, the introduction of a $20USD/kg carbon dioxide (CO2) tax, and efficiency improvement through reducing transmission and distribution losses as stipulated in government plans. Furthermore, Awopone et al. [51] simulate the impact of demand-side efficiency improvements on GHG emissions and power investment costs.

4.3.2 Decentralized generation policy

This sub-section summarizes the results from models that evaluate the role and cost of decentralized generation technologies in achieving universal access to energy. Szabó et al. [46] use SECM to investigate the least-cost decentralized energy generation option for mini-hydro, off-grid PV, and diesel generator options for different geographic locations in SSA. A bottom-up simulation approach is applied to evaluate the cost of meeting demand in 2013 using both grid and decentralized power generation. Lucas et al. [42] use TIMER for their quantitative analysis of capital investment and technology needed to achieve universal access for the SSA region by tapping into the decentralized generation technologies. The model uses a top-down simulation approach and covers the 2010-2030 period. Moksnes et al. [39] soft-link and use OnSSET and OSeMOSYS to investigate pathways that would allow Kenya to reach its electrification targets by 2030. Hypothetical scenarios and their implications are analyzed in a top-down simulation and optimization approach. Two demand scenarios were developed based on low- and high-end user consumption goals. The combined centralized grid and decentralized generation resources required to meet these scenarios were evaluated accordingly. Moner-Girona et al. [40] investigate possible pathways of achieving Sustainable Energy for all (SE4All) initiative targets for Burkina Faso. The least-cost options were modeled for each settlement area by comparing scenarios, each comprising a different mix of four decentralized generation technologies: grid extension, diesel genset, solar PV, and small-scale hydropower. Geospatial Analysis and Mapping (GAM) and a Geographical Information System (GIS)-based tool were used as modeling interfaces.

4.3.3 Power trade and transmission policies

As previously mentioned, six of the reviewed models mainly concern the simulation of power trade. On a regional scale, Sanoh et al. [60] use Linear Generated Equation (LGE) in GAMS and GIS to forecast demand and investigate the optimal option for supplying electricity to national economies either from domestic energy resources or from both domestic and imported electricity by interconnecting high voltage lines within the power pools in SSA. The model uses a bottom-up approach simulation and optimization methodology from 2010-2025, where simulation of clean energy and fossil fuel scenarios are done according to power pools and fully liberalized power trade among the countries concerned in each of the four power pools. Battery storage is also simulated under the clean energy scenario. Taliotis et al. [52] use TEMBA-OSeMOSYS, which uses a bottom-up analytical approach and optimization methodology, to evaluate the potential for a relationship between electricity investments and power trade across the entire African continent from 2015-2040. The model is applied to two scenarios to estimate the future demand and untapped energy resource potential on a national scale for each country, which are then linked to other countries via trade links under varying levels of transmission expansion. Unlike the LGE & GIS model that uses geospatial data, the TEMBA-OSeMOSYS model uses data estimates obtained from countries' power utilities.

Wright [54] uses the hourly demand level in the PLEXOS model to evaluate demand statistics and demonstrate the benefits of interconnection among EAPP countries. PLEXOS is a bottom-up optimization model that uses SSA's 2010 electricity demands to assess potential savings that might be made in meeting this demand assuming the enhancement of power trade. Saadi et al. [45] used the SPLAT model developed on the MESSAGE platform to assess the cost-benefits of linking the SAPP and EAPP power pools through power trade and transmission interconnectivity from 2010-2030. Two scenarios are tested; BAU assumes the current renewable and regional integration trends, while the Africa Clean Energy Corridor initiative (ACEC) scenario assumes favorable conditions for renewable energy, and regional integration between the two power pools through the Ethiopia-Kenya–South Africa transmission line.

At the national level, Arndt et al. [53] soft-link SATIM and SAGE to evaluate South Africa's main 2010-2035 energy policy using two scenarios, that is, the BAU and policy scenarios. The BAU scenario simulates current trends, while the policy scenario simulates the carbon tax scenario and liberalization of the power import scenario. The liberalization of imports scenario removes the cap on the maximum capacity allowed for imported power. The model further simulates a third scenario comprising both the BAU and policy scenarios. Marong et al. [61] use MESSAGE to optimize Gambia's national electricity supply pathway by two scenarios covering the 2015-2030 period. The scenarios include the Electricity Independent Scenario (EID) called the BAU scenario and the Electricity Dependent scenario (EDD). The EID encompasses existing policy, consists of some interventions but excludes hydropower imports from neighboring countries. Conversely, EDD comprises the current policy, which consists of some interventions and hydropower imports from the neighboring countries.

4.3.4 Universal access

Four of the reviewed studies comprise models that assess the expansion pathways for attaining universal electrification for their country of focus. These four models cover the governments' national energy plans for Nigeria, Ghana, South Africa, and Kenya. Lahmeyer International [38] uses LIPS-OP and LIPS-XP, an in-house developed tool, to simulate and forecast a power development plan for Kenya, covering the period 2015-2035. The model assesses the cost of the various expansion pathways that will meet different demand scenarios under different economic growth rates, that is, reference (6.6% annual growth rate), vision (8.8% yearly growth rate), low scenarios (5% yearly growth rate). The model further tests the impact of reduced transmission losses on the capital cost of the power system. The Department of Energy for South Africa uses PLEXOS [37] to simulate the power expansion pathways for the country. It evaluates 100% urban and 90% rural electrification for the central grid from 2010-2030. The expansion pathways for the different demand levels are investigated. The issues considered in this investigation include either having limits on the renewable energy share or having no limit, GHG emission reduction constraints, decommissioning dates of existing cola generation plants, and transmission expansion costs. On the other hand, the Energy Commission of Nigeria uses MESSAGE (35) to assess the generation mix necessary to meet Nigeria's required energy needs to transform into an industrialized nation from 2000-2050. The expansion pathways are simulated over different demand levels as defined by the different levels of economic growth. They include reference scenario at 7% GDP growth, high growth rate at 10% GDP growth, and Optimistic scenario at 11.5% GDP growth rate. The Energy Commission of Ghana uses LEAP [36] to assess the demand-side forecast and the supply technologies necessary to achieve 100% electrification in the country, with 15% penetration of decentralized generation for the rural electrification from 2008-2020. The themes simulated included the demand-side management, i.e., improved efficiency of domestic and commercial appliances, and a 10% overall share of renewable resources in the energy mix by 2020.

5. Discussion

This paper explores efforts to develop energy models for SSA and reviews 30 integrated energy modeling studies. Areas reviewed include the role of various world institutions in developing energy models for the SSA region, the structures and features of these developed models, and the policies and themes addressed by the models. This section will articulate efforts in developing energy models for SSA and emphasize areas for improvement.

5.1 From expatriates to local expertise

This review has established that European-based institutions are the main drivers of SSA's energy modeling studies. On the contrary, relevant institutions in the SSA region have made minimal contributions to the modeling studies reviewed. For example, a few countries, Nigeria, Ghana, and South Africa, use local human resources to develop models for their power expansion plans. The lack of contribution by the relevant SSA institution and governments can be attributed to the inadequate energy modeling capacity in the SSA region [38][65]. The existence of national energy planning capabilities and capacities increases a country's ability to anticipate and respond to the occurrence of rapid changes, as well as new issues and opportunities arising within its energy system [66]. Therefore, there is an urgent need for national governments in SSA to utilize advanced energy modeling expertise that already exists among developed countries to build and retain a pool of local experts for their own countries. The key is to facilitate partnerships between local academic institutions in SSA and the modeling experts of academic and energy institutions from developed countries. Once a pool of local expertise is established, governments in SSA will need to work alongside regional academic institutions and private sector energy stakeholders and provide necessary data to develop energy system models for the region.

5.2 Need for synchronized short- to medium-term hybrid power planning models for SSA

This paper has reviewed modeling studies covering medium- and long-term time horizons in almost equal numbers at national, regional, and continental levels. Three of the studies reviewed only cover short-term time horizons. Most of the reviewed modeling studies use a bottom-up rather than a top-down approach, and only two models use a hybrid approach. The SSA region is challenged to balance the attainment of universal energy access, economic growth, and poverty eradication while limiting GHG emissions [4][6]. Unlike the top-down and bottom-up approach, the hybrid approach presents a reliable tool for analyzing complex interactions among economic, energy, and environmental issues related to energy policies [63,67]. Therefore, there is a need to synchronize the short- to medium-term time horizons with hybridized modeling approaches to develop energy models for SSA.

5.3 Climate, techno-economic, and environmental policy models for development rate of renewable energy resources

Some of the reviewed studies evaluate the impact of carbon taxes, energy subsidies, technology learning, storage deployment, climate change, the geographical distribution of renewable energy resources, and efficiency and demand response measures toward development rate and cost of renewable energy in the energy mix. The reviewed studies provide insights into future technology responses to economy-wide carbon prices [33][34], fossil-fuel subsidies [34][50][51] technology learning [49], and the impact of the geographical distribution of the renewable energy resources in meeting regional demands within SSA [49].

Others evaluate the effects of storage technology [58] and climate change on renewable energy uptake [44][56][48]. Several simulate the effect of efficiency policies on GHG emissions and energy investment costs [57][50][51]. Of the four national power plan models, only two [37][36] simulate the GHG emissions and renewable energy penetration policies, respectively. The remaining two focus on the expansion pathways with little consideration for environmental implications [38][35]. Generally, the reviewed studies indicate that the geographical distribution of renewable energy resources is an impetus for meeting SSA's regional energy demand services while concurrently limiting GHG emissions. Additionally, the adoption of storage technology, subsidies for renewable energy technologies, and technology learning can accelerate the uptake of renewable energy. From the review, each modeling study simulates different expansion policy scenarios under different frameworks. Yet to achieve a consolidated and comprehensive forecast of climate, techno-economic, and environmental energy policies required to address energy poverty in SSA, it is imperative to develop an all-in-one national-level energy planning model for each country. This model can be fused into one model for the entire region, i.e., one that is capable of incorporating all these policies under similar boundary conditions [65]. In contrast to the reviewed studies, the new models should consider the finer representation of key power system elements; such as spinning reserves, peak loads, ramping rates, and quick start reserve margins. These power system elements have a long term effect on the cost of power generation and rate of development of renewable energy [68]. The national power plans models are mainly focused on simulation rather than optimization of the expansion pathways. There is need for governments to adopt a balance and simulate as well as optimize the expansion pathways while capturing the environmental considerations, effect of demand drivers' disruptions on supply, the role of demand-supply efficiency in production cost reduction, subsidies and technology learning and its impact on the penetration of renewable energy and the cost of generation. The use of smart grids in attaining load control is needed in future SSA energy models to improve the efficiency and reliability of the regions power systems as well as the security and quality of electricity services [69]. Finally, simulations need to be undertaken for the impact of technology learning on the cost of storage technology. Only two of the studies reviewed attempt to simulate the impact of battery storage technology on renewable energy uptake.

5.4 Centralized and decentralized generation and grid solutions for universal access

The discussions on universal access to electricity in SSA have been dominated by arguments that pit centralized solutions, such as grid extensions, against decentralized solutions, such as mini-grids [4]. Four of the reviewed studies evaluate the role and cost of decentralized generation technologies in achieving universal access to energy. The results of these studies generally indicate that the least-cost energy access solution will not be a one-size-fits-all solution but rather one that incorporates a mixture of different technologies [46]. Additionally, different technologies perform better in specific locations while remaining unattractive for others [39]. Lastly, the results of this review indicate that mini-grid and stand-alone systems can accelerate universal access to electricity and reduce carbon emissions, but at a higher capital cost [42][40]. Four of the studies reviewed use geospatial data estimates for critical parameters, such as population density and the distance of the renewable energy resource from load centers. In addition, none of the studies simulates the effectiveness of subsidies in adopting decentralized generation for addressing rural and universal access to electricity. Due to the diseconomies of scale, the cost of setting up decentralized electricity generation, for example, through the use of mini-grids, is higher when compared with grid extension [70]. Only one out of the four national power plan models assesses the role of decentralized generation in attaining universal access. Scattered rural villages characterize a higher percentage of the SSA settlements. Previous studies indicate that decentralized generation is the most feasible electricity supply mode for such scenarios. In this regard, national power plans should include the decentralized generation mode in the national plans. The models should evaluate a hybrid system of attaining universal electrification through grid extension and decentralized generation. Geospatial data is vital in mapping out scattered rural population density, distance from the central grid, and distance from the energy source, for example, mini-hydropower resource. Therefore, using real-time geospatial data in future modeling simulations is imperative to present a cost estimate to energy stakeholders with a certain degree of reliability. Furthermore, there is a need to simulate the effect of subsidies on all decentralized generation technologies to facilitate cost comparison. Some decentralized generation technologies are associated with variable energy sources, such as solar and wind resources. Such sources require storage, mainly batteries, which are currently the most advanced storage technology [58]. Battery storage increases generated capacities because batteries place an additional strain on the system, increasing the cost of decentralized generation [67,71]. Future studies need to incorporate the impact of storage technology in detail to fully capture the overall cost of harnessing wind and solar energy sources.

5.5 Power trade for sustainable energy development

Six of the studies reviewed simulate the impact of power trade on the cost of meeting electricity demands and the accelerated use of renewable energy resources. All six studies are based on conventional grids and indicate that an enhanced trade scenario would require increased annual investment in generation transmission infrastructure by the region concerned [52]. Secondly, some of the six studies note that enhanced power trade accelerates the uptake of renewable energy [60][45]. Lastly, the studies indicate that operational power pools will reduce the wholesale price of electricity and the amount of capital investment required by each country, as compared with non-operational power pools and power trade cases [54][53][61]. Four of the six studies are simulated at the regional level [60][52][54][45] and use more aggregated data. The remaining two studies were simulated at a national level and only assessed the impact of imported hydropower from neighboring countries [53][61]. However, the studies do not account for transmission expansion costs. Unlike the current models, future power-trade modeling studies that apply to the region of SSA need to incorporate smart grids to enable decision makers to undertake cost comparisons between the conventional and smart grid systems. Smart grids are key in addressing the technical, economic, logistical, and administrative realities of generating and delivering electricity through a giant regional power grid [72]. Furthermore, to capture and synchronize the disaggregated data on the socio-economic, technical, logistical, environmental, and administrative parameters for each country within a regional power-trade model, the modeling work should adopt a cyclic approach. A cyclic approach will further help to address the balance between the national interests of individual countries while retaining the benefits of regional cooperation. Under this approach, national plans should be prepared based on common regional planning horizon and demand forecast scenario boundaries. Once the foundation has been established at the national level, regional inputs can then be incorporated by interlinking the national plans using power pools. The national plans should then be revised so that the desired balance between national and regional interests can be achieved.

6. Conclusions

This paper reviews 30 integrated energy modeling studies on the SSA region. European-based institutions are the main drivers of these studies. This paper provides a database for researchers and energy stakeholders by summarizing each model's model features and policy themes in the tables, thereby easing their search for a model suitable for their national energy system characteristics and objectives. SSA needs a deliberate effort to employ already existing advanced energy modeling expertise among developed countries to develop local energy modeling capacity in the region. The reviewed modeling studies encompass both the technology-rich bottom-up method and the economically oriented top-down method, where only two models use a hybrid approach. Future modeling studies need to adopt a hybrid approach to address the challenges facing SSA in meeting electricity demands while simultaneously mitigating GHG emissions. A hybrid approach presents a reliable tool for analyzing the complex interactions among economic, energy, and environmental issues related to energy policies.

The reviewed studies' policies and themes covered by models include demand response, energy efficiency, storage, universal access, techno-economic and environmental policies, climate policy, decentralized generation, and power trade and transmission expansion. Future modeling studies should incorporate crucial energy system elements, unlike current studies. The current models lack a more refined representation of essential factors such as spinning reserves, ramping rates, peak loads, and quick-start reserve margins. These elements affect the long-term power generation costs. In addition, developing detailed models of various storage technologies are needed to highlight and identify the cost and impact of adapting to a high rate of renewable energy development. This incorporation will also assist energy decision makers and stakeholders in understanding the effect of storage on using decentralized power generation to supply the grid. The reviewed power-trade studies indicate that connecting SSA power pools through expanded transmission networks is essential for increasing the use of abundant renewable energy resources in the region. However, the reviewed national power-trade modeling studies only consider hydropower as the source of traded power when simulating local generation scenarios. In addition, the reviewed regional power trade studies use highly aggregated and estimated data. It is essential that proper analysis and planning be undertaken before establishing such a relatively complex supply-demand power trade system efficiently and effectively. The SSA governments are part of the international community and signatories to international guidelines, for example, the UNFCCC climate change guideline through their Nationally Determined Contribution. Models developed for the national power expansion plans must consider low-carbon policies to mitigate GHG emissions and evaluate their impact on generation cost. It is also essential to assess the optimal expansion pathways by running a wide range of scenarios instead of only simulating a narrow set of scenarios as depicted in the reviewed national energy plans. The adoption of a cyclic approach is also recommended. After the foundation of supply-demand balance has been established at the national level, models can then be interlinked using power pools. An optimal configuration can be researched and developed considering future demand uncertainties and guided by the objective of attaining universal energy access and cost-effectively reducing GHG emissions.

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3. Paper 2

Environmental and techno-economic assessment of power system expansion for projected demand levels in Kenya using TIMES modeling framework

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Abstract

This study develops a new national-scale bottom-up energy system optimization model called Kenya-TIMES. The model evaluates the implication of greenhouse gas emission reduction on Kenya's power system's techno-economic and environmental evolution under three government-projected electricity demand levels, which covers the 2020–2045 period. A business as usual and a carbon emission cap scenarios were developed to assess the implications of greenhouse gas emission reduction measures. The model shows that energy security can be achieved under the two scenarios for all three demand levels. The generation mix suggested by the model is dominated by renewable sources under the carbon emission cap scenario compared to the business as usual scenario. The higher share of renewable technologies under the carbon emission cap scenario results in lower emission but increased electricity cost. Consequently, to meet its emission reduction targets, the Kenyan government needs to enact and implement policies that will enhance the deployment of renewable energy technologies. The findings indicate that the Kenyan government should prioritize developing geothermal and hydropower resources in the short- to medium-term, providing affordable and secure energy while limiting GHG emissions.

Keywords: Kenya-TIMES; Demand levels; Nationally Determined Contribution; Generation expansion; Renewable Technologies; Greenhouse gas emissions.

1. Introduction

The provision of secure, reliable, affordable, and environmentally benign energy is required to address global challenges related to sustainable development, including poor health services and quality of education, high levels of poverty, climate-change associated risks, food insecurity, and gender disparities (Bazilian et al., 2012). Understanding current and future energy needs, particularly in developing countries where these issues are acute, is a global concern. In 2019, 770 million people, mainly in low- and middle-income countries in Asia and Sub-Saharan Africa (SSA), lacked access to electricity (IEA, 2020a). Furthermore, 2.6 billion people, mainly from the same regions, lacked access to clean cooking energy (IEA, 2020a). Developing countries are challenged to find a balance between attaining universal energy access for their population at an affordable cost while limiting greenhouse gas (GHG) emissions. To achieve this, effective energy planning, policy assessment, and robust forecasts for both demand and supply functions are critical (Musonye et al., 2020).

Over the last 50 years, energy stakeholders in advanced economies have developed and improved energy planning modeling tools to assist in making informed decisions concerning energy-sector planning and development at the global, regional, and national levels (Debnath & Mourshed, 2018). These modeling tools either adopt a top-down or bottom-up approach, simulation, optimization, or hybrid methodology, covering local, national, regional, or global geographic areas and short-term, medium-term, or long-term time horizons (Van Beeck, 1999). The top-down modeling tools are largely aggregated macro-economic tools, focusing on market processes rather than technology detail. In contrast, bottom-up tools are technology-rich tools, which focus on energy technologies and how they can be substituted based on the relative cost to provide the required energy services (van Vuuren et al., 2009). Simulation tools are descriptive models, which describe an energy system based on a set of rules that do not necessarily lead to a full equilibrium (van Vuuren et al., 2009). Conversely, optimization tools apply a methodology where several decision variables are computed that minimize or maximize an objective function subject to constraints. The main difference is that simulation models intend to envisage the performance of a given energy system, given certain assumptions, while optimization models seek for the optimal system design (Lund et al., 2017). Hybrid tools combine both simulation and optimization methodologies. There exists no standard definition of the number of years that form time horizons. However, the commonly used period is 5 years or less for short-term, 5 to 15 years for medium-term, and 10 years or more for long-term (Van Beeck, 1999). The geographical coverage reflects the level at which the analysis takes place.

Unlike other energy carriers, electricity can provide an array of energy services hence, plays a central role in energy access (Morrissey, 2017). As a result, efforts to enhance energy access have focused more on the provision of electricity. Economically-developing countries can leverage existing energy modeling platforms to perform robust demand-supply planning that is critical in achieving universal access to modern energy services at minimum cost (Musonye et al., 2020).

Most of Kenya's population lacks access to modern energy services. The 2018 statistics indicate that Kenyan households utilized 192,915 TJ of biomass in the form of wood fuel and charcoal, out of the total 488,780 TJ of primary energy consumed (KNBS, 2019). The consumption was mainly in rural and informal urban-settlement households. Electricity generation accounted for only 8% or 39,786 TJ of consumed primary energy. Electricity generated from domestically available resources — wind, solar, hydro, and geothermal — accounted for 34,213 TJ, while that generated from imported fossil fuels accounted for 5573 TJ (KNBS, 2019). By December 2019, the total installed power capacity was 2846 MW, with estimated electrification of 75% (IEA, 2019). Kenya's access rate value is higher than the average SSA value of 45% (IEA, 2020a); this result is, however, qualified, as it is directly equated to the connectivity rate, yet not all connected customers consume electricity (Taneja, 2018). The 2019 per capita annual electricity consumption of 217 kWh (Ritchie & Roser, 2020) is low compared to the average per capita annual electricity consumption for all African countries of 600 kWh (EIA, 2020), and the worldwide per capita average annual electricity consumption of 3200kWh (EIA, 2020). In addition to its low access rate, Kenya faces other challenges, including a demand-supply mismatch, urban-rural access disparities, an insufficient and unreliable electricity supply, and high electricity costs (Avila et al., 2017).

The government has rolled out various plans to accelerate electricity access: the Least Cost Power Development Plan, which is reviewed every two years, the Last Mile Connectivity Project, the Slum Electrification Program, the Kenya National Electrification Strategy (KNES), the Rural Electrification Project, the Kenya Electricity Modernisation Project, and the Boresha Umeme Network Upgrade Project (KPLC, 2018). Despite the advances made by these programs, Kenya still seems to lag in meeting the goal of universal energy access by 2022 established in the Kenya National Electrification Strategy (MoEP, 2018). Furthermore, some connected customers are either unable to consume electricity or limit consumption due to high prices. In contrast, those who can afford the cost of electricity are subjected to regular blackouts (Taneja, 2018).

The Kenyan government currently lacks an appropriate application of energy modeling tools (Musonye et al., 2020). These tools are critical in achieving optimal, integrated energy planning and policy formulation, hence secure, affordable, and reliable universal energy access. Instead of building local modeling expertise, the government relies on expatriates to make forecasts and plan the energy system, as is evident from the three previous government national energy master plans (ERC, 2010; EPRA, 2018; Lahmeyer International, 2016).

Recently, researchers have attempted to simulate various aspects of Kenya's power system. The Open Source Spatial Electrification Toolkit (OnSSET) and Open Source Energy Modeling SYStem (OSeMOSYS) were used to investigate pathways that would allow Kenya to reach its electrification demand by 2030 (Moksnes et al., 2017). Irungu simulated the cost implications and the associated GHGs emission for three possible development pathways using the Long-range Energy Alternative and Planning (LEAP) (Irungu et al., 2018). Carvallo et al. used Solar and Wind energy Integrated with Transmission and Conventional sources (SWITCH-Kenya) to explore low-carbon development pathways for Kenya between 2020 and 2035 (Carvallo et al., 2017). Kenya's Energy and Petroleum Regulatory Authority (EPRA) has been developing Kenya's energy plans. EPRA contracted expatriates who used the Lahmeyer International Power System Operational/Expansion Planning (LIPS-OP/XP) model, an in-house developed tool, to simulate and forecast Kenya's power development plan for the period 2015–2035 (Lahmeyer International, 2016).

These studies found that while energy models were viable tools in energy demand-supply planning and forecasting, there was still room for improvement in the country's energy modeling studies and planning. Some of the areas yet to be addressed by the previous research include assessing the techno-economic implication related to the three government projected demand levels. For instance, no published study has evaluated the impact of subsidies, emission mitigation measures, technology learning curves, and power importation on generation technology mix, GHGs emission and their mitigation costs, and assessment of the overall power system cost associated with meeting the three projected demand levels. Further, an evaluation of the short-term operational constraints, for example, the hourly variability of renewable resources, hourly load curve, unit commitment, operating reserves, and ramp rates in the long-term power planning, is yet to be assessed by any study. In addition, all previous studies either used simulation tools, econometric tools, or less technologically detailed optimization tools to evaluate a limited number of scenarios instead of using advanced optimization tools to identify optimal solutions.

This brief review underscores Kenya's complex energy situation and its challenges. These challenges stem from the lack of robust demand-supply forecasting and planning and energy investment decisions that are politically driven and ignore the existing generation-expansion model recommendations (Newell & Phillips, 2016). Moreover, energy modeling expertise for the government's institution mandated with energy planning is inadequate. The energy-planning model LIPS-OP/XP that the government currently uses as a guide is insufficient (Carvallo et al., 2017).

Kenya should develop and adopt a technology-rich, data-driven, and integrated demand-supply energy model at a national level for effective energy system planning and operation. For ease of development and regular model updates, the government can utilize existing energy modeling tools by acquiring a perpetual license and then building and retaining a pool of local experts to update the model on an as-need-be basis. A well-documented account of how national energy planning models for SSA countries can be developed is found in Musonye et al. (2020).

The study presented in this paper uses the International Energy Agency’s (IEA) TIMES-VEDA energy modeling framework to develop a national-scale, bottom-up energy system optimization model for Kenya — the Kenya-TIMES. The TIMES modeling framework is an economic modeling platform, which provides a technology-rich basis for representing energy dynamics over a multi-period time horizon (Loulou, Lehtila, et al., 2016; Loulou, Remne, et al., 2016). The TIMES modeling framework is highly detailed and can evaluate various demand-supply energy planning-related themes. Some of the themes that can be assessed using the TIMES framework include endogenously forecasted energy demand, generation expansion pathways and policy instruments, endogenous technology learning, energy storage, energy and GHG emission trading, short term operational constraints — for example, the hourly intermittency of renewable sources and the resultant ramp-up and ramp-down rates of peaking and baseload plants — on the long term planning, among others (Loulou, Remne, et al., 2016). The framework also allows for imputing age-dependent emission factors for technologies, flexible time slices disaggregated into seasonal, weekly, and daily periods, discrete investment, and retirement of technologies, among others. Lastly, the TIMES framework has been tried and tested exhaustively over the years, and the methodology is well documented. Even though the current study does not assess all the listed themes, the Kenya-TIMES model development is continuous. Resultantly, the use of the TIMES framework provides an opportunity for further development and refinement of the Kenya-TIMES model with further data acquisition.

This is the first time the TIMES modeling framework has been applied to assess Kenya's power-generation expansion scenarios. Furthermore, the study is the first attempt to investigate the techno-economic-environmental aspects of Kenya's three forecast power demand levels. This study aims to evaluate the impacts of meeting the GHG emissions reduction target as guided by the Nationally Determined Contribution (NDC) under the three government's projected power demand levels. This assessment uses the Business As Usual (BAU) and the Carbon Emission Cap (CEC) scenarios. Consequently, the study evaluates the GHG emissions, technological choices, and economic implications of meeting the three demand levels using domestic and imported primary energy resources under the BAU and CEC scenarios. The analysis covers the 2020–2045 period, with the base year set in 2018. The current study is restricted to the grid-connected supply. The Kenya-TIMES model was developed in a data-scarce environment. The data was collected through literature searches, field visits, and interviews with the authorities in the various power utilities. Because some of the required data were not available at the time of the study, the model could be further refined in the future with additional information. The rest of the paper consists of an overview of the current energy status for Kenya (Section 2), the methodology (Section 3), results (Section 4), discussion (Section 5), and conclusions (Section 6).

2. The current energy system status

2.1 The current installed power generation capacity and consumption

Until 2003, Kenya's electricity generation relied solely on hydropower and imported crude oil and petroleum products, with hydropower generating 60% and crude oil and petroleum products 40% of total consumed power (EPRA, 2018). With the recent commissioning of geothermal power plants, wind turbines, and off-grid renewable sources, the dependency on crude oil has decreased.

The current grid-connected total installed power capacity is 2846 MW (KNBS, 2019; MoEP, 2020). The mini- and micro-grid supply have around 76 MW installed capacity and consists of solar, wind, and thermal sources. The country's overall power generation mix includes hydro, thermal, geothermal, wind, and solar resources with an installed power of 826 MW, 769 MW, 865 MW, 336 MW, and 50 MW, respectively (see Fig. 1). The fuel used for thermal generation is Heavy Fuel Oil (HFO), Gasoil, and Kerosene, which are all imported. A new 83 MW geothermal plant (Richter, 2019) and 100 MW wind power plant (REVE, 2020) are being constructed, with completion and commissioning set for 2021. In addition to the power consumed from the grid, mini-grid, and micro-grid, there is an estimated 9 GWh annual power consumption from stand-alone home solar systems (EPRA, 2018). Kenya imports an insignificant amount of electrical energy from neighboring Uganda and Tanzania. In 2018, out of the 11,182 GWh of the total electricity consumed, imports accounted for a paltry 130 GWh.

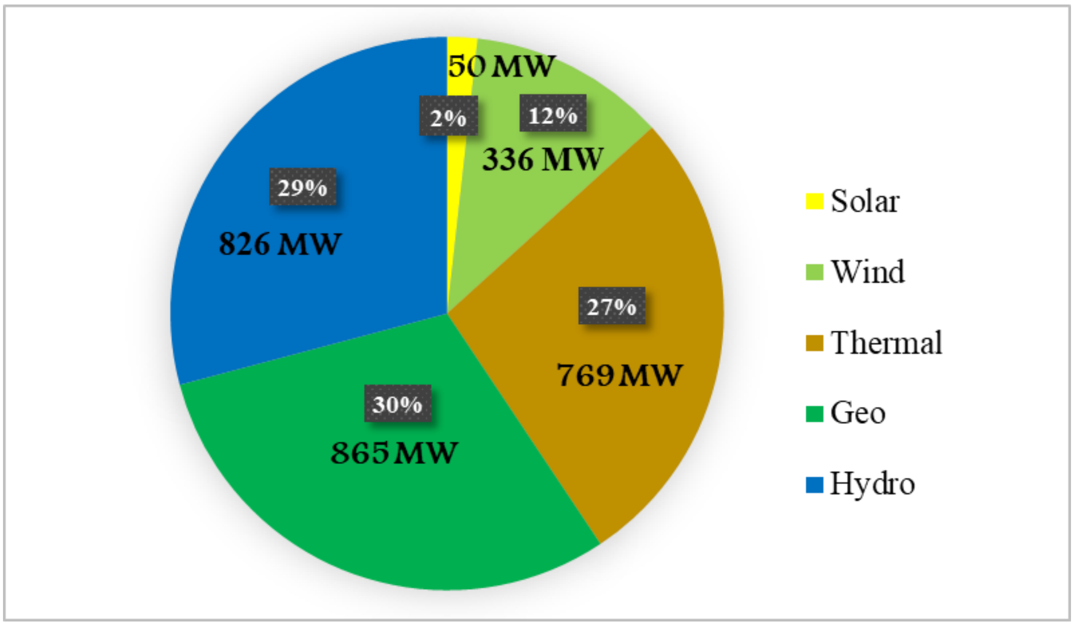

Figure 1: Installed power capacity mix for Kenya in 2018 (EPRA, 2018; KenGen, 2020; KNBS, 2019; MoEP, 2020).

2.2 Forecasted electricity demand levels

Through the Least Cost Power Development Plan (LCPDP) simulation, the Kenyan government expects power consumption to increase from 11,032 GWh in 2018 to 34,691 GWh in 2035, as per their reference demand scenario (EPRA, 2018). Table 1 shows the projected increase in power demand under three levels — low, reference, and vision — 2020 to 2035, as presented in EPRA, 2018. The authors derived the 2040 and 2045 demand using the average annual demand growth rates for the three demand levels reported in EPRA, 2018.

Table 1: The Kenyan government's projected power demand levels 2018-2045 (EPRA, 2018)

Year	**Low**		**Reference**		**Vision**	
	Energy (GWh)	Capacity (MW)	Energy (GWh)	Capacity (MW)	Energy (GWh)	Capacity (MW)
2018	11,032	1,842	11,169	1,866	11,470	1,917
2020	12,071	2,021	12,546	2,103	13,676	2,299
2025	15,229	2,563	17,750	2,989	22,056	3,705
2030	19,475	3,293	25,195	4,244	34,847	5,780
2035	25,297	4,305	34,691	5,859	50,595	8,468
2040	32,286	5,494	47,753	8,065	77,135	12,909
2045	41,206	7,011	65,733	11,101	117,596	19,680

These three demand levels describe a range of power demand drivers from a worst (low) case to a best (vision) case, running from 25% below (for the low) to 50% above (for the vision) the reference scenario. The demand drivers used in this forecast are the projected demographic changes for Kenya, its Gross Domestic Production (GDP) growth rate, and the Vision 2030 flagship projects. Demographic factors include population growth rate and urbanization. The GDP projection is based on the International Monetary Fund's (IMF) projection for Kenya. Vision 2030 flagship projects include an electrified mass rapid transit system, an electrified standard gauge railway system, refinery and petrochemical industries, Techno Cities, special economic zones, and the Lamu Port-South Sudan-Ethiopia Transport Corridor (LAPSSET) (Government of Kenya, 2020). The vision-demand scenario assumes 100% electrification by 2022 and full development and implementation of the flagship projects, most of which will rely on electricity for operation. The average annual peak demand growth rate in this scenario is 8.8%. The reference scenario applies the electrification rate and flagship projects' development pace using assumptions based on a combination of historical trends and actual plans, with a simulated average annual peak demand growth rate of 6.6%. With a 5% average yearly peak demand growth rate, the low scenario is for sensitivity and risk analyses, applying more conservative assumptions than the reference scenario (EPRA, 2018). The total installed capacity by December 2018 was 2846 MW, while the government's forecast value is 1842 MW, as shown in Table 1. However, the difference between energy consumed and projected energy consumption is insignificant. The total power consumption in 2018 was 11,182 GWh, while the projected power consumption was 11,032 GWh.

2.3 Energy resource potential in Kenya

If fully harnessed, Kenya's abundant renewable energy resources are enough to meet the population's projected future power demand. Compared to current installed capacities, only a fraction of the renewable energy resources have been developed (see Table 2).

Table 2: Kenya's energy resource potential and the current installed capacity (EPRA, 2018; REREC, 2020)

Generation Resource	Resource potential (MW)	Installed capacity (MW)
Hydropower	2,326	826
Geothermal	8,000	865
Solar PV	70,000	50
Wind	4,600	336
Coal	95,000	0
Oil	Appraisal stage	0
Gas	Appraisal stage	0

The value of 50 MW for the installed solar power capacity in Table 2 might be underestimated since there is no clear documentation of the number of home solar systems operating in the country. Recently, the country discovered coal reserves with a proven technical resource potential of 400 million tons (EPRA, 2018). To date, coal is the only domestic fossil fuel available for extraction and potential use for power generation. The commercial viability of the extraction and either export or local refining of newly discovered crude oil deposits is still under analysis, while exploration activities for natural gas deposits are underway and in the appraisal stage.

3. Materials and method

The methodology used in this study is designed to assess the GHG emission reduction target's impact on the technological choices and economic cost for the different demand-supply expansion pathways. The method integrates available energy resources, current and future conversion technologies, and demand projections under the BAU and CEC scenarios. This analysis only considers grid-connected generation comprising government and Independent Power Producer (IPP)-owned power plants. Electricity generated by individual homes and private businesses is not included due to a lack of data.

3.1 TIMES model

The Integrated MARKAL-EFOM System (TIMES) is a bottom-up energy optimization model generator developed by the Energy Technology System Analysis Programme (ETSAP) based on the General Algebraic Modeling System (GAMS) (Loulou and Labriet, 2008). The TIMES modeling platform incorporates the Versatile Data Analyst (VEDA) user interface. VEDA-FE (Front End) handles data input, while the TIMES code receives the input data from VEDA-FE and generates a model under the GAMS environment and a solver (Fig. 2). The VEDA-BE (Back End) is then used to read the results produced by the TIMES model (Cosmi et al., 2006).

The TIMES modeling framework is mainly based on linear programming. However, certain themes within the model adopt a different mathematical approach. For instance, the discrete early retirement and the discrete addition to the capacity of any technology and the endogenous technology learning curves use mixed-integer programming. On the other hand, optimization under risks related to uncertainty regarding certain parameters, such as emission mitigation level and energy demand growth rate, uses stochastic programming. The detailed algorithm behind the TIMES modeling framework can be found in Loulou, Remne, et al. (2016) and Loulou, Lehtila, et al. (2016).

TIMES derives optimal energy–economy–environmental scenarios at the level of a single community, province, country, region, or the entire globe, in a unilateral, bilateral, or multilateral approach (Di Leo et al., 2014). The scenarios are created through user-defined constraints, which are set to evaluate the impacts of different energy policies on the evolution of an energy system. For each of the scenarios, the TIMES model determines the optimal energy supply and technology mix required to meet the energy demand of an energy system using available energy resources and transformation technologies.

The TIMES model primarily helps policymakers and decision makers identify optimal and effective energy policies for future demand-supply generation expansion. The TIMES optimization is done on a medium-long term time horizon from 10 to 50 years, divided into periods of fixed or variable length (Di Leo et al., 2014). The TIMES model typically consists of one objective function and a set of constraints (Mondal et al., 2018), both of which are expressed using decision variables and parameters. The parameters are exogenous inputs specified by the modeler, while TIMES endogenously determines the decision variables, retrieved as the model output. Fig. 2 shows the input and output data of the TIMES model, with GHG emissions from the base case as inputs for the emission reduction scenarios.

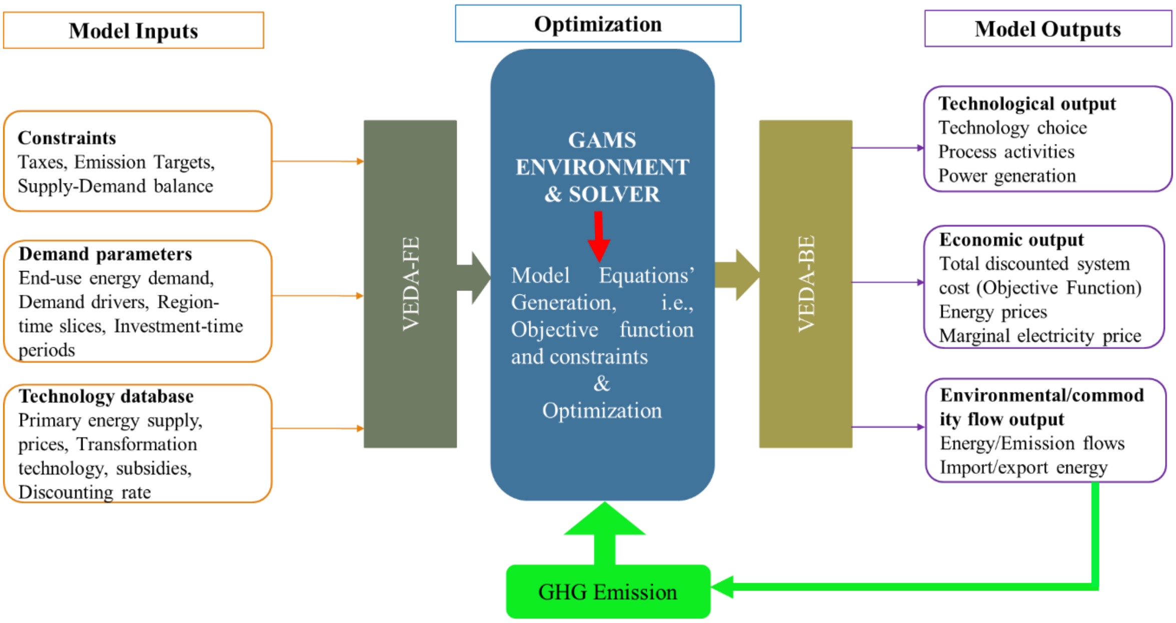

Figure 2: Schematic representation of the TIMES modeling framework showing the model inputs and outputs.

Exogenous input parameters include energy demand and supply curves, policies, and techno-economic parameters for each technology (Balyk et al., 2019). Energy demand comprises the demand drivers and time slices. Supply curves show the available quantities of domestic or imported primary energy resources. The techno-economic parameters are assigned to the currently available and anticipated new technologies in an energy system — both transformation and demand — that convert one or more commodities into one or more other commodities. Examples of technical parameters are efficiency, technical lifespans, and availability factor, while economic parameters include investment and operation costs (Balyk et al., 2019). The assessed policies include the effects of legislation, such as taxes on GHG emission, on specific technologies or fuels.

The model outputs comprise technologies' annual activities (for example, installed capacity and produced energy), technology investment, the required primary energy, marginal energy prices, GHG emission, and the total system cost discounted to the net present value. The model is first run for the base case to capture the GHG emission constraints. The resulting GHG emissions are then used as input for the desired GHG emission scenarios, and an emission constraint is defined on it. TIMES dynamically adjusts the defined reference energy system (RES) to satisfy all the modeled equations, and the long-term total system costs are minimized based on net present value (Mondal et al., 2018). The minimized total system cost takes into account the sum of investment, fixed and variable operation and maintenance costs, and export revenues. If the economic lifetime of technology goes beyond the modeling horizon, its salvage value is deducted from the objective function.

The TIMES modeling platform has been used to assess various aspects of energy systems, including energy policy measures, and to optimize demand-supply expansion planning at the national level, for example, the United Kingdom (Daly & Fais, 2014), Pakistan (Ur Rehman et al., 2019) and Denmark (Balyk et al., 2019), and also for a region within a country, for example, Northern India (Gaur et al., 2019). TIMES has been used to assess generation expansion under high penetration of intermittent renewable generation sources (Tigas et al., 2012). TIMES has also been used at the national level to analyze the economic impact of clean energy, for instance, in Kuwait (Yessian, 2013), to evaluate support systems for renewable electricity (Fais et al., 2014), and to assess the effect of efficiency on energy systems (Calvillo et al., 2017). TIMES has been used to evaluate demand and the subsequent generation expansion pathways, for instance, in South Africa (Arndt et al., 2016) and Denmark (Tattini et al., 2018). Further, TIMES has been used to evaluate policy constraints for regional expansion planning, for example, in Basilicata in Italy (Di Leo et al., 2014) and California in the United States (Yang et al., 2015). On a continental scale, TIMES has been used to integrate the life-cycle emission assessment (LCA) and external costs for the European Union (Kypreos et al., 2008) and to evaluate the policy measures required by member countries to achieve their GHG emission reduction targets (EU, 2020).

3.2 The reference energy system of the Kenya-TIMES model

The reference energy system (RES) description informs the TIMES model generator of the intended energy model's nature, components, and structure in the TIMES modeling framework. The elements of RES are energy carriers for primary energy supply, the transformation process, which converts the primary energy into useful forms of energy, and end-use energy demand devices. This study develops a Kenya-TIMES model that is updateable to improve the model elements with time.

The RES layout for Kenya-TIMES includes primary energy sources, conversion sectors, the transmission process, and demand sectors (Fig. 3). Kenya's electricity demand data is highly aggregated. Even though the TIMES modeling framework divides energy demand into industrial, residential, agricultural, and commercial, Kenya‘s demand is divided into domestic, small commercial, street lighting, and large commercial and industrial consumers. The current study uses the government's total projected demand values presented in the LCPDP report (EPRA, 2018). The total projected demand for the whole modeling period — including auxiliary consumption, peak reserve, and losses — is an exogenous input to the model. Domestic and import supply processes define the primary energy supply for renewable and fossil fuel energy carriers. The considered energy carriers under Kenya-TIMES include oil, coal, natural gas, nuclear, electricity, and renewable energy sources. The selection of these energy carriers is based on the primary energy resources considered in the government's energy planning LCPDP report (EPRA, 2018). Coal is the only fossil fuel with a proven technical potential for domestic supply; hence, the domestic and import supply options are presented in the model. The rest of the fossil fuels only have the import option, while the renewable energy sources only have the domestic supply option. Only 4 out of the 8 GW geothermal potential mentioned in EPRA, 2018 was considered because so far, only four out of 23 geothermal prospects have been studied to the exploration drilling stage, and the feasibility of the others is uncertain. Furthermore, the 1.5 GW potential considered for hydropower relates to the estimated available potential of economic value (EPRA, 2018). The modeling horizon covers the 2020 to 2045 period, with five-year investment periods and the base year set in 2018.

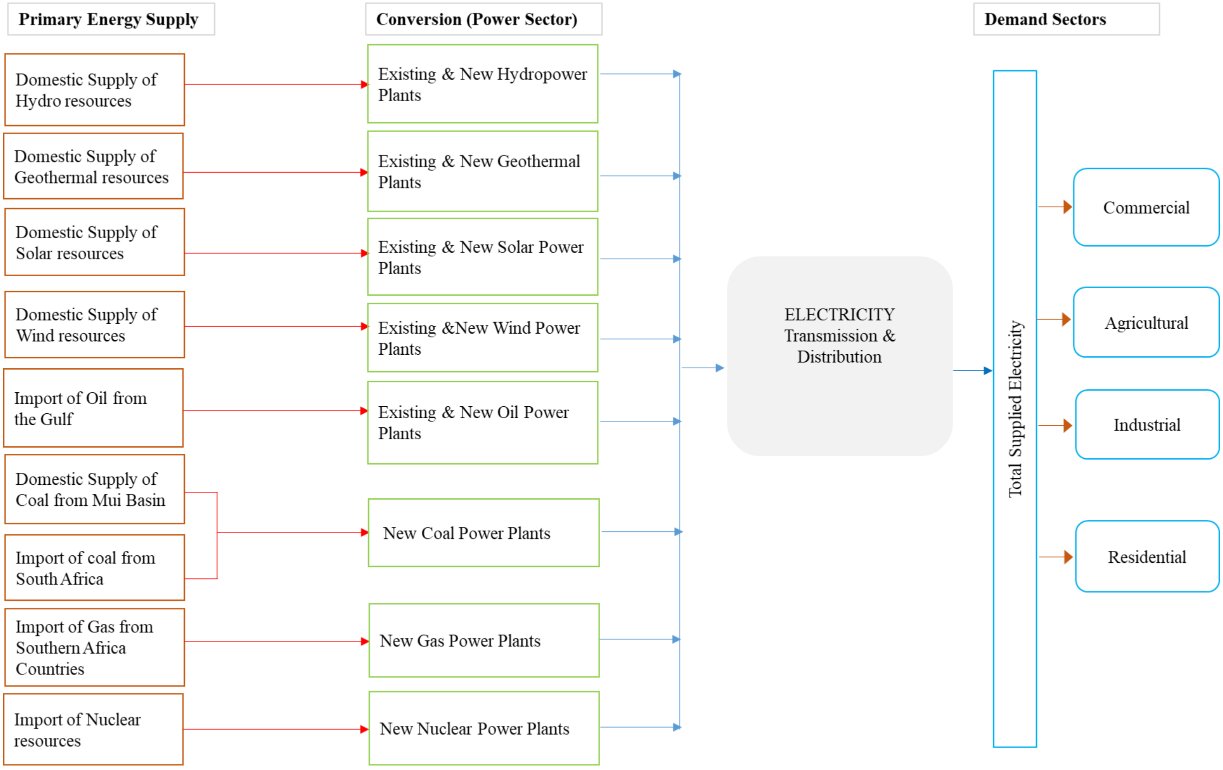

Figure 3: The Reference Energy System for Kenya-TIMES.

Kenya-TIMES is not constrained to the 80 MW geothermal and 100 MW wind power plants currently under construction. EPRA recommended delaying the development of new geothermal plants after implementing those in development and the phasing out of committed medium-term solar and wind under the Feed-in-Tariff policy (EPRA, 2018). The researchers, therefore, chose not to restrict the Kenya-TIMES model to give preference to generation technologies that are currently under construction. The model uses the U.S. dollar at the 2018 exchange rate. The discount rate is 7%, in line with the average median Kenya Central Bank rates between 2015 and 2020 (Trading Economics, 2020). The energy unit is Peta-Joule (PJ) for the transformation process, while the primary transformation process is electricity generation, which is the dominant form of final energy use.

The model considers four annual time slices. Although inter-day electricity demand fluctuations in Kenya are insignificant (EPRA, 2018), yearly use has a relatively low-demand period from January to June compared to July to December. A typical average demand for a 24-h day for each of the two periods was chosen and further divided into two periods of peak and off-peak demand. The electricity generation technologies modeled include fossil fuels, nuclear, and renewables power plants (see Fig. 3). Renewable sources include hydropower, geothermal, wind, and solar, while fossil fuel sources include oil-based thermal, gas-run, and coal-fired plants. The generation technologies incorporated in this model corresponds to Kenya's current and planned future electricity generation technologies.

The base year's primary energy supply, transformation technologies, and future energy demand are from the government's LCPDP report (EPRA, 2018) and Kenya National Bureau of Statistics (KNBS) report (KNBS, 2019). The data for the GHG emission coefficients for fossil fuel technologies is from the IEA's database (IEA, 2020b), and GHG emissions for the renewable energy technologies are from different life-cycle emission assessment (LCA) research (Amponsah et al., 2014; NREL, 2012; NREL, 2020; Raadal et al., 2011; Singh et al., 2013). Even though LCA emissions for power plants are site-specific (Martínez Cámara et al., 2013), we use global average estimates in the current study since no research details LCA emission values for Kenya. Further, the LCA emission values exclude emissions related to mining, processing, and manufacturing of turbines and solar panels and their accessories because, currently, Kenya does not manufacture these components. For hydropower emission, we use emission value for the reservoir but exclude emissions from flooded land because, based on the existing hydro dams in Kenya, reservoir flooding is not a regular or an annual occurrence but largely depends on climatic conditions in a year (Maingi & Marsh, 2002). Fuel prices and techno-economic parameters for the transformation technologies are from the IEA-International Energy Agency (IEA, 2020b), IEA-International Energy Agency (IEA, 2020c), the U.S. Energy Information Administration database (U.S. EIA, 2020), and the LCPDP report (Lahmeyer International, 2016). Lastly, the techno-economic parameters for the existing power plants are from the Kenya Power and Lighting Company's internal report (KPLC, 2018) and the LCPDP report (Lahmeyer International, 2016). Before feeding the data into Kenya-TIMES, the data was analyzed and converted to the required units. See Table 3, Table 4 for the economic and technical parameters, respectively, as used in Kenya-TIMES.

Table 3: Costs for power generation technologies

Energy carriers	Capital Cost in Million USD/GW	Fixed Operation and Maintenance costs in Million USD/GW	Variable Operation and Maintenance cost in Million USD/PJ
Geothermal	3595	155.4	1
Hydro	3741	19.6	0.5
Oil	2032	32	10
Solar	1780	27.3	0
Coal	2542	75.39	(domestic coal) 3.5 (imported coal) 4.3
Gas	1083	25.2	13.5
Nuclear	8068	7.5	10
Wind	2132	76	0

Table 4: Utilization factors and % contribution to peak by the generation technologies

Technology	Acronym	Utilization factors	% contribution to peak
Geothermal	GEO	0.9	100
Hydropower	HYD	0.5	100
Oil	OIL	0.2	100
Solar	SOL	0.19	0
Coal	COA	0.85	100
Gas	GAS	0.75	100
Nuclear	NUC	0.85	100
Wind	WIN	0.36	20

The current study did not account for technology learning curves and their impact on future technology costs. Even though global trends show an overall decline in the cost of renewable energy technologies, there is significant variation by country and region (REN21, R.E.P.N, 2020). For instance, the development of solar PV markets requires different periods of learning before installed costs decline to efficient levels (IRENA, 2016). On the other hand, the grid-tied solar PV is in its very early stages of adoption in Kenya and Africa at large (IRENA, 2016). Therefore, the current study considered constant prices for all the technologies since there is no reliable data on the projected rate of adoption and the resulting cost reduction. There is a grid-expansion cost of 3505 USD per GW for every newly installed GW above the base year's installed capacity. The higher fixed operation and maintenance cost for geothermal relates to the high cost of drilling make-up wells. See Appendix A for detailed assumptions about the technical and economic parameters used.

3.3 Scenario development

The study evaluates the generation expansion pathways under BAU and CEC scenarios for the three demand levels, which are a sum of the demand plus a 15% peak reserve margin value, as presented in the LCPDP report (EPRA, 2018). Consequently, the analysis assesses the overall system cost, five-year period energy system costs, technology choices, installed capacity and energy production technology mix, GHG emissions, energy security, and unit electricity cost under the BAU and CEC generation expansion pathways.

3.3.1 The BAU (business as usual) scenario

The BAU scenario serves as a reference for comparing alternative pathways under the carbon emission cap (see Fig. 4). This scenario assumes that there are no policy interventions. The GHG emission results obtained in BAU are used as inputs to the CEC scenario.

3.3.2 The CEC (carbon emission cap) scenario

The introduction of a carbon emission cap aims to evaluate the evolution and cost of Kenya's energy system under GHG emissions constraints. The carbon emission cap is estimated based on the Nationally Determined Contribution (NDC) report (MoENR, 2017) set by Kenya as part of its commitment to meeting the Paris Agreement of capping atmospheric temperature at 2 °C above pre-industrial levels by 2050. It is noteworthy that the NDC report and its values are only used to set the percentage targets for this study. The NDC report emission projections were based on the 2016 government sectors' policies and development projections. As indicated in the report, these policies and development forecasts are revised from time to time, affecting the projected sectoral emissions. Therefore, the results obtained under the CEC scenario should not be interpreted as the absolute pathway but as a benchmark given the assumptions in the CEC scenario. According to the NDC report, out of the country's total projected emission of 200MTCO2eq by 2050, power generation under the vision demand scenario is expected to contribute 50MTCO2eq (MoENR, 2017). Since the NDC report calculates the total emission from all sectors up to 2050 but only stipulates the percentage emission reduction required from the sectors up to 2030, this study applies the 2030 percentage value, which is 45% (MoENR, 2017), to calculate the emission cut estimates expected from power generation by 2050. Therefore, power generation is expected to cut 22.5MTCO2eq of emission under the vision demand level by 2050. Critical to note is the difference between the actual and technical emission reduction potential (MoENR, 2017). The technical potential is the total emission reduction expected from a given sector, while actual emission reduction potential is the achievable reduction limit if all the feasible policies are effected.

The NDC report gives sectoral ranges of emissions — from low to high, based on actual reduction potential — along-which each sector can plan their emission reductions. For instance, the low and high target emission reduction for the power sector by 2030 is 5.2MTCO2eq and 9.3MTCO2eq, respectively. For a 9.3MTCO2eq emission cut to be achieved between 2020 — 2030, the current study applied an emission cap of 20% in 2025 and 25% in 2030. The sum of 20% of 22.5MTCO2eq in 2025 and 25% of 18MTCO2eq in 2030 is 9MTCO2eq, which closely matches the NDC power sector 2030 upper range value of 9.3MTCO2eq. The 2030 emission reduction target was 18MTCO2eq because the 20% emission cap applied in 2025 reduced the 22.5MTCO2eq by 4.5MTCO2eq.

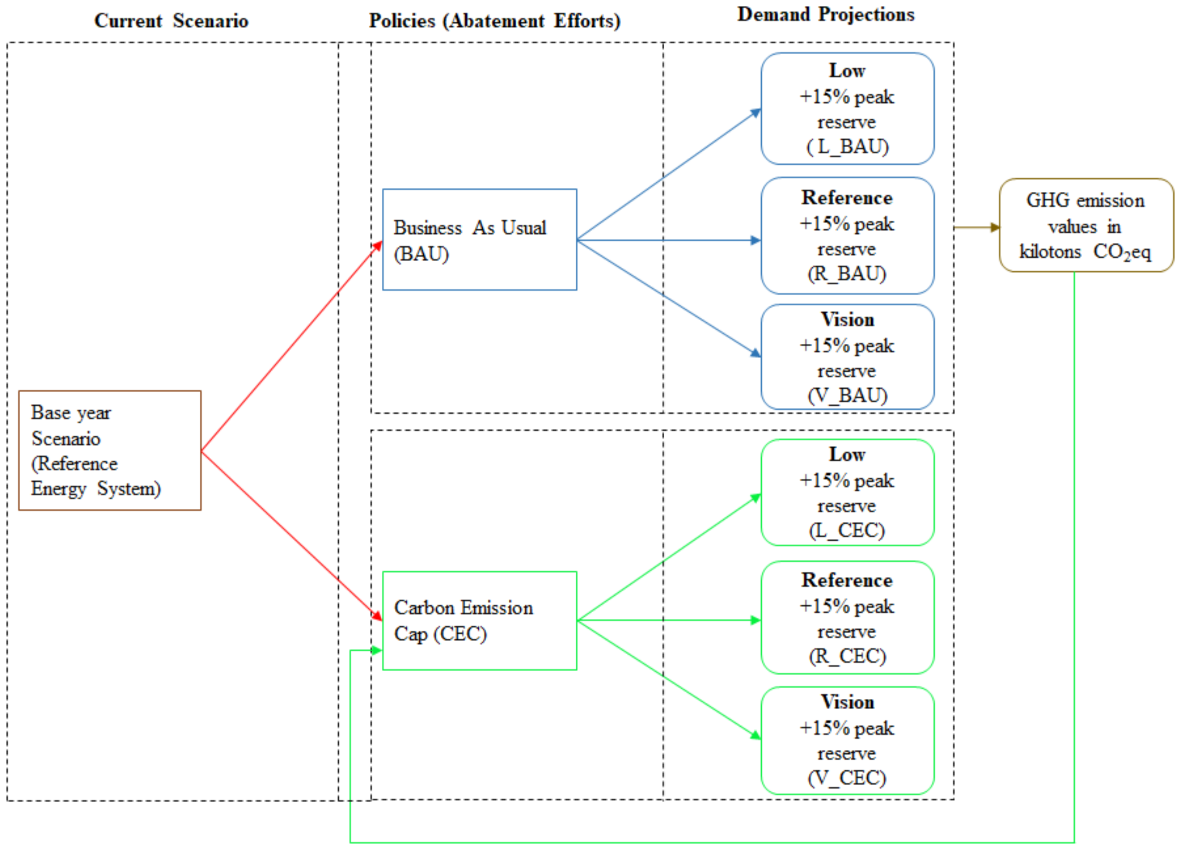

Figure 4: Scenario tree summarizing the Kenya-TIMES BAU and CEC scenario-building process.

Based on the 2025 and 2030 CO2eq emission cuts, the 2040 emission cap was set at 30%, which further decreased the 22.5MTCO2eq total emission reduction target by 4.05MTCO2eq. Even though these percentages are based on emission reduction targets related to the government's planned generation expansion technology mix derived using the vision demand scenario as indicated in the NDC report, they were applied across the three demand levels. This is because the NDC emission reduction target report assumes a high penetration of renewable technology under the vision compared to the low and reference demand levels. The researchers, therefore, assume that the same or even higher percentage emission reduction caps might be required under the low and reference demand levels. To run the CEC scenario, the BAU scenario was first optimized, and GHG emission values associated with the power sector were retrieved through the VEDA-BE. These emission values, expressed in kilotons CO2eq, were then used as inputs in the CEC scenario (see Fig. 4) and the percentage emission caps defined on them.

4. Results

This section presents Kenya-TIMES modeling outcomes for Kenya's power demand-supply expansion pathways under the BAU and CEC scenarios for the three projected demand levels for 25 years. The results are organized by technology choice, economic and environmental analyses.

4.1 The BAU (business as usual) scenario

4.1.1 Technology choice

The Kenya-TIMES model results show that the optimized mixture of installed capacity changes significantly beyond 2040, 2035, and 2030 under the low (L_BAU), reference (R_BAU), and vision (V_BAU), respectively, with the introduction of coal technology (see Fig. 5). Coal technology is selected after the 4 GW geothermal and 1.5 GW hydropower resource potentials are exhausted.

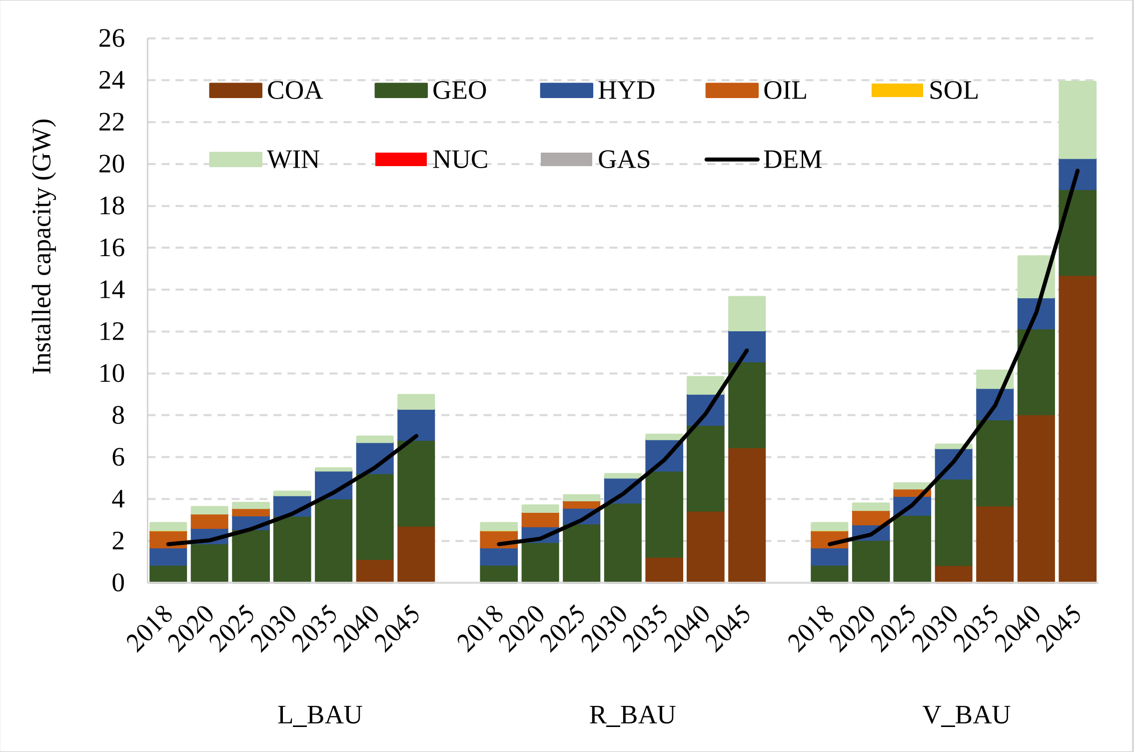

Fig. 5. Installed power capacity mix in GW with a line curve (DEM) showing the government's projected demand levels for the BAU scenario.

The cost of imported fossil fuels increases the variable cost of technologies that rely on imported fuel. The model chose the domestic coal supply for the selected coal-fired power plants, rejecting imported coal. Similarly, high gas prices and high capital costs associated with nuclear power plant construction made gas and nuclear technologies an unfavorable priority for the optimum generation technology mix under the BAU scenario. Overall, the total annual installed capacity was slightly higher than the projected demand (see Fig. 5) because, unlike the projected peak demand, the model results included a 15% reserve margin value.

Oil and solar power plants' installed capacity fell to zero after retiring existing oil-based and solar PV plants, whose economic lifetime was set to 10 and 20 years, respectively, starting in 2020. Solar PV has the least utilization factor among the technologies modeled in Kenya-TIMES. Further, solar PV's firm capacity during peak time in Kenya's energy system, which typically occurs in the evening after sunset, is zero. Therefore, solar becomes an unsuitable choice for additional capacity without storage or demand-side response policy interventions. The high oil prices and its low utilization factor also inhibit new oil-based power plants. In the case of wind power, its utilization factor — the third lowest after solar PV and oil-based power plants — and its 20% firm capacity during peak time made it less competitive than geothermal and hydropower technologies.

The percentage share of installed capacity for renewable sources is high for the entire modeling period under the L_BAU and R_BAU scenarios closing at 70% and 53%, respectively, in 2045. For the V_BAU, renewable share dominates the energy mix up to 2035, with a fall to 38% share in 2045 (see Fig. 6). The decrease in the percentage share of renewable sources with growing demand pertains to the exhaustion of the geothermal and hydro resource potentials.

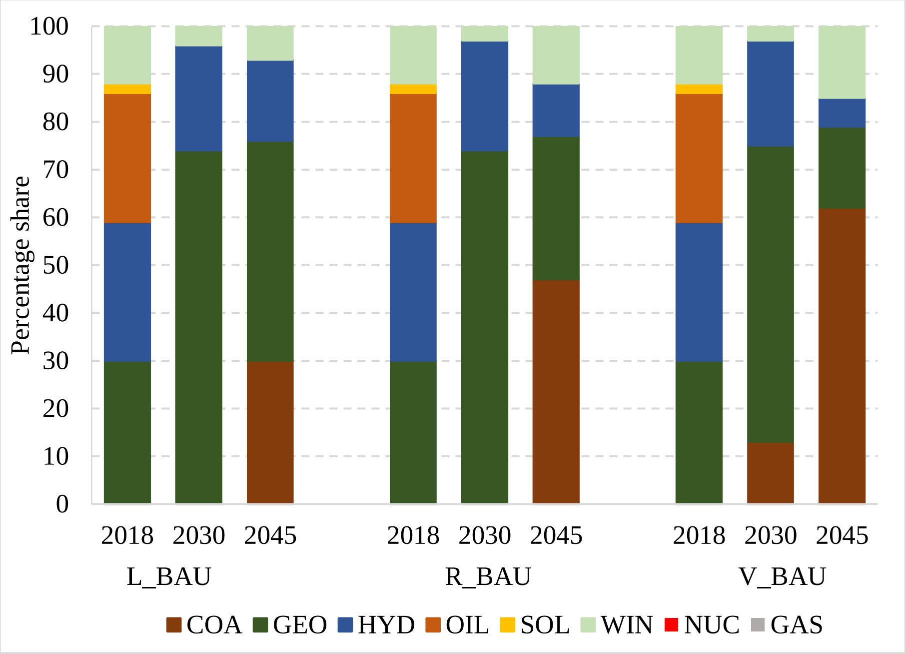

Figure 6: The percentage share of the installed capacity mix in 2018, 2030, and 2045 in the BAU scenario.

Renewable sources dominated the generated electricity for the entire modeling period in the L_BAU scenario. For the R_BAU and V_BAU scenarios, the generation technology mix changed significantly in 2045 and 2040, respectively, as shown in Fig. 7. These changes included the increasing dependency on coal-run power plants, with some additional contribution from wind generation.

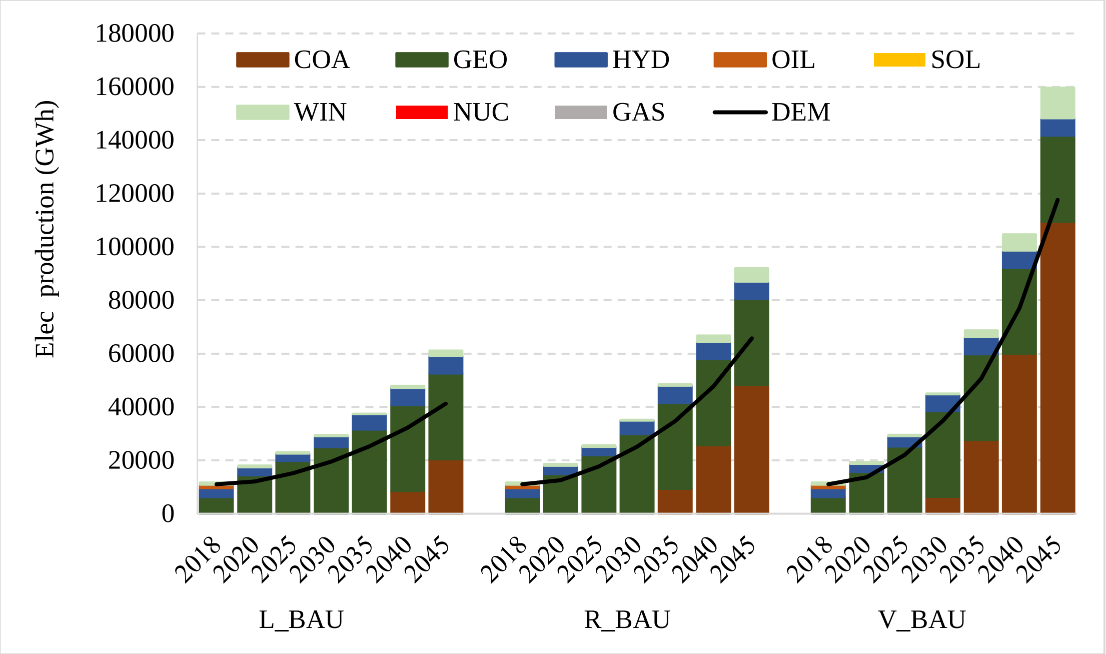

Figure 7: Electricity generation mix for the three demand levels in GWh with a line curve (DEM) denoting the government's projected energy demand levels.

4.1.2 Economic analysis

The economic analysis presents the total system cost, the five-year investment period breakdown of the total system cost, and the electricity production cost. The total system cost, which was the models' objective function, was discounted to the base year 2018 and presented in USD million based on the 2018 exchange rate. The total system cost accounted for the annual capital costs incurred for investing in and dismantling processes, fixed and variable annual operation and maintenance costs, annual costs incurred for exogenous imports, and revenues recuperated from embedded commodities during process dismantling, for example, during decommissioning of a power plant. The costs are summed over the modeling period, from which the salvage value of processes and embedded commodities existing at the end of the planning horizon are subtracted. The total system costs required by the Kenyan government to meet the low, reference, and vision demand levels under BAU were USD 40,466 million, USD 46,328 million, and USD 57,967 million, respectively.

The undiscounted five-year investment period breakdown for the total system cost is presented in Fig. 8. FIX is the sum of fixed operation and maintenance costs; INV is the sum of the capital costs; VAR is the sum of variable operations and maintenance costs. The high share of VAR for 2018, compared to 2020 to 2030 (see Fig. 8), was related to the high percentage of oil power plants in the energy generation mix that year, hence the inclusion of fuel cost. From 2020, the model stopped generating electricity from oil-ran power plants. Accordingly, the increased percentage mix of renewable energy technologies reduced VAR costs from 2020 to 2030.

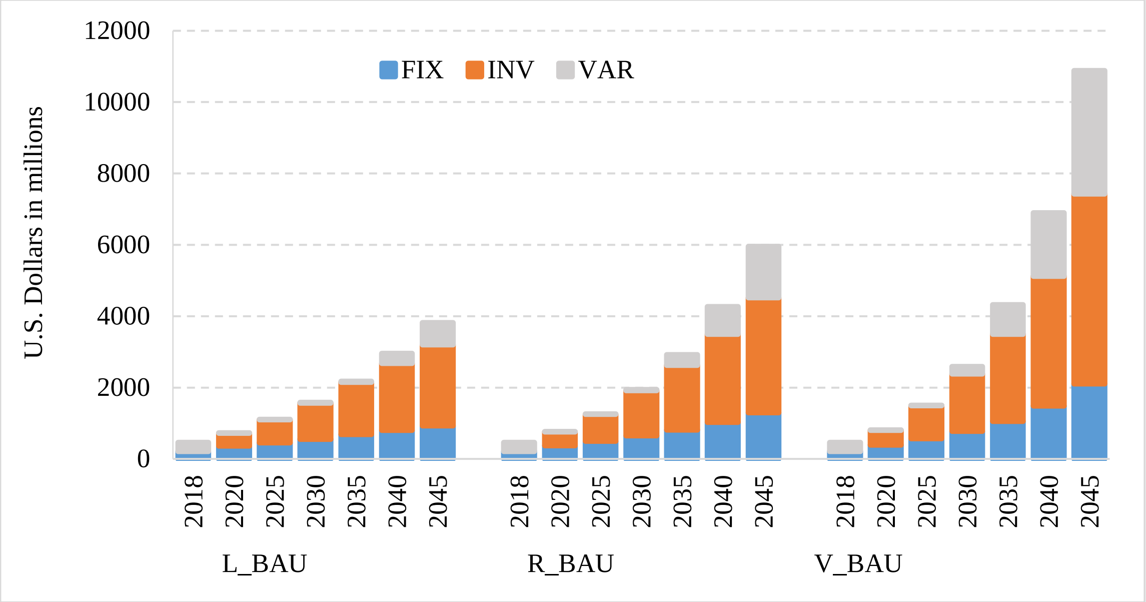

Fig. 8. The undiscounted five-year investment period breakdown for the total system cost concerning each of the three demand levels under the BAU scenario.

Critical to note is the steady increase of VAR beginning 2040, 2035, and 2030 for the L_BAU, R_BAU, and V_BAU, respectively, coincide with the rise in the share of coal capacity. The increase in VAR relates to production costs for primary coal. Overall, there was an increase in VAR, INV, and FIX from the L_BAU, R_BAU, to V_BAU scenarios, respectively. As the model increased the installed and generated capacity to meet growing demand, the cost increases were bound to occur.

The total minimum cost incurred to generate one unit of electricity for the grid — excluding government taxes levied on electricity — is the electricity production cost. At 8.34 US cents/kWh, the production cost was relatively higher in 2020 because of the installed capacity mix, which included a significant percentage share of oil and wind carried forth from the base year (see Table 5).

Table 5. Average unit electricity production cost in US Cents/kWh under the BAU scenario.

	2020	2025	2030	2035	2040	2045
L_BAU	8.34	6.83	7.06	7.02	8.07	7.89
R_BAU	8.34	6.83	7.06	7.85	7.85	7.89
V_BAU	8.34	6.83	8.49	8.11	8.21	8.39

With geothermal dominating the installed and generated electricity share in 2025, the cost fell to its lowest point across the three demand levels before steadily increasing with the addition of new hydropower, wind, and coal, respectively.

4.1.3 Environmental analysis

The environmental analysis in Kenya-TIMES considered the GHG emission expressed in kilotons CO2eq. The GHG evaluated in Kenya-TIMES included CO2, CH4, and N2O emission estimates for all power technologies defined under the RES. The effect of technological change on GHG emission was significant across the modeling period in all three demand levels (see Fig. 9). At each demand level, electricity generation from oil-based power plants fell to zero by the end of 2018, and coal-fired production began in 2030, 2035, and 2040 for V_BAU, R_BAU, and L_BAU, respectively. With no power generated from the oil-based power plants after 2018, the GHG emission levels, mainly from renewable sources, remain low until 2025. However, since coal is a highly polluting fuel with higher CO2, CH4, and N2O emission factors, increasing coal-fired power plants' contribution increased GHG emissions significantly starting in 2030.

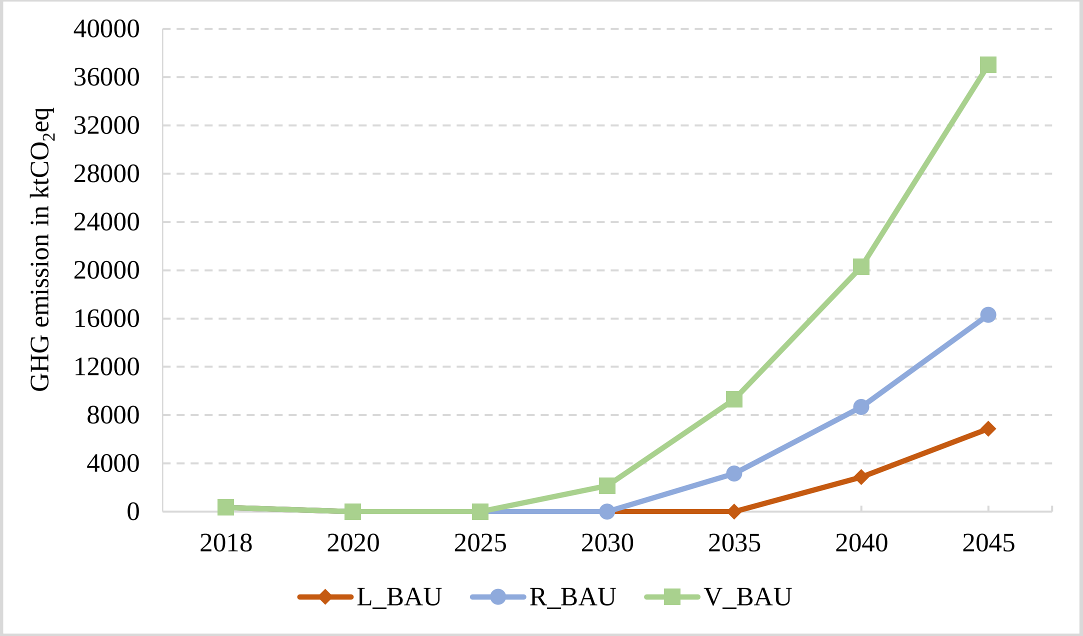

Fig. 9. GHG emission (in ktCO$_2$eq) under BAU across the three demand levels from the base year to the end of the modeling period in Kenya-TIMES.

4.2 The CEC (carbon emission cap) scenario

The CEC scenario evaluated the impact of abatement efforts guided by the Kenyan government's NDC targets on the energy system. This section discusses the technology choices and economic analysis of the CEC scenario for the low (L_CEC), reference (R_CEC), and vision (V_CEC) demand levels.

4.2.1 Technology choices

Under the CEC scenario, the model adopted more renewable technologies with wind capacity and nuclear technology, replacing part of the coal-fired capacity seen in the BAU scenario (see Fig. 10). In 2025, the energy mix was dominated by renewable sources. Therefore, when the first carbon emission cap was defined in 2025, it inhibited the adoption of geothermal, preferring wind technology, which has a lower LCA value than geothermal. Once the emission cut targets were achieved, the model reverted to the cheaper geothermal option and increased its installed capacity to its maximum potential in 2030, 2035, and 2040 for the L_CEC, R_CEC, and V_CEC, respectively.

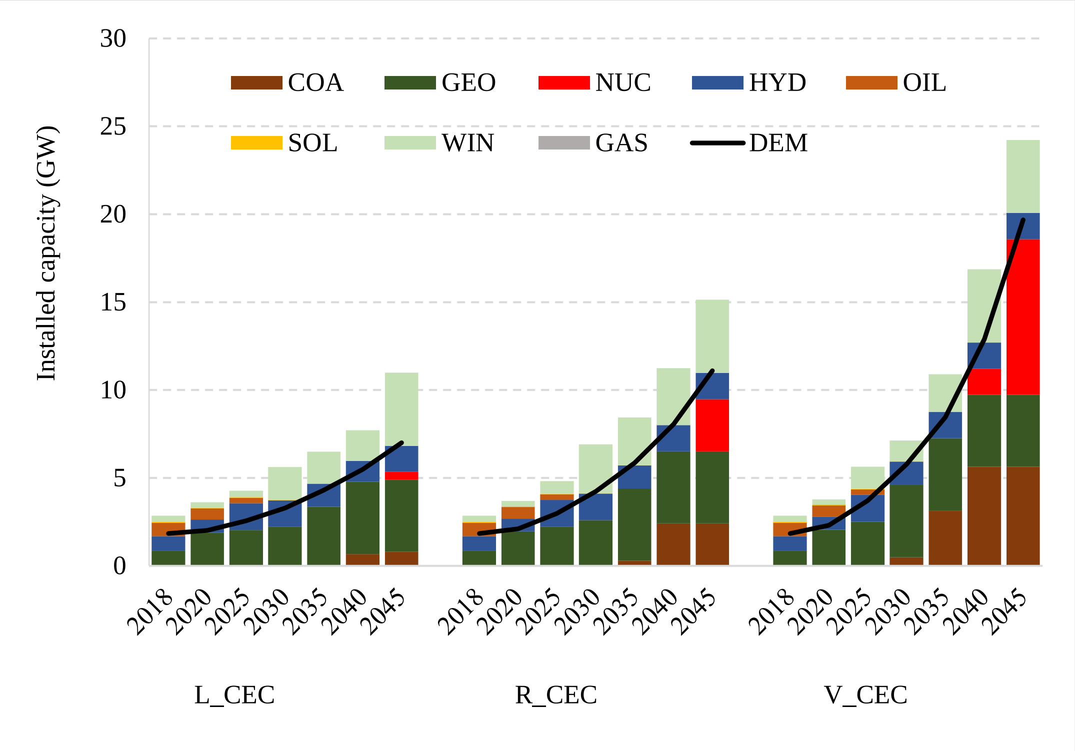

Fig. 10. Installed power capacity mix in GW with a line curve (DEM) denoting the government's projected capacity demand levels.

Electricity production was more or less proportional to the installed capacity for geothermal, coal, and nuclear across the modeling horizon for the three demand levels (see Fig. 11). Wind technology had a lower percentage share in the generated electricity than its percentage share in installed capacity due to its variability; thus, it had a low percentage of firm capacity and low utilization factor. Overall, renewable sources dominate energy production, which generates 90%, 80%, and 68% of consumed electricity for the low, reference, and vision demand levels, respectively, in 2045.

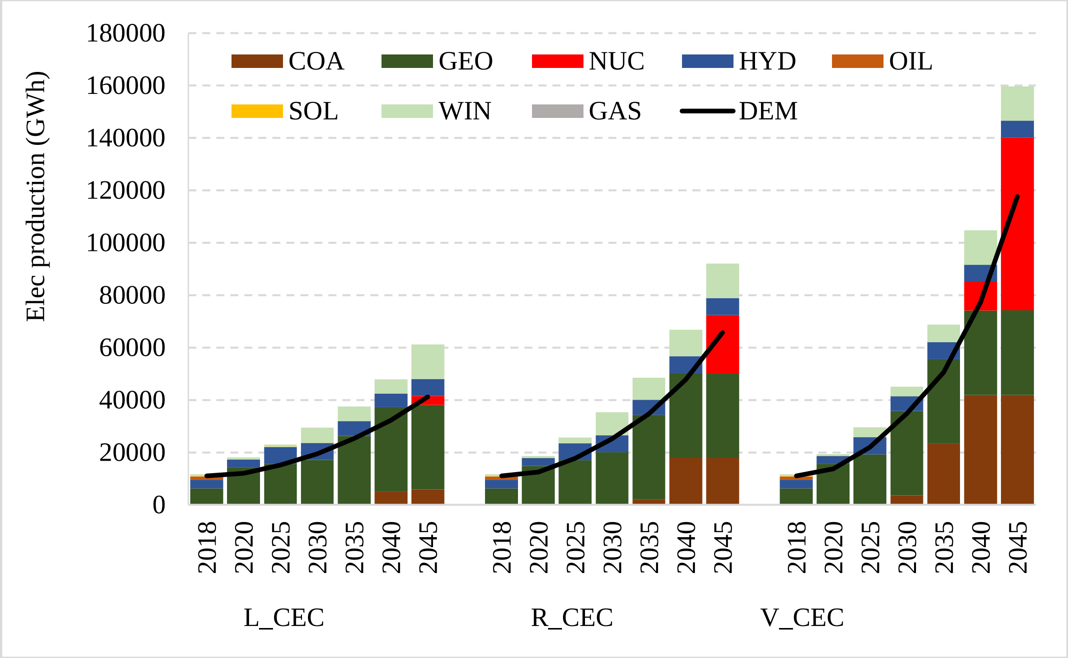

Fig. 11. Electricity production mix for the three demand levels in GWh with a line curve (DEM) showing the government's projected energy demand levels.

4.2.2 Economic analysis

The total system cost is presented in USD million value based on the 2018 exchange rate. The costs for the CEC scenario under the L_CEC, R_CEC, and V_CEC were USD 41,442 million, USD 48,157 million, and USD 61,325 million, respectively. These costs denoted a 2%, 4%, and 6% increase from the L_BAU, R_BAU, and V_BAU, respectively. The increased share of wind and nuclear technologies and fewer coal-fired plants caused the rise in the system cost under the CEC scenario. The higher capital cost and fixed operation and maintenance costs associated with nuclear and wind, respectively, increased the INV and FIX under CEC compared to the BAU scenario (see Fig. 12). In contrast, wind technology's zero variable operation and maintenance cost resulted in a low VAR cost under CEC compared to the BAU scenario (see Fig. 12).

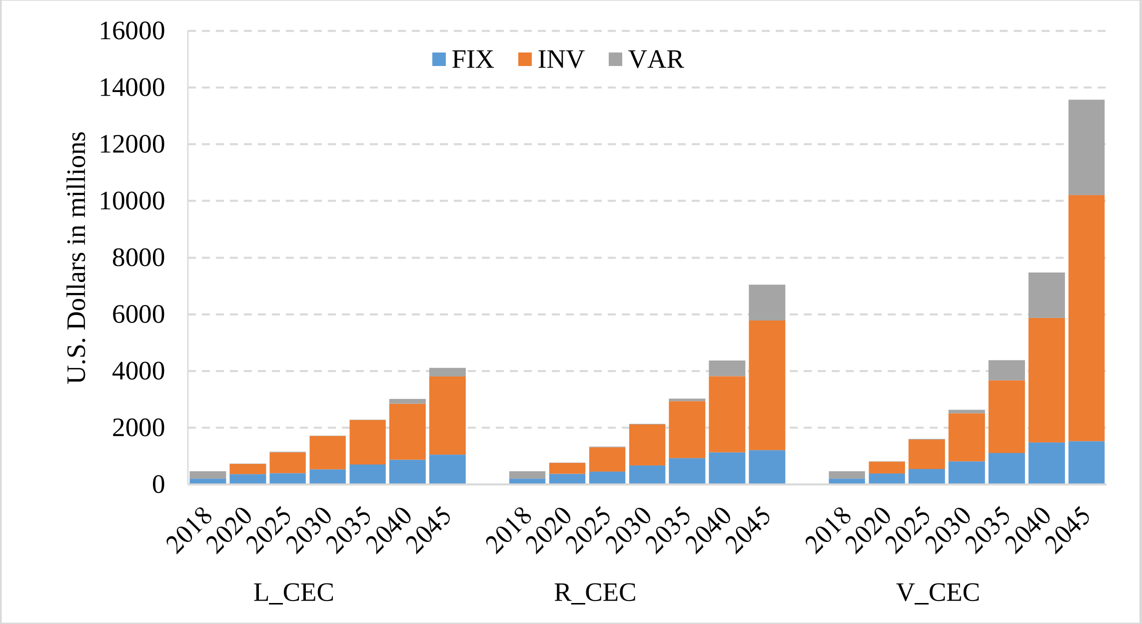

Fig. 12. The undiscounted five-year investment period breakdown for the total system cost concerning the three demand levels under the CEC scenario.

Similarly, the higher share of nuclear and wind technologies resulted in a higher unit electricity production cost in the CEC scenario than in the BAU scenario (Table 6). The production cost changed with the introduction of emission caps starting in 2025. For instance, the high cost of production observed in 2025 and 2030 in the L_CEC scenario relates to an increase in the share of wind in the energy mix. With the introduction of the emission cap, the model only developed 2.03 GW of geothermal and met the remaining demand with new wind capacity. The reverting to the cheaper geothermal after attaining the set emission target was reflected in the drop in unit electricity production cost in 2035 and 2040 compared to 2025 and 2030. The higher production costs in 2040 and 2045, compared to 2035, were due to the installation of nuclear and extra wind capacity after exhaustion of geothermal and hydro potential.

Table 6. The unit electricity production cost in US Cents/kWh under the CEC scenario.

	2020	2025	2030	2035	2040	2045
L_CEC	8.34	11.01	15.46	7.29	8.36	14.14
R_CEC	8.34	11.01	13.10	8.36	10.09	14.14
V_CEC	8.34	12.79	8.36	10.09	14.03	14.14

5. Discussion

Overall, the Kenya-TIMES results show that energy security can be achieved for Kenya's energy system for the three demand levels, with 100% of primary energy carriers being supplied from domestic sources under the BAU scenario. However, to meet the three levels of demand beyond 2030 under BAU, the government will need to fast-track the development of domestically-supplied coal-run power plants. As seen under the vision demand level, Kenya’s energy system will not meet its 2030 or 2050 NDC GHGs emission reduction targets without any emission abatement policies. For instance, GHG emissions under the vision demand in BAU is 38MTCO2eq in 2045. This value already exceeds the 27.5MTCO2eq of the allowable emission level in 2050, as calculated under the CEC scenario. The low GHG emissions and unit electricity production costs witnessed in the initial years in BAU when the generation mix is dominated by geothermal and hydropower technologies — before increasing generation from coal and wind in the later years — indicate that geothermal and hydro technologies have the potential to provide comparatively affordable energy while mitigating GHG emissions. Therefore, to concurrently address unit electricity production cost and GHG emission reduction while meeting demand in the short- to medium-term, the Kenyan government will need to fast-track the exploration and exploitation of potential geothermal prospects and potential hydropower resources.

However, the Kenyan government can meet the NDC emission reduction targets by enacting policies that will facilitate investment in renewable energy, as demonstrated under the CEC scenario. The CEC scenario still achieves energy security with only 4%, 20%, and 36% of generated energy in the low, reference, and vision demand, respectively, generated from imported nuclear primary energy carriers in 2045. The CEC scenario comes with extra costs associated with nuclear and wind technologies. However, in an energy system already dominated by renewable energy technologies like the Kenyan one, the introduction of the CEC does not significantly affect the technology choices; thus, the overall system cost. These technology mix dynamics explain the small increase of 2%, 4%, and 6% in the total system cost seen in the low, reference, and vision demand levels under the CEC compared to the BAU scenarios. Increased share of wind capacity under CEC increases the amount of installed capacity starting in 2025 compared to BAU (see Fig. 13). Wind power is non-dispatchable and has a low utilization factor. Consequently, the excess wind capacity in the current model leads to overcapacity without storage. In a country where power sales are based on long-term power purchasing agreements (PPAs) contracts, overcapacity might increase consumer unit electricity prices. Hence, the Kenyan government should consider re-evaluating scheduled wind power development projects in the short- to medium-term.

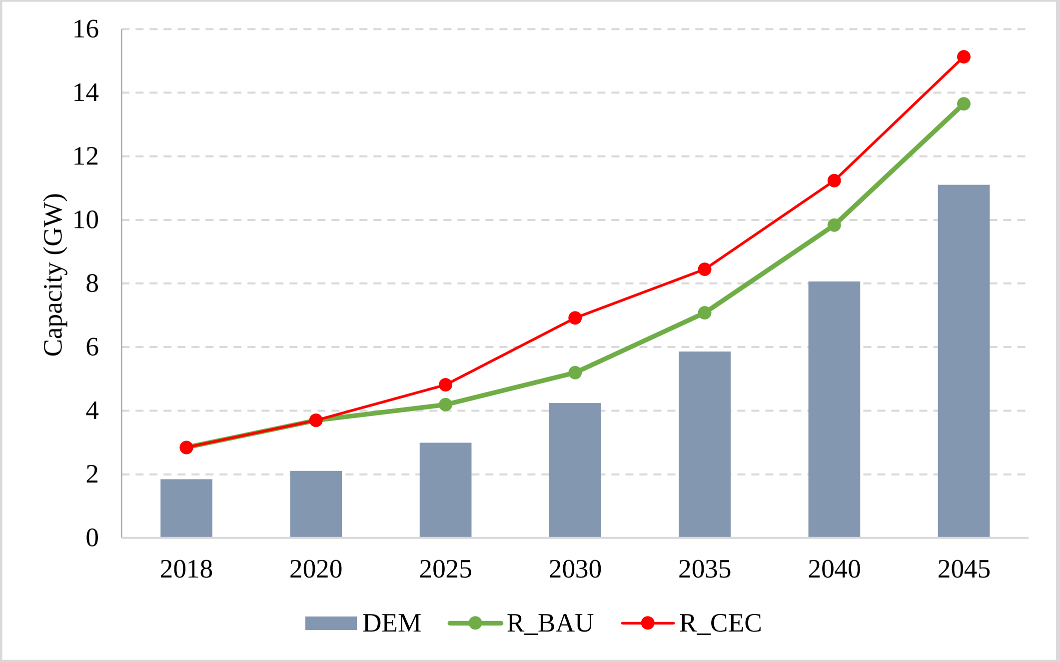

Fig. 13. A comparison between the government's projected demand level and the installed capacities in the BAU and CEC scenarios for the reference demand level (DEM).

A comparison of total GHG emissions in ton CO2eq per GWh between the BAU and CEC scenarios suggests the significance of carbon caps in abating emission for Kenya (Fig. 14). Without a carbon cap, the emission per GWh steadily grew with the increase in power consumption across the modeling period under the BAU scenario. Moreover, the selection of coal-fired power plants resulted in a steep rise in GHG emissions per GWh in 2030, 2035, and 2040 for the V_BAU, R_BAU, and L_BAU scenarios, respectively. The increase in the share of renewable technology in the energy consumption mix under CEC led to a steady decline in the GHGs emissions GWh from 2040 towards 2045. To meet its NDC emission reduction targets, therefore, the government should fast-track the enactment of energy policies on renewable and storage technologies that will foster the uptake of renewable energy.

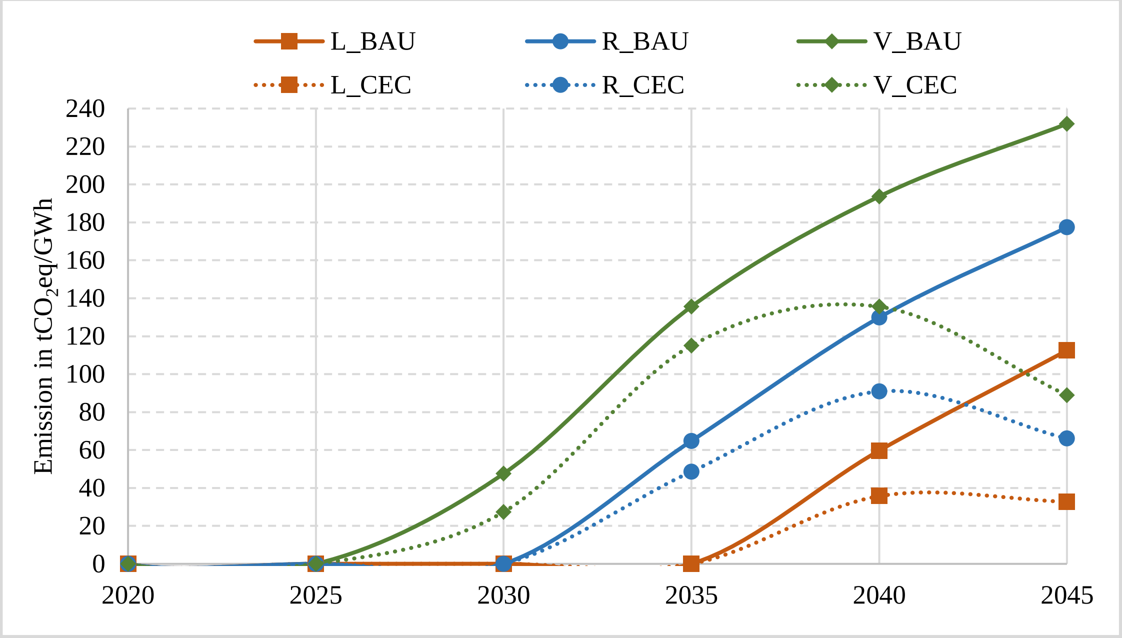

Fig. 14. A comparison of the GHG emission in tCO$_2$eq per GWh consumed for the three demand levels in BAU and CEC scenarios.

A comparison between the LIPS-OP and LIPS-XP (Lahmeyer International, 2016), SWITCH-Kenya (Carvallo et al., 2017), and the Kenya-TIMES models' results (see Table 7) for capacity and energy in 2035 in the business as usual case shows some consistency but also varies as a result of the different assumptions and constraints. Kenya-TIMES used projected demand levels presented in EPRA, 2018. The demand value in EPRA, 2018 were forecasted using the LIPS-OP and LIPS-XP model developed in Lahmeyer International (2016) by updating demand growth parameters used therein. Hence, the small difference between the Kenya-TIMES and LIPS-OP and LIPS-XP capacity and energy values compared to SWITCH-Kenya (Table 7), which simulated its generation expansion using demand values derived from a coarse estimate of demand projections.

Table 7. A comparison of installed and generated energy results for Kenya-TIMES, SWITCH-Kenya, and the LIPS-OP LIPS-XP models in 2035.

Technology	**Capacity (MW)**			**Energy (GWh)**		
	LIPS-OP&LIP-XP(2035)	SWITCH-Kenya (2035)	Kenya-TIMES (2035)	LIPS-OP&LIPS-XP(2035)	SWITCH-Kenya (2035)	Kenya-TIMES (2035)
Coal	981	0	1,250	1,533	0	9,291
Geothermal	3,082	7,953	4,100	23,194	65,387	32,278
Hydro	1,759	792	1,490	5,688	3,457	6,500
Oil	0	4,087	0	0	1,067	0
Wind	1,140	6,071	210	4,337	29,132	575
Solar	250	0	10	430	0	12
Natural Gas	0	5,860	0	0	12,108	0
Nuclear	0	n/a	0	0	n/a	0
Imports	400	n/a	n/a	2,678	n/a	n/a
Storage	n/a	n/a	n/a	n/a	n/a	n/a
Cogeneration	200	n/a	n/a	876	n/a	n/a
Generic backup	1,610	n/a	n/a	157	n/a	n/a

All three models prioritize geothermal technology. LIPS-OP and LIPS-XP, and Kenya-TIMES models select hydropower as the second-most economical technology. Wind power is the dominant variable resource adopted in the three models. However, Kenya-TIMES prioritizes coal technology adoption over the wind, unlike the other two models. In Kenya-TIMES, the firm capacity for wind during peak demand — set at 20% — makes it an unfavorable choice compared to coal technology. The high share of wind capacity in SWITCH-Kenya relates to the storage option available in the model. Neither Kenya-TIMES nor SWITCH-Kenya harnesses solar PV. The capacity for solar in Kenya-TIMES is the remnant of the installed capacity in the base year. The absence of nuclear, gas, and oil-based generators is common in the LIPS-OP and LIPS-XP, and Kenya-TIMES models.

Under the abatement policies' simulation, we compare the ZeroCO2 emission's target scenario by 2035 simulated by SWITCH-Kenya and the CEC scenario simulated by the Kenya-TIMES model. There is no energy generated from gas-fired and diesel-based plants in both Kenya-TIMES and SWITCH-Kenya models in 2035 (see Table 8). Geothermal is the primary source of consumed energy for both models. Wind technology makes 32% and 37% of the total installed capacity in Kenya-TIMES and SWITCH-Kenya, respectively. However, wind technology only contributes 18% of the total consumed energy in Kenya-TIMES while contributing 33% in SWITCH-Kenya. The inclusion of storage technology under the SWITCH-Kenya model reduces idle capacity from wind power plants, thus enhancing wind energy consumption.

Table 8. A comparison of installed and generated energy results for Kenya-TIMES and SWITCH-Kenya models in 2035.

Technology	Capacity (MW)			Energy (GWh)		
	LIPS-OP&LIP-XP(2035)	SWITCH-Kenya (2035)	Kenya-TIMES (2035)	LIPS-OP&LIPS-XP(2035)	SWITCH-Kenya (2035)	Kenya-TIMES (2035)
Coal	981	0	1,250	1,533	0	9,291
Geothermal	3,082	7,953	4,100	23,194	65,387	32,278
Hydro	1,759	792	1,490	5,688	3,457	6,500
Oil	0	4,087	0	0	1,067	0
Wind	1,140	6,071	210	4,337	29,132	575
Solar	250	0	10	430	0	12
Natural Gas	0	5,860	0	0	12,108	0
Nuclear	0	n/a	0	0	n/a	0
Imports	400	n/a	n/a	2,678	n/a	n/a
Storage	n/a	n/a	n/a	n/a	n/a	n/a
Cogeneration	200	n/a	n/a	876	n/a	n/a
Generic backup	1,610	n/a	n/a	157	n/a	n/a

Several shortcomings that arise from simplifications of the model, inadequate data, uncertainties, and the structure of the Kenya-TIMES modeling platform can be addressed in future research. Among them are accounting for the impacts of drawdown and climate change on geothermal and hydropower resources, respectively. Furthermore, there is a need to evaluate the role of storage in addressing GHG emissions reduction, the impact of short-term constraints, for example, the variability of renewable sources, unit commitment, hourly load curve, and ramp rates on the long-term power planning. The inclusion of storage in future work will further provide a clear perspective of the role of utility-scale solar PV adoption in meeting grid-supplied demand.

Additionally, a study with a finer representation of the intra-country transmission expansion costs and power trade between Kenya and the neighboring countries will give a more reliable transmission expansion cost. In Kenya, solar power is a widely adopted off-grid solution through the home solar system. An integrated model comprising both grid and decentralized generation would provide a clear view of the role of off-grid supply in meeting Kenya's energy demand. A comprehensive and regularly updated demand-supply data and emission reduction targets' for Kenya's energy sector should be developed and made available to researchers and stakeholders. A centralized energy planning department, with energy statisticians, scientists, and engineers trained in energy modeling and simulation, should be established within the Ministry of Energy and Petroleum.

6. Conclusion

This study developed the Kenya-TIMES, a national scale, bottom-up energy optimization model. Here, the model has been used to assess the implication of greenhouse gas (GHG) emission reduction targets on the techno-economic parameters of Kenya's energy system for the three government's projected power demand levels and made recommendations on how this reduction can be achieved. Kenya's NDC guides the emission reduction targets. This study is the first of its kind in which the TIMES platform is used to assess Kenya's energy system. Kenya-TIMES results provide insights into the technology choices, GHG emissions, energy security, and economic implications under two scenarios: the BAU scenario with no active emissions reduction targets and the CEC scenario, which includes emissions reduction targets.

The results suggest that energy security can be achieved under both scenarios. The percentage share of the renewable energy mix is more than 50% for all the demand levels in both scenarios, except the vision demand in the BAU scenario. Under the BAU scenario, the energy system cannot meet its reduction targets while satisfying demand. The CEC scenario shows that the emission reduction targets can be achieved by setting a carbon emission cap. However, this will increase system and unit production costs as it favors the adoption of comparatively more expensive renewable generation technologies. Moreover, the higher level of variable sources in the energy mix under the CEC scenario results in overcapacity, consequently increasing system cost and unit electricity cost.

However, overcapacity could be addressed by government interventions that promote the uptake of storage technology. Kenya-TIMES results indicate that the best-suited technologies to meet Kenya's future power demand, while concurrently limiting GHG emissions in short- to medium-term, are dispatchable renewable energy technologies such as geothermal and hydropower.

The current analysis shows that research and policy tools, such as the Kenya-TIMES model, should be considered for future energy planning, management, and policymaking. The findings and recommendations of this study can help improve energy accessibility at an optimum cost while limiting GHG emissions, guiding the Kenyan economy towards a future with a sustainable energy supply.

Declaration of competing interest

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

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Appendix A

Table A.1: Evaluation and assumptions made concerning primary energy supply and associated costs

Energy carriers	Capital Cost in Million USD/ GW	Fixed Operation and Maintenance costs in Million USD/ GW	Variable Operation and Maintenance cost in Million USD/ PJ	Evaluation/Assumptions
Geo	3595	155.4	1	Only 4 GW out of the 8 GW mentioned in EPRA (2018) was considered because so far, only four out of the 23 geothermal prospects that host the 8 GW have been explored to the exploration drilling stage. As per the Lahmeyer International (2016) report, the capital cost presented includes the cost for exploration, drilling, and operating geothermal units, including make-up wells. The cost is based on conventional technology.
Hydro	3741	19.6	0.5	The 1.5 GW resource potential considered is as presented in EPRA (2018). This is the estimated undeveloped hydroelectric potential of economic value. The cost of hydropower is based on the assumption that dam hydropower will be the only technology used to harness the existing hydro resources. EPRA (2018) does not divide the resource potential between the run-off-the river and dam hydropower. This separation can later be incorporated into the model once the data is available.
Oil	2032	32	10	We did not present a choice for domestic oil, considering that its exploration is still at the appraisal stage. Oil was, therefore, imported. The unit price of 7.67 USD/GJ, as presented in Lahmeyer International (2016), was used. We do not take into account the oil price volatility risks.
Solar	1780	27.3	0	The analysis only considered solar PV potential because the Concentrated Solar Power technology has yet to enter the Kenyan market. Moreover, the scope of this study was limited to grid-connected generation. So far, it‘s only solar PV that the government of Kenya has incorporated in

				grid generation expansion plans. The costs adopted in the current study are for commercial solar PV.
Coal	2542	75.39	3.5 (domestic) 4.6 (imported)	The model considered both imported and domestic coal supply. It was assumed that 70% of the 400 million tons of the recently discovered domestic coal resources would be used for power generation. It is noteworthy that the 70% chosen value does not relate to any empirical studies. The adopted unit price of coal of 2.94 million USD/PJ for domestic coal and 3.26 million USD/GJ of imported coal was from the Lahmeyer International (2016) report.
Gas	1083	25.2	13.5	Kenya has no domestic gas supply; hence, the model only had the import option. The unit price of gas of 12.7 USD/GJ was from Lahmeyer International (2016). The adopted costs are for Gas Turbine (GT) running on Liquefied Natural Gas.
Nuclear	8068	7.5	10	Kenya has no domestic supply of nuclear resources; hence, the model only had the import option at a unit price of 2.94 USD/GJ (Lahmeyer International, 2016).
Wind	2132	76	0	The current study only considers on-grid wind technology. A 4.2 GW resource potential was considered.

Table A.2: Assumptions made about conversion technologies' technical parameters

Technology	Utilization factors	% contribution to peak	Evaluation/Assumptions
Geothermal	0.9	100	All the capacity factors were as presented in Lahmeyer International (2016). Percentage contribution to the peak was derived from the firm capacity (Lahmeyer International, 2016). Kenya experiences 8 hours of solar intensity, i.e., from 8 am to 4 pm. On the other hand, the demand curve for Kenya indicates peak hours from 6 pm to 10 pm. Hence, solar has no contribution to the peak, considering that storage is not part of the current scope of the study. On the other hand, the wind has a 20% peak-hour firm capacity.

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4. Paper 3

Evaluation of low carbon development strategies for power generation expansion in Sub-Saharan Africa: the case of Kenya

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Abstract

Globally, energy production and consumption represent by far the largest source of greenhouse gas (GHG) emissions from human activities. Energy demand in Sub-Saharan Africa is projected to grow significantly due to its growing population. The Sub-Saharan African governments face the challenge of providing affordable energy for their increasing populations while limiting GHG emissions. Kenya is one of the Sub-Saharan Africa countries whose population growth and ambitious sustainable economic growth plans will significantly increase its energy demand. Using the optimization-based bottom-up Kenya-TIMES model, this study evaluates the impact of low-carbon development strategies on Kenya's power generation expansion required for the planned economic growth. The effect on the generation technology mix, greenhouse gas (GHG) emissions in relation to the nationally determined contribution (NDC) reduction target, and system costs are assessed using five scenarios for the 2020 to 2050 period. The five scenarios include the business as usual scenario and four other low-carbon scenarios in which policy instruments are used to reduce emissions, including a carbon tax, renewable portfolio standards, renewable energy subsidies, and a hybrid of renewable energy subsidy and carbon tax. The model results show that the generation technology mix is predominantly geothermal, wind, and hydropower from 2020 to 2035 in all the scenarios. Except for the renewable subsidy scenario, all the low-carbon scenarios achieve the NDC emission cut targets in 2050. The carbon tax and renewable portfolio standard have higher system costs than the business as usual scenario, while the renewable energy subsidy and hybrid scenarios have lower total system costs. The model results indicate that advanced optimization-based energy planning tools could be more efficient in guiding energy planning decisions to achieve low-carbon pathways and sustainable energy access in the Sub-Saharan Africa countries.

Keywords: Kenya; low-carbon; generation expansion; policy instruments, nationally determined contribution; greenhouse gas emissions.

1. Introduction

Globally, energy production and consumption represent by far the largest source of greenhouse gas (GHG) emissions from human activities (1). The burning of coal, natural gas, and oil for electricity and heat accounts for 25% of total emissions, the highest single source of global GHG emissions (2). Governments, mainly in high-income countries, have aligned their energy strategies to achieve low-carbon power development pathways to reduce the GHG emissions associated with heat and electricity generation. The strategies include economic incentives, such as environmental taxes, subsidies, feed-in-tariffs, and command and control policies such as renewable portfolio standards (RPS) and energy efficiency standards (3). These strategies aim to achieve the Nationally Determined Contributions (NDC) GHG emission reduction targets agreed upon under the Paris Agreement (4).

The projected growth in energy demand in the Sub-Saharan African (SSA) countries resulting from their projected rapid population growth (5), economic development, and accelerated urbanization (6) has the potential to increase GHG emissions significantly if not well planned. The SSA governments face the challenge of providing affordable energy for their population's current demand-supply deficit and future demand while limiting GHG emissions (7). Adopting and implementing efficient and effective strategies to cut energy-related GHG emissions while maintaining affordability and satisfying the energy needs in the SSA countries is critical for future global energy sustainability (8).

Advanced and refined energy planning tools are ideal for evaluating the potential strategies that can be used to reach national energy-related GHG emission reduction objectives (9). The feasibility of low-carbon power demand-supply expansion strategies can be assessed by models developed using bottom-up energy optimization planning tools, for example, in (10), (11), (12), (13), (14), (15), and (16). These models can evaluate policy instruments such as subsidies on energy technologies, efficiency standards, carbon tax, carbon emission caps, and renewable portfolio standards on power generation expansion and their feasibility regarding the country of focus. The bottom-up optimization models are prioritized in this case over the top-down simulation models because of their high level of conversion technologies' detail (17) and ability to derive optimal solutions (e.g., energy system costs) for energy systems under predefined policy constraints (18). They select the least-cost mix of technologies for the evaluated pathways.

Contrary to the high-income economies, the SSA countries have not sufficiently utilized energy planning tools to inform their national low-carbon power development strategies (19). The energy decisions are often political, and energy models are either not used, flawed, or non-transparent. Some countries, e.g., Kenya, use top-down simulation models for their national energy decision-making (12), (16), (20). In other instances, the scenario-based models used in decision-making often rely more on assumptions and political targets than on being data-driven (21). The lack of efficient planning using advanced energy planning tools is manifested in the never-ending energy poverty. The SSA countries should develop and adopt national-scale bottom-up energy optimization-based models using advanced energy planning tools to guide their low-carbon development energy decisions. The models should be data-driven, and the assumptions should reflect each country's local conditions (19).

In this paper, we use an optimization-based bottom-up energy planning tool to explore the low-carbon development strategies for power generation expansion in the SSA region through a case study of Kenya. As one of the fastest-growing economies in the SSA region (21), Kenya's energy demand is projected to increase from 11,700 GWh in 2019 to 91,400 GWh in 2045 (12). So far, out of the total grid-connected installed power capacity of 2,846 MW in December 2020, 73% was from renewable sources comprising 826 MW from hydro, 865 MW from geothermal, 336 MW from wind, and 50 MW from solar resources. The installed thermal capacity, generated using heavy fuel oil, gasoil, and kerosene (22), was 769 MW and accounted for 27%. The off-grid installed capacity in 2020 was 76 MW and consisted of solar, wind, and diesel generation. The estimated consumption from stand-alone home solar was 10 GWh in 2020. Overall, electricity access from both grid and off-grid supply was 75% in 2018 (23).

Through its NDC objectives, Kenya has committed to cut the 19.4 $MtCO_2e$ of the 2030 projected baseline electricity-related GHG emissions by at least 5.2 $MtCO_2e$ (4), (24). To achieve this target, the switching off the Independent Power Producer's (IPP's) oil-based power generators is part of the government's gradual phase-out plan of the fossil fuel-based generators. A task force report, however, indicated that retiring the plants before the expiry of their Power Purchase Agreements (PPAs) would be costly for the government compared to paying a capacity charge for the idle generators (25) (26). Moreover, despite the plan to phase out the oil-based generators in short to medium term, Kenya plans to meet its long-term electricity demand using both renewable and fossil fuel sources (20). The government has also enacted strategies to increase the share of renewable electricity in the power mix (20) with the short-term goal of a 100% renewable generation by 2022 (23). Yet, the current energy system status indicates that meeting electricity demand by 100% supply from renewable sources by 2022 is highly infeasible. Previously, Kenya also granted subsidies through tax exemptions on imported "specialized solar and wind equipment" to accelerate the uptake of renewable energy (27). However, because of the government's revenue reduction resulting from the effects of Covid-19, the government removed this exemption in July 2020 (27).

The definition of these strategies and targets and the use, or lack of use, of policy instruments has not been adequately supported by energy planning tools (12). To achieve a sustainable, reliable, affordable, and modern electricity supply defined under Sustainable Development Goal number 7 (28) and meet its NDC objectives, the Kenyan government needs to use advanced energy planning tools to carry out efficient and effective energy planning.

Some researchers have assessed a few low-carbon policy instruments' implications on Kenya's energy system. Longa and van der Zwaan (28) used the TIAM-ECN (TIMES Integrated Assessment Model-Energy Research Center), a version of the established TIAM global energy model developed by the International Energy Agency-Energy Technology Systems Analysis Program (IEA-ETSAP), to analyze Kenya's GHG mitigation ambitions from an entire energy system perspective. They evaluate mitigation measures on energy-related emissions in a holistic approach, combining transport, agriculture, industry, and power sectors. The study uses the reference scenario, two carbon cap scenarios with emission reduction targets set at 20% and 30% in 2050, respectively, and a carbon tax with the carbon price increasing from 50 USD/tCO_2e in 2020 to 162 USD/tCO_2e in 2050. Carvallo et al. used Solar and Wind energy Integrated with Transmission and Conventional sources (SWITCH-Kenya) to explore sustainable growth paths for power systems in emerging economies through a case study of Kenya's power system (16). Among other scenarios, the study evaluates two climate policy scenarios. The first scenario evaluates a carbon tax of 10 USD/ton and 30 USD/ton of CO_2. The second scenario assesses the impact of zero-emission policy by 2030 through a carbon cap.

However, the mentioned studies only evaluate the impact of two policy instruments ─ carbon cap and carbon tax ─ on power demand-supply expansion future. Longa and van der Zwaan

(28) assess the carbon cap and carbon tax policy instruments on the entire energy system. Consequently, the model does not provide a detailed evaluation of their impact on the power sector in solitude, which is projected to have the highest emissions in 2050, as presented in Luna et al. (24). Further, the exclusion of domestic coal supply denies the model the choice of a relatively cheaper energy source. This exclusion might result in the model prioritizing a less polluting fuel source contrary to what it would have selected if the more affordable domestic coal supply option were present. Thus, the model might give underestimated GHG emissions compared to emissions from a practical demand-supply generation situation. Lastly, the power demand forecast used in the studies is an estimate that significantly vary from the government's forecasted power demand.

The current study uses an optimization-based energy planning tool to assess low-carbon policy instruments for Kenya's power generation expansion. In studies linked to this research, a review of the SSA's existing national-scale energy system models was done (19). The results indicated that using advanced energy planning tools would be vital in informing efficient energy decisions to achieve universal energy access while limiting GHG emissions by countries in the SSA region. It was recommended that the SSA countries develop data-driven national scale energy optimization models. The models should be based on the same framework, should be replicable but with the ability to be adjusted to each country's local energy system assumptions. The output from such models can then be used to develop a regional model.

As a result, a national scale bottom-up energy system optimization model for Kenya ─ the Kenya-TIMES (12) ─ was developed using the Integrated MARKAL-EFOM System-VEDA (TIMES-VEDA) framework. The Kenya-TIMES model was used to evaluate grid-supplied generation-expansion pathways for three government-forecasted demand levels under the business as usual scenario and carbon emission cap scenario based on Kenya's NDC's GHG emission reduction targets (12). The model results indicated that to meet the NDC's GHG emission reduction targets under the Vision demand level, the Kenyan government needs to enact and implement policies that will accelerate the uptake of renewable energy technologies and limit GHG emission in the long term.

Therefore, the current study aims to assess the implication of three low-carbon policy instruments on Kenya's power generation expansion using a bottom-up energy optimization-based planning tool ─ the Kenya-TIMES. The exogenous demand projection for the government's Vision demand level (12) is used, and the analysis covers the 2020 to 2050 period. The policy instruments considered include the carbon tax, renewable portfolio standards, and renewable subsidies. The objective is to evaluate the impact of these policy instruments on Kenya's power generation expansion regarding generation technology mix, GHG emission, and the energy system cost and inform the nation's low-carbon development strategy. Consequently, five scenarios are analyzed, one using the business as usual assumptions, and each of the four using a different policy instrument or a combination of more than one. The themes evaluated under the five scenarios include the installed capacity and power generation technologies' adoption, the GHG emission levels compared to the projected baseline emissions and the NDC reduction targets, the total power system, capital and operational costs, and the marginal electricity prices. The evaluation informs the implication of the policy instruments on these themes.

The current analysis uses an advanced version of the recently developed Kenya-TIMES model (12). The advancement includes twelve-time slices, technology learning curves, peaking reserve constraint, and time-slice-related capacity factors for the intermittent sources. Apart from introducing an advanced version of the Kenya-TIMES model, the novelty of this study lies in the fact that it is the first to evaluate and compare the three policy instruments using one energy model and the same assumptions. The study evaluates up to 2050, uses the most current government's forecasted electricity demand growth for Kenya and the energy sector's most recent data and future assumptions. Furthermore, it is the first to analyze the impact of an energy subsidy, mainly targeting solar and wind, on Kenya's power sector. Lastly, it is the first to run a hybrid of renewable subsidy and carbon tax scenarios for Kenya's power sector, where the revenue accrued from the carbon tax is used as a subsidy for renewable uptake. The study further illustrates the importance of using optimization-based bottom-up energy planning tools to guide the SSA's strategic low-carbon power expansion pathways. This analysis can be replicated in other SSA countries using the same modeling framework but adopting local assumptions. In the rest of the paper, Section 2 covers Kenya's current GHG emissions, Section 3 presents the methodology, and Section 4 presents results, while discussion and conclusion are presented in Sections 5 and 6, respectively.

2. GHG Emissions in Kenya

To join in the global effort in mitigating GHG emissions and their resultant impacts, the Government of Kenya ratified the United Nations Framework Convention on Climate Change (UNFCCC) in 1994 (29). Although Kenya has relatively insignificant GHG emissions compared to the average global emission per country, it is highly vulnerable to climate change (29).

2.1 Sectoral GHG emissions

Kenya's Second National Communication (SNC) to the UNFCCC presents an inventory of national GHG emissions from 2010 to 2050 (24). The SNC projects the total emissions to increase by 286% from 2010 to 2050 (see Figure 1).

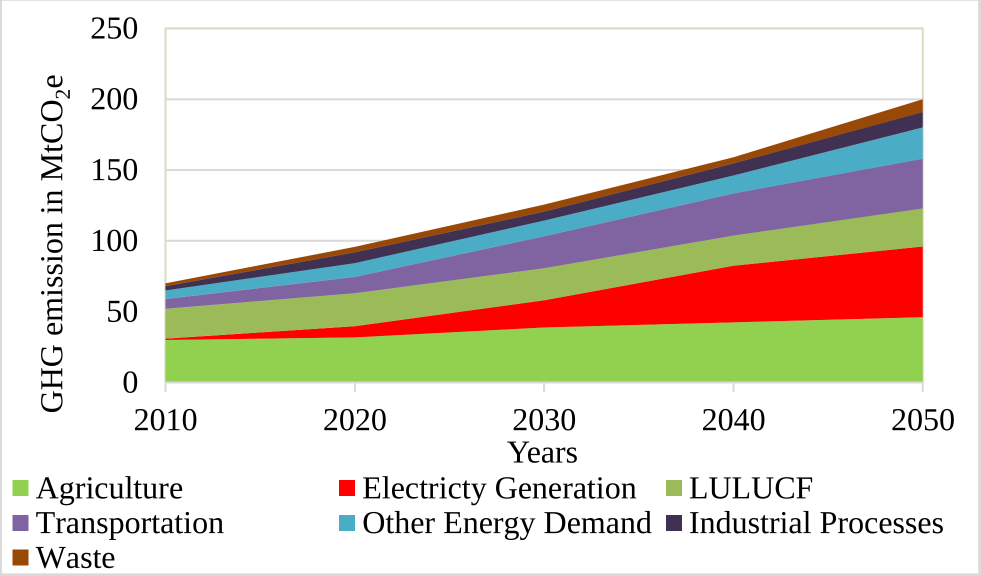

Figure 4: Sectoral GHG emission projections for the seven sectors in Kenya (data was derived from (24), and the authors did the analysis).

The electricity sector's emission grows from 7 $MtCO_2e$ in 2010 to 50 $MtCO_2e$ in 2050, constituting the highest growth (714%) among all sectors. The growth, mainly related to the projected increase in power demand and generation from fossil fuel, is driven by the rapid economic and population growth envisaged under the Vision 2030 blueprint (28). It is critical to note that there is high uncertainty in the emission projections, especially concerning the development of emission-intensive industries (30).

2.2 Reduction potential of sectoral emissions

Despite the uncertainties in the projected GHG emissions, Kenya has committed to cutting down its overall emissions by 30% in 2030 relative to the projected 2030 baseline emissions shown in Figure 2. The assessment of the emission reduction potential from each of the six emission sectors forms the basis for the 30% overall emission cut target. All seven sectors have set a reduction target, and the agencies and ministries responsible for each sector must support and implement the sector's emission cuts. Sectoral reduction potentials are derived using the Intergovernmental Panel on Climate Change (IPCC) guidelines (24). Instead of having a fixed emission cut target for each sector, the NDC strategy proposes a range from low to high targets. The high target is achievable with full implementation of emission abatement policies, while the low target accounts for medium-level implementation of abatement policies. For instance, the projected 2030 electricity generation sector's baseline emission is 19.4 $MtCO_2e$. The reduction target range from 5.2 $MtCO_2e$ to 9.3 $MtCO_2e$, which equals 27-48% reduction, respectively.

Currently, the Kenyan government does not have emission reduction targets beyond 2030. The 2030 emission reduction target from power sector-related emission is 30%. Accordingly, we set the reduction target at 30% for all the time periods from 2030 to 2050 and use it as an objective for GHG emission reduction in the current study. It is critical to note that no empirical reference is available to select the percentage reduction target beyond 2030.

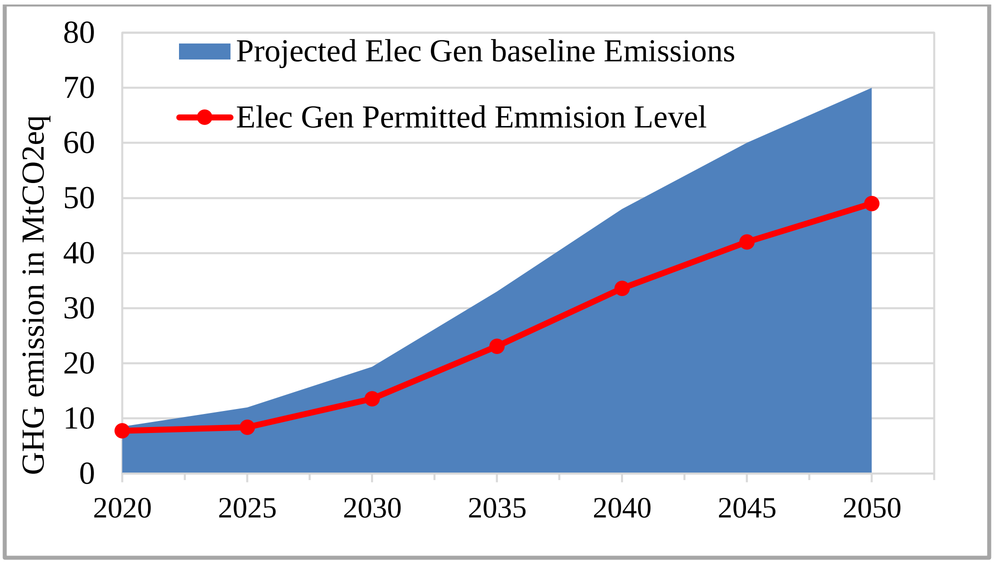

Figure 5: The projected GHG emissions from the electricity sector and a line depicting the maximum permitted emission level based on a 30% reduction target.

3. Methodology

The study develops and applies a quantitative energy system-planning tool, the Kenya-TIMES model, fed by actual data collected from the energy sector in Kenya, literature reviews, and expertise predictions where actual data is not available. The Kenya-TIMES model is a single region integrated energy-environmental-economic system optimization model developed in the TIMES modeling framework. The methodology uses scenario analysis to appraise low-carbon policy instruments and Kenya's future demand-supply power generation expansion.

The study seeks to answer the following questions: How do the low-carbon policy instruments affect the evolution of the installed capacity and power generation's technology mix, the GHG emissions and the total cost of the energy system, capital and operations costs, and the marginal electricity prices? Kenya-TIMES model development is an ongoing process. The model description presented in this study mainly refers to the first version (12). Therefore, the description of the methodology will be concise.

3.1 Modeling approach

Kenya-TIMES is built in the TIMES partial equilibrium energy modeling framework. TIMES is a technology-rich, bottom-up model generator that uses linear programming to produce a least-cost energy system over a medium to long-term time horizon, optimized according to an objective and a set of user constraints (31). TIMES can be used to model the evolution of an energy system or a sector within an energy system in a single community, province, country, region, or the entire globe, in a unilateral, bilateral, or multilateral approach (32). The TIMES framework comprises an objective function and constraints, expressed using parameters and decision variables. Parameters are exogenous inputs and include technology cost, efficiency, availability factors, end-use energy demand, primary energy supply curves, a general discounting factor, and policy instruments. Decision variables are endogenously generated model outputs. The main decision variables are new technology capacity and technology activity level. From these main decision variables, the model generates the total cost of the system discounted to net present value, marginal energy prices, and GHG emissions decision variables. In the following model equations, all parameters are written with lowercase letters while all variables with uppercase (capital) letters. The sets and indices used in the model are:

- y for any running year in the modeling period such that $y \in Y$, where Y is the set of all the years in the modeling period
- t for any given 5-year time interval such that $t \in T$, where the set T contains all the 5-year time intervals
- s for any given time-slice such that $s \in S$, where the set S contains all the time-slices
- p for any technology or process that consumes or generates energy, e.g., demand device or energy generation technologies such that $p \in P$, where P is the set of all the processes or technologies in the model
- c for any commodity, e.g., energy carriers such as coal, such that c is a subset of a commodity group set CG
- d for end-use energy services, e.g., lighting, cooking, and heating, such that $d \in D$, where the set D contains all the end-use energy services
- i for the form of energy, e.g., primary energy (energy from coal, diesel, etc.) such that $i \in I$, where I is the set of all the forms of energy
- x for any pollutant resulting from the construction and operation, and maintenance of a power plant such that $x \in X$, where the set I contains all the types of pollutants

Further, since Kenya's inter-day electricity demand variation is insignificant, each running year was divided into four physical quarters called seasons. A typical 24 hour demand day in each of the four quarters was selected, and its demand was divided into the following time-slices: day (D) from 7 am to 6 pm, night (N) from 10 pm to 7 am, and peak (P) from 6 pm to 10 pm. Consequently, twelve annual time slices are considered (see Figure 3). A twelve annual time slice approach presents a detailed accounting of the day, night, and peak capacity factors for wind and solar technologies, hence an efficient representation of the level of utilization of these intermittent sources in Kenya's power generation. Figure 4 presents the average daily load curve and average daily solar radiation showing the variation between the maximum solar radiation and peak demand within a day.

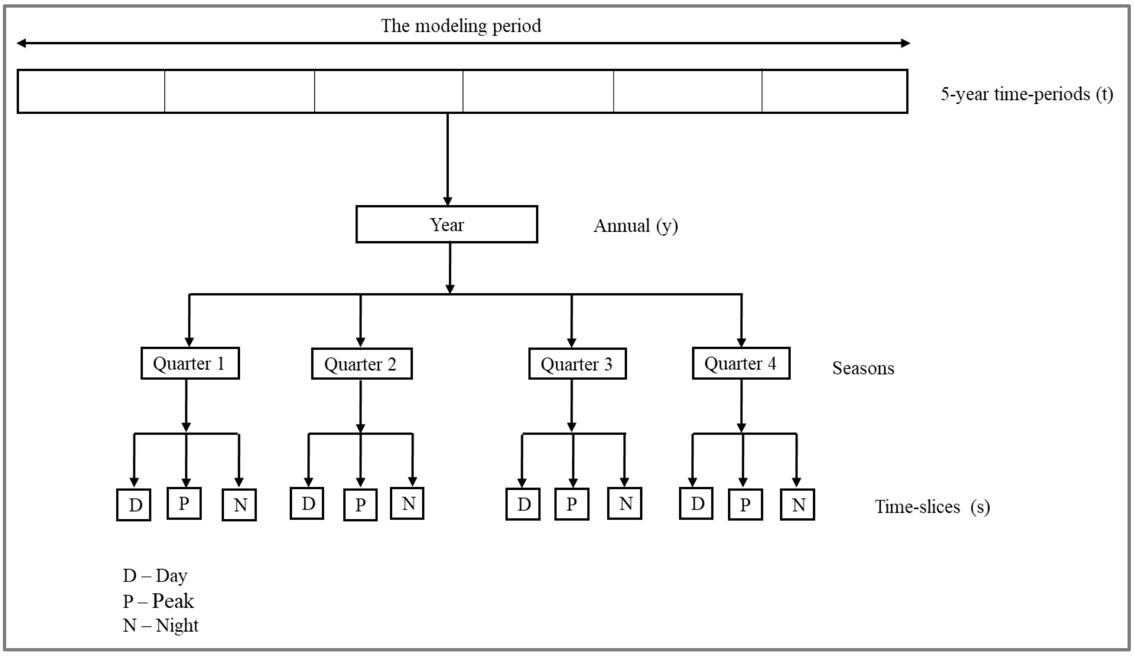

Figure 6: Time slice division for the model.

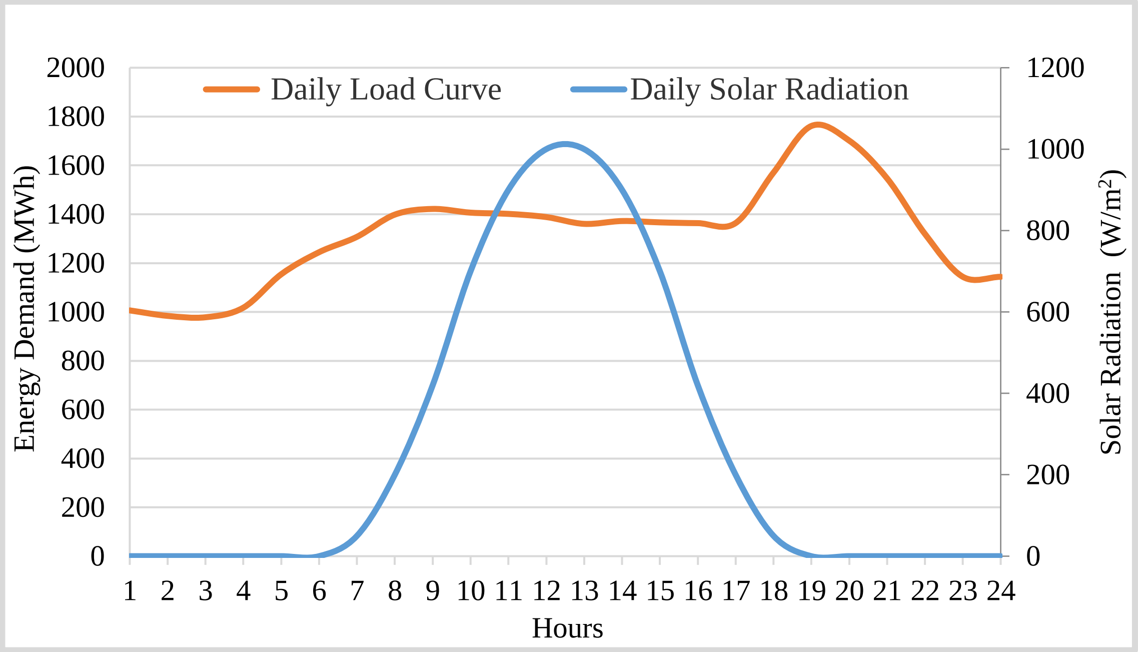

Figure 7: The average daily solar radiation profile and the average daily load curve for Kenya (Data for solar radiation adapted from (50)).

3.1.1 The objective function

The objective function minimizes the total cost of the whole system for the planning period for a single region with all the cost elements discounted to the base year. The system cost includes primary energy delivery, energy transformations, operation and maintenance, and transmission and distribution costs. The TIMES objective function is:

$$\text{MIN OBJ} = \sum_{y \in Y} [DISC(y) * [INVCOST(y) + FIXCOST(y) + VARCOST(y) + ELASTCOST(y) + IMPCOST(y) + EMCOST(y) - EXPREV(y) - SALVAGE]] \qquad (1)$$

where OBJ is the total system cost, covering all the years in the modeling period and discounted to the base year, the *DISC(y)* is the value of a unit dollar payment made in a year *y* for all the years in the modeling period, and discounted to the base year using the general discounting factor parameter entered in the model, *INVCOST(y)* is the investment (capital) cost, and the associated tax and subsidies, and decommissioning capital cost in a year *y*, *FIXCOST(y)* is the fixed annual operational and maintenance cost and its taxes and subsidies in a year *y*, *VARCOST(y)* is the variable operation and maintenance costs and their taxes and subsidies in a year *y*, *ELASTCOST(y)* is the cost incurred as a result of a reduction in demand in a year *y*, *IMPCOST(y)* is the cost of importing primary energy supply in a year *y*, *EMCOST(y)* is the emission cost if the user specifies an emission tax per ton of emission in a year *y*, *EXPREV(y)* is the export revenue earned from exporting energy in a year *y*, *SALVAGE* is the residual monetary value of all the investment made in the modeling period that is remaining at the end of the modeling horizon (33). Subsidy values are subtracted from the cost in cases where they are applied.

3.1.2 Constraints

Constraints are defined by several equations, which must be satisfied by the model when minimizing the total system costs. The main constraint formulations were adopted from (31), (33), and (34) and include:

Demand satisfaction

For all the demand – including transmission and distribution losses – for end-use energy service *d* at any given time-slice *s*, the total available activity of technologies *p* providing energy for the energy service demand *d* must satisfy the demand through the following equation:

$$\sum_{p\in P} ACT_{p,s} \geq dem_{d,s} \quad \forall\, s \in \mathrm{S}, d \in \mathrm{D} \tag{2}$$

where $dem_{d,s}$ is the (exogenously provided) gross demand for end-use energy service *d*, at time *s* that should be met by energy from the sum of activity level $ACT_{p,s}$ of technology *p* at time *s*.

Capacity utilization

For each technology *p*, activity (e.g., power generation) should not exceed the installed capacity at any time *s*:

$$ACT_{p,s} \leq cf_{p,s} \cdot CAP_{p,s} \quad \forall\, p \in \mathrm{P}, s \in \mathrm{S} \tag{3}$$

where $cf_{p,s}$ is the capacity factor (exogenously provided) of technology *p* and at time *s*, and $CAP_{p,s}$ is the total installed capacity of technology *p* at time *s*.

Capacity transfer

For a given technology *p*, the total available capacity of *p* at time-period *t* must be equal to the sum of capacity investments made by the model in the past and current time-periods, and whose technical life has not yet ended, plus the capacity in place at the base year that is still available. The constraint is expressed as follows:

$$CAP_{p,t} = \sum_{t=0}^{t} NCAP_{p,t} + residCAP_{p,t} \quad \forall\, p \in \mathrm{P}, t \in \mathrm{T} \tag{4}$$

where $NCAP_{p,t}$ is the new capacity additions made by the model for technology *p* in the past and current time-periods t; $residCAP_{p,t}$ is the exogenously provided capacity of technology p due to investments that were made before the model period and still exist at time-period t.

Commodity balance equation

For a consistent flow of each energy form, consumption (including exports) must not exceed availability, which includes domestic production and imports:

$$\sum_{p\in P} inp_{p,i} \cdot ACT_{p,s} + EXP_{i,s} \leq \sum_{p\in P} out_{p,i} \cdot ACT_{p,s} + IMP_{i,s} \quad \forall\, i \in \mathrm{I}, s \in \mathrm{S} \quad (5)$$

where i is the form of energy in the model; $inp_{p,i}$ is the amount of energy i consumed by one unit of activity $ACT_{p,s}$ (e.g., petajoules of coal consumed to produce 1MWh) of technology p at time s summed over p; $EXP_{i,s}$ is the amount of energy of the form i exported in time s; $out_{p,i}$ is the amount of energy form i produced by a unit of activity $ACT_{p,s}$ (e.g., petajoules of coal production per hour from the mining process) of technology p and summed over p; $IMP_{i,s}$ is the imported energy in the form of i at time s.

Emission constraints

Emission constraints can be defined by an emission cap or an emission tax. When applied as an emission cap, the emission cap is defined on the overall emissions of certain pollutants in a given year or time period or cumulative over the whole planning horizon. The emission cap limit is expressed as follows:

$$ENV_{x,y} \leq env_{limt_{x,y}} \quad \forall\, x \in \mathrm{X}, y \in \mathrm{Y} \quad (6)$$

where $env\_limt_{x,y}$ is the upper limit set by the user on total emissions of pollutant x in year y and $ENV_{x,y}$ is total emissions of pollutant x, in year y, and;

$$ENV_{x,y} = \sum_{p\in P}[emINV_{x,p,y} \cdot INV_{p,y} + emCAP_{x,p,y} \cdot CAP_{p,y} + emACT_{x,p,y} \cdot ACT_{p,y}] \quad \forall\, x \in X, y \in Y \quad (7)$$

where p is the technology type, y is the running year, and x is the type of pollutant, and $emINV_{x,p,y}$ is the emission coefficient of a pollutant x corresponding to the construction of the new investment $INV_{p,y}$ in technology p in year y; $emCAP_{x,p,y}$ is the emission coefficient of pollutant x in year y, linked to the unit capacity $CAP_{p,y}$ of technology p; $emACT_{x,p,y}$ is the emission coefficient of pollutant x in year y, related to the activity $ACT_{\mathrm{p,y}}$ of technology p. The user can also define an emission tax instead of an emission limit constraint, formulated as follows, and added to the objective function:

$$\sum_{y\in Y} \sum_{x\in X} ENV_{x,y} \cdot\ Etax_{x,y} \quad (8)$$

where $Etax_{x,t}$ is the emission tax coefficient (exogenously provided) on pollutant x in year y.

Other constraints

Other constraints, for instance, the discrete investment, capacity growth rate, renewable portfolio standards, renewable energy subsidies, and peaking reserve can be built by the modeler. Discrete investment constraint is an equality constraint that restricts investments in chosen technologies to specific discrete sizes. Capacity growth rate specifies that the market share of a particular technology or group of technologies cannot exceed a user-defined fraction.

The renewable portfolio standards specify that a defined minimum percentage share of electricity supply must come from designated renewable energy technologies at a stipulated time-period. While, the subsidy constraint specifies that for every new investment in a specified renewable technology, the unit investment cost must be reduced by a percentage determined by the user.

The peaking reserve constraint specifies that the total available capacity of all technologies producing a commodity (e.g., electricity) at each time-slice must exceed the peak demand for the commodity in the time-slice where peaking occurs by a certain percentage. The peaking reserve constraint is expressed as follows:

$$\sum_{p\in P} CAP_{p,c,s} \cdot CAP\_PKCNT_{p,c,s} \geq dem_{c,s} + PKRSV_{c,s} \cdot dem_{c,s} \qquad \forall\, s \in \mathrm{S}, c \in \mathrm{CG} \tag{9}$$

where $CAP_{p,s}$ is the installed capacity of technology p, producing a commodity c (in this case, electricity) during peak demand time s; $CAP\_PKCNT_{p,s}$ specifies the fraction of technology p's capacity (defined by the user) that contributes to the peak load for commodity c in time s; $dem_{c,s}$ is the peak demand capacity for commodity c produced by a technology p at time s; $PKRSV_{c,s}$ is the percentage peak reserve factor defined by the user for commodity c at time s.

3.2 The Kenya-TIMES Reference Energy System

The reference energy system used in the earlier developed Kenya-TIMES (12) is retained in the current study, with a few updates on the input data. The main components of the reference energy system include primary energy supply, conversion technologies, and the energy demand sector (see Figure 5).

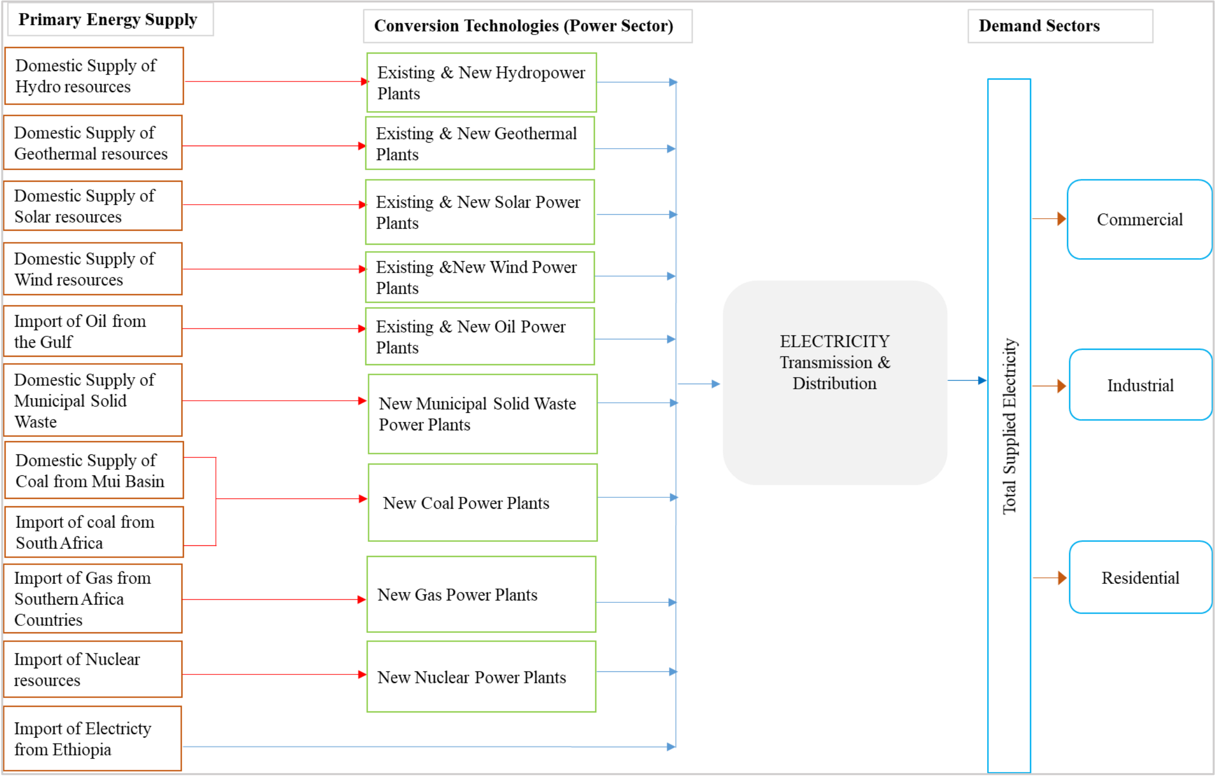

Figure 8: The Reference energy system (modified from Musonye et al. (12)).

3.2.1 Primary Energy Supply

The energy supply in Kenya-TIMES includes fossil fuel and primary renewable energy from domestic and imported sources. Apart from the domestic supply of natural gas, the supply of all the other fossil fuels is the same as those used in Musonye et al. (12). The fossil fuels considered are based on the government's future planned power generation technologies (20) and are supplied in the model from either imported or both domestic and imported processes (see Figure 5). The future prices for fossil fuel and nuclear resources are calculated based on the base years price presented in the government's Least Cost Power Development Plan (LCPDP) (35), and the five year-period global percentage increase in price as presented in the International Energy Agency's power generation technology's database (36).

On the other hand, primary energy from renewable resources is supplied by domestic sources. Biomass is an additional renewable resource in the current study as opposed to the earlier version of Kenya-TIMES (12). Biomass is added because, in December 2020, the government initiated plans to develop a 40 MW municipal solid waste biomass plant in Nairobi city (37). Therefore, the current study evaluates its competitiveness in optimized low-carbon power development for Kenya's power development plan. Table 1 presents the maximum available potential for domestic primary energy sources used in this study. The assumptions regarding the available potential used in the current study except for biomass and domestically supplied natural gas are explained in Musonye et al. (12). A feasibility study funded by the Kenya Electricity Generating Company (KenGen) (38) indicates a maximum potential of 115 MW from the municipal solid waste by 2035 within the Nairobi metropolitan area alone. This generation capacity is considered under the incineration technology, operating at medium case assumptions regarding pre-biological and thermal treatment processes and 90% waste collection efficiency. The current study uses an estimated maximum available annual potential of 3500 MW for biomass (municipal solid waste) for the whole country and 4000 MW for domestic natural gas. In 2019, Kenya imported a paltry 1% of its electricity demand. However, Kenya has signed a PPA with Ethiopia to import a 400 MW firm capacity with 85% availability, at 7 US Cents/kWh, and on take-or-pay terms, on an energy basis from Ethiopia's Grand renaissance hydropower plant (20). Therefore, the Ethiopian power import option is available in the current model version, unlike the earlier Kenya-TIMES version. No limit is defined on imported primary energy supply resources.

Table 1: The available domestic primary energy resources potential as used in the model

Resource	Available Potential (MW)	Developed Potential (MW)
Geothermal	4,000	865
Hydropower	2300	826
Wind	4,600	336
Solar	70,000	50
Coal	95,000	0
Natural Gas	4,000	0
Biomass	3,500	0

3.2.2 Conversion technologies

The conversion technologies considered are electricity generating plants, including hydro, oil, geothermal, biomass, wind, solar, and nuclear power plants (see Figure 5). The technical parameters, for instance, power generating technologies' contribution to peak demand, and the capital cost (CC), fixed operation and maintenance cost (FOM), and variable operation and maintenance cost (VOM) (see Table 2) at the start of the modeling horizon are adopted from the government's power planning LCPDP reports (20) (35). Technology learning curves are considered for all the technologies beginning with base year's costs presented in the LCPDP reports and projected future costs based on cost reduction rates adopted from the IEA's technology database (36).

The capacity factors and efficiency for the generation technologies existing in the base year are computed from the base year's installed capacity and the energy generated in the same year. On the other hand, coal, gas, and nuclear capacity factors are adopted from the LCPDP report (35). The biomass technical parameters were adopted from IEA's database (36). Fossil fuel GHG emission coefficients are from IEA's database (36), while renewable energy lifecycle emission assessments (LCA) are from different research papers (39) (40) (41) (42) (43). The LCA emissions associated with the manufacturing of power turbines were subtracted from the total emissions since Kenya does not currently manufacture turbines. Lastly, all the existing power plants at the base year will operate at a generation level desired by the model until the end of their technical life.

Table 2: Technical parameters for the conversion technologies considered in the model

Conversion Technologies	CC Million USD/GW	FOM Million USD/GW	VOM Million USD/PJ	Capacity factors	Contribution to peak (%)
Geo	3595	155.4	1.0	0.90	95
Hydro	3741	19.6	0.5	0.65	95
Oil	2032	32.0	10.0	0.20	95
Solar	1780	27.3	0.0	0.19	0
Gas	1083	25.2	13.5	0.75	95
Nuclear	8068	7.5	10.0	0.85	95
Wind	2132	76.0	0.0	0.36	20
Biomass	3045	50.2	9.0	0.80	90
Coal	2542	75.4	(domestic) 3.5 (imported) 4.3	0.85	95

3.2.3 Energy demand

Kenya's electricity demand data is highly aggregated. The demand data is divided into domestic, small commercial, and large commercial and industrial consumers and street lighting. Since the total demand is exogenously input, demand in the reference energy system is simplified to residential, commercial, and industrial (see Figure 5). The parameters used to project future demand are adopted from the government's power planning reports (20) (35). The demand projection is based on the Vision 2030 economic transformation and is projected to increase by 8% per year. Therefore, electricity demand is projected to grow from 11,800 GWh in 2019 to 146500 GWh in 2050 and includes transmission and distribution losses. The study defines a peak reserve equation in the model, specifying that the available capacity in any time slice must exceed the overall peak demand by 20%. The overall peak demand covers both transmission and distribution losses. The losses and reserve capacity requirement is adapted from the government's LCPDP report (20).

3.2.4 Other model parameters

The Kenya-TIMES model base year was set in 2020, and the modeling horizon from 2020 to 2050 with a five-year investment period. The general discounting factor is 7% and relates to the average median Kenya Central Bank value for the past five years (44). The energy unit for the transformation process follows the general TIMES guidelines (45) and is a Peta-Joule (PJ).

3.2.5 model assumptions

Some of the model's general assumptions are that there will be no financial insufficiencies since the private sector is expected to be highly involved in future power sector development (46). Hence, no constraint is imposed on the availability of financial resources. Power export and off-grid generation are not considered in the current model.

3.3 Scenario development

The study develops four scenarios with the BAU as the reference case. The scenarios are based on Kenya's demand-supply expansion plan (20), Kenya National Electrification Strategy (23), Kenya's Energy Act 2019 (47), Kenya National Energy Policy (48), the recently amended Import Tax Act concerning solar and wind power development accessories (49) and the environmental policy goals outlined in the NDC for Kenya. The scenarios evaluate the impact of implementing three low-carbon development policy instruments and a hybrid of two policy instruments of Kenya's power generation expansion.

3.3.1 The BAU (Business As Usual) scenario

The BAU scenario serves as a reference for comparing alternative pathways under different low-carbon policy instruments. This scenario assumes that there are no new policy interventions.

3.3.2 The Ctax (Carbon Tax) scenario

In the Ctax scenario, a GHG emission tax is levied on all GHG emissions associated with power generation. Even though Kenya currently does not have any proposal to implement a carbon tax, the carbon tax has been used throughout the European economic area countries, for instance, Denmark, Sweden, Iceland, Germany, and Finland (50), as a tool for reducing GHG emissions. The carbon tax policy tool is also under consideration to achieve GHG emission reduction targets in many other countries around the globe (51). Based on the analysis done for Africa's power sector (52) and projected global carbon pricing (53) (54), the carbon tax scenario was set at 10 USD/ton and 50 USD/ton in 2022 and 2050, respectively. The tax is defined to increase by 10 USD every ten years. The model interpolates the costs between 2022 and 2050.

3.3.3 The RPS (Renewable Portfolio Standards) scenario

The RPS is a renewable-target generation scenario in which a particular share of renewable-based power generation is implemented. The BAU scenario is first optimized, and the power generation results from the different technologies used as input in the RPS scenario. The RPS renewable target share is then defined based on BAU renewable share.

Kenya's renewable energy policy promotes renewable energy technology advancement and uptake. The Kenyan government aims to supply all its citizens with clean and affordable energy under this policy. On the other hand, Kenya does not have a defined targeted share of renewable generation beyond 2022, even though it targets a 100% renewable share by 2022. Beyond 2022, the government plans to meet the forecasted electricity demand using renewable and fossil fuel sources. For instance, the government's LCPDP plan (20) indicates that the share of renewable energy under vision demand will be 55% in 2037 (23). The BAU result has 100% renewable generation until 2035, when it drops to 91%. Since the government does not have a defined target of renewable share beyond 2022 and no studies are forecasting the required renewable share, the current study defines the renewable share in 2050 to be 100%. The model interpolates the percentage values between 2035 and 2050. Consequently, the renewable share will be 72% in 2040 and 83% in 2045. The 100% renewable share in 2050 is pegged on Kenya's abundant renewable energy resources potential. It is critical to note that the 100% value is not based on any empirical studies regarding Kenya's future power generation mix and can vary in the future Kenya-TIMES model depending on the available data and defined assumptions.

3.3.4 The RenSub (Renewable Energy Subsidy) Scenario

In the RenSub scenario, a capital subsidy is defined for all the new solar photovoltaic and wind capacities. With the recent scrapping of 14% VAT exemption for imported specialized solar and wind equipment by the Kenyan government (49), it is essential to assess other alternative policy interventions. In this case, direct subsidies on the unit electricity generation cost. Solar photovoltaic and wind technologies were considered for subsidies because the resources are fairly distributed in the country and can be installed in smaller units compared to other renewable technologies. Additionally, solar photovoltaic technology is fairly adopted all across the country. Moreover, the recently enacted net-metering regulation (47) enables individual home solar systems and small wind turbines to supply power to the main grid. The subsidy value is set at 18%. This value was calculated using the price-gap method (55) based on the grid-connected feed-in-tariff Kenyan policy document (56). The feed-in-tariff value for the grid-connected hydropower is used as the reference price against the grid-connected solar and wind tariffs.

3.3.5 The TaxSub (Taxes and Subsidies) Scenario

Countries like Germany and Britain have applied carbon tax and subsidies on renewable energy sources to reduce GHG emissions (57). In this study, the hybrid scenario tests the concurrent implementation of the carbon tax and renewable subsidy policy instruments. In this scenario, it is assumed that the proceeds accrued from the CTax scenario are used to subsidize wind and solar power development.

4. Results

The following sub-sections describe the model results for the five scenarios based on the installed capacity, power generation, GHG emissions, and system costs.

4.1 Installed capacity

The Kenya-TIMES results indicate that the different technologies' adoption levels vary across the modeling period (see Figure 6). The notable difference is the high share of renewable sources' capacity, mainly solar, and the reduction in coal capacity in the low-carbon scenarios compared to BAU. For instance, in the CTax scenario, the increasing carbon tax from 2020 to 2050 reduces the economic viability of coal power with the capacity increase due to rising GHG emissions. As a result, the installed coal capacity in BAU is partly replaced with biomass, gas, and solar in the CTax scenario beginning in 2045, with solar power constituting 34% of the total installed capacity in 2050. Similarly, coal capacity is partly replaced with biomass, gas, and solar capacities in the RPS and TaxSub scenarios. However, unlike in the CTax, solar capacity is adopted earlier in the RPS and TaxSub scenarios. In the RPS, solar constitutes 25% and 59% in 2045 and 2050, respectively. The adoption of new solar capacity in the TaxSub scenario starts in 2025 and increases to 39%, 45%, and 50% in 2040, 2045, and

2050, respectively. The subsidy component in the TaxSub scenario accounts for the earlier adoption of solar capacity, while the combined carbon tax and subsidy accounts for the higher percentages of solar witnessed from 2040 onwards. In the RenSub, coal is partly replaced with solar and gas. New solar capacity is adopted beginning 2025 and constitutes 34% in 2045 and 2050. In the absence of direct restrictions on GHG emission (e.g., carbon tax) or renewable share, coal and gas are more economical than biomass. Consequently, unlike in the other low-carbon scenarios, biomass does not replace coal in the RenSub scenario.

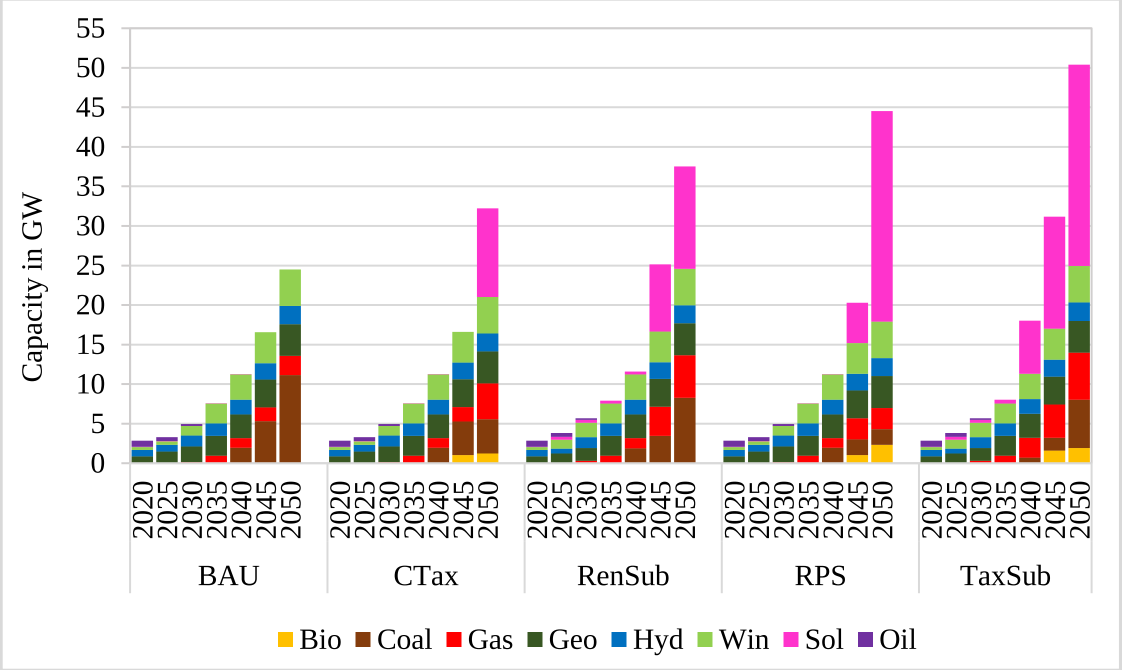

Figure 9: Installed power capacity for the five scenarios.

The total installed capacity varies across the scenarios. For instance, the total installed capacities in the RPS and TaxSub scenarios are higher than the BAU, CTax, and RenSub in 2050. The TaxSub scenario has 50 GW, the highest total installed capacity, while BAU has 24 GW, the lowest total installed capacity. The level of installed capacity relates to the share of intermittent sources, particularly solar, in the capacity mix. Solar radiation is only available between 7 am and 6 pm throughout the year in Kenya and has an overall capacity factor of 20% (see Figure 4). Therefore, to meet demand, the model adopts a higher installed solar capacity to account for the low capacity factor in scenarios where solar is the most economical option.

4.2 Power generation

The electricity generation profiles are similar to the installed capacity in the corresponding scenarios (see Figure 7). For instance, in 2050, coal will generate 56% of the total energy in the BAU scenario, while it will generate 0% in the RPS scenario in the same year. Further, coal generation is partly replaced with solar and biomass generation in the low-carbon scenarios. Domestic coal supply is prioritized in coal power generation because of its low cost. The high cost of oil-based generation prohibits power generation from these generators after the base year. In all the scenarios, imported power becomes competitive beginning in 2035 after the exhaustion of geothermal, hydropower, and wind resources, with the system consuming the maximum available capacity. However, in RPS, imported energy share drops to 46 % and 0% in 2045 and 2050, respectively. The imported energy is replaced with solar generation as the model targets to meet the 83% and 100% renewable share in 2045 and 2050, respectively. Imported energy is neither categorized under renewable nor fossil fuel in the model. The high percentage of solar capacity in the RPS scenario in 2050 compels the scenario to generate 20.8 TWh in excess energy compared to the other four scenarios. The extra energy accounts for the low capacity factor associated with solar energy and the mismatch in the peak and night demand and supply profiles, as seen in Figure 4.

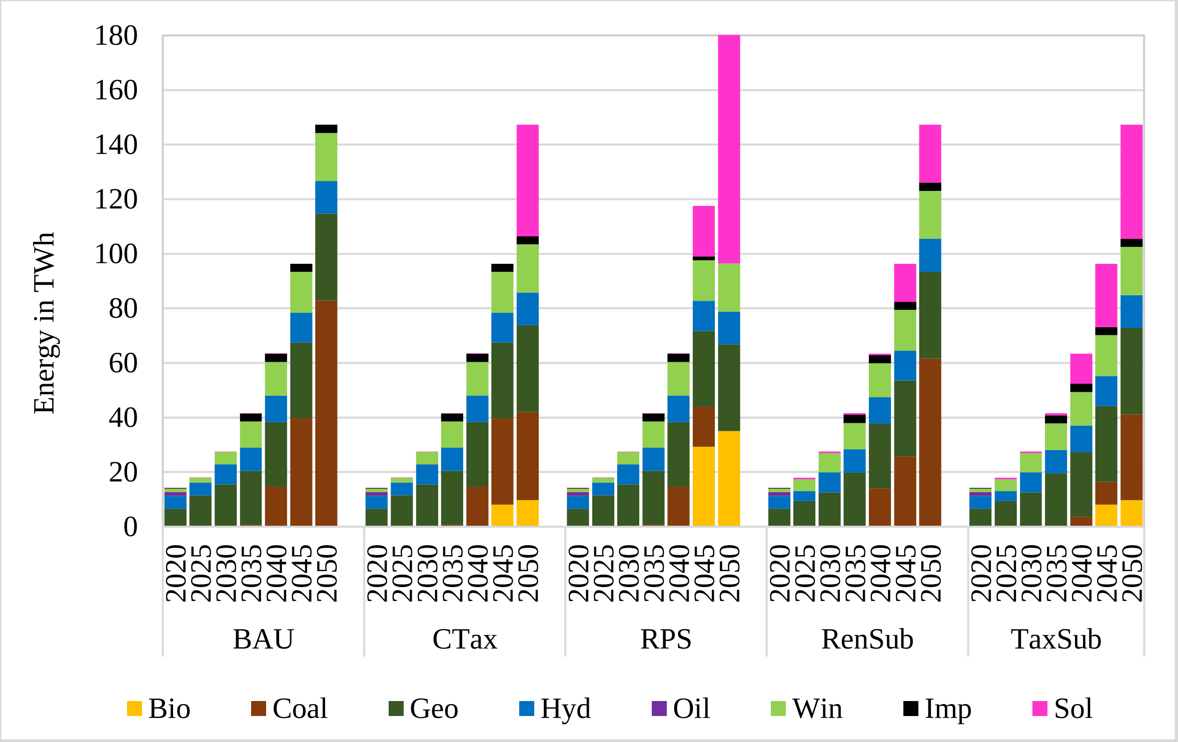

Figure 10: Electricity generation mix for the five scenarios in TWh.

Despite gas capacity share in the installed power capacity, there is no energy generated from the gas units. This occurrence relates to the inclusion of the peaking reserve constraint in the model, which specifies that the available capacity must exceed the demand of a selected commodity by a certain margin in any time slice. Except for the RPS scenario, which has a strict constraint on the share of energy that should come from renewables, the natural gas installed capacity increases with the wind and solar capacity. The higher the percentage of intermittent sources power generation, the more peaking reserve is required; hence, the relation between gas and the total solar and wind capacity presented in Figure 8.

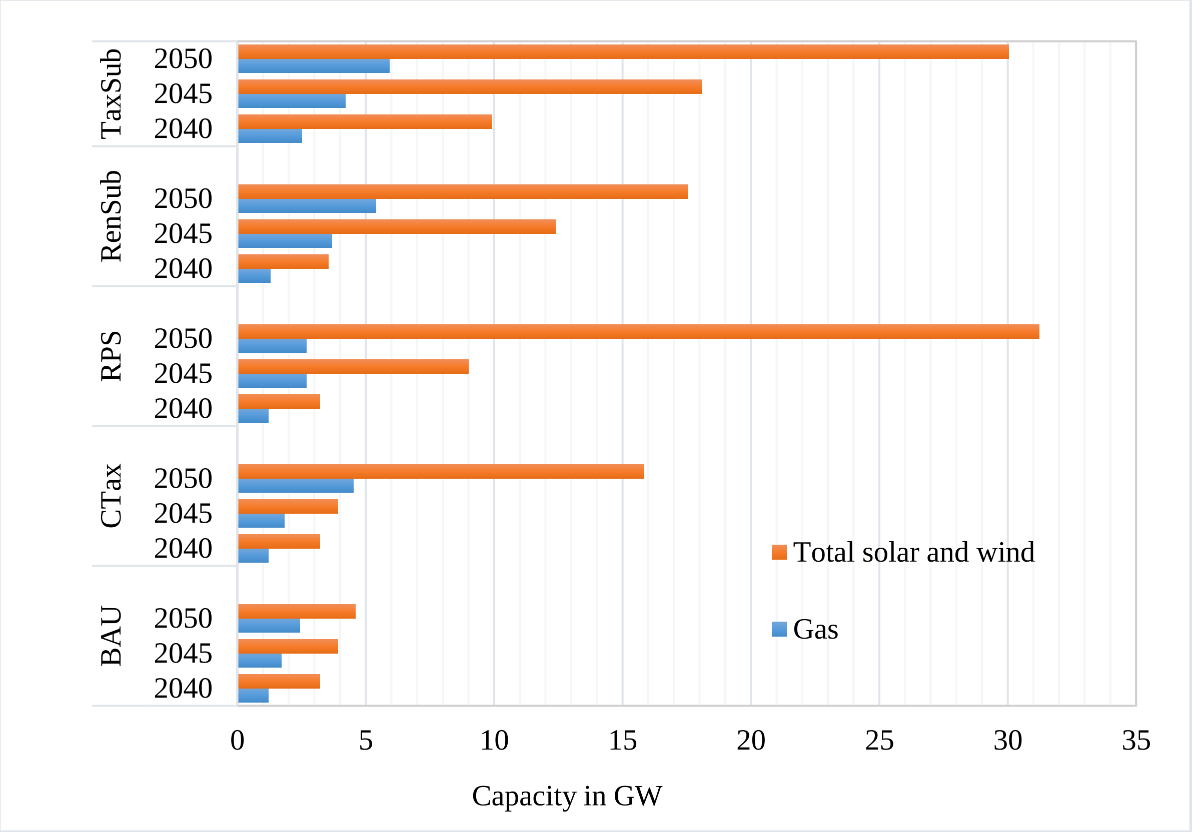

Figure 11: A chart showing the relationship between the total solar and wind and gas capacities in the last fifteen years of the modeling period.

4.3 GHG emissions

Figure 9 presents the government's projected power sector-related GHG baseline emission, the NDC's allowable emission level, and the emissions under the five scenarios. The GHG emission levels are predominantly below the NDC's acceptable level in all five scenarios until 2045. The government's power sector-related GHG baseline emission projections are based on power generation expansion simulated using an econometric model. Unlike the current optimization study, the government's power generation forecast envisages the use of fossil fuels earlier in the modeling period. For instance, diesel generation is expected to contribute to the peak demand by between 15% and 30% from 2017 to 2037 (20) (35). Further, coal and natural gas generation is expected to come on the grid in 2024 and 2028, respectively, under the government's power generation expansion plan.

In all the scenarios, there is an increase in GHG emissions after 2035. The sharp increase in emissions after 2035 relates to the uptake of coal generation in 2040 in all the scenarios. The introduction of coal power generation, a source with high GHG emissions, in a system that is 100% renewable, significantly changes GHG emission levels. After 2045, the GHG emission in the RenSub scenario is above the NDC permitted level by 12%. The BAU GHG emission is 4% above the government's projected baseline and 49% above the NDC allowed emission levels. These levels relate to the relatively high share of coal in the energy generation mix in the two scenarios after 2045. The RPS scenario is bound to have insignificant emissions in 2050 because of the 100% renewable generation constraint. The growing tax value on coal in the CTax scenario further increases the cost of coal generation towards the end of the modeling horizon. Resultantly, GHG emission reduces as coal generation is partly replaced by solar generation in the CTax scenario after 2045. The slightly high-level emission in the base year relates to the diesel generators, whose contribution to the energy mix ends in the base year.

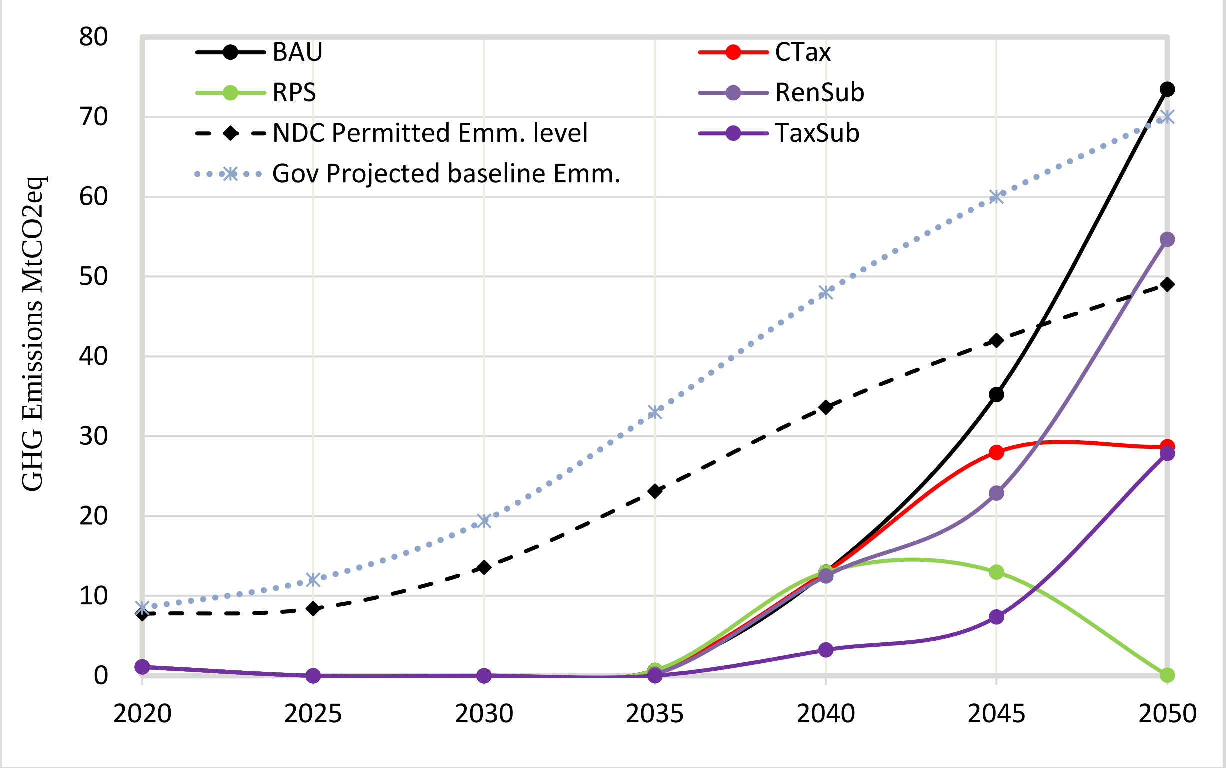

Figure 12: GHG Emissions for the five scenarios, projected baseline emissions, and the acceptable level of emissions under NDC.

4.4 The system cost

Under this sub-section, the total system cost, which represents the objective function, the system cost breakdown, and the marginal electricity prices, are presented. The total system cost is the sum of capital for power plants, operation and maintenance, decommissioning, and tax (e.g., carbon tax) costs. The grid construction costs are also added. The salvage value, which is the monetary value of any investment remaining at the end of the modeling horizon, and subsidies values (e.g., renewable subsidy) are then subtracted. These costs and values are summed over the entire modeling period and discounted to the net present value to give the total system cost. The RPS scenario's total system cost, the highest of the five scenarios, is 33% more than RenSub, which has the least cost (see Figure 10). The high share of solar in the RPS scenario accounts for the high system cost. In contrast, the 18% subsidy on investment cost per new GW wind and solar capacity, catered for by the taxpayers, accounts for the least cost in the RenSub scenario. The system cost for the TaxSub and RenSub is 3 and 5 billion USD, respectively, lower than the BAU, resulting from the subsidized wind and solar capacity. The subsidy on new solar capacity is 322 million USD per GW. On the other hand, the subsidy for wind ranges from 384 to 381 million USD in 2021 to 2050, respectively, due to a reduction in the capital cost associated with the technology learning curve for wind technology, unlike solar.

The CTax scenario's total system cost is 9% more than BAU. With the exhaustion of the most economical geothermal, hydropower, and wind resources potential, the CTax scenario remains with the taxed coal and the expensive solar generation options. The taxation cost of coal generation and the adoption of solar generation in 2050, which are absent in the BAU scenario, increases the CTax total system cost compared to BAU.

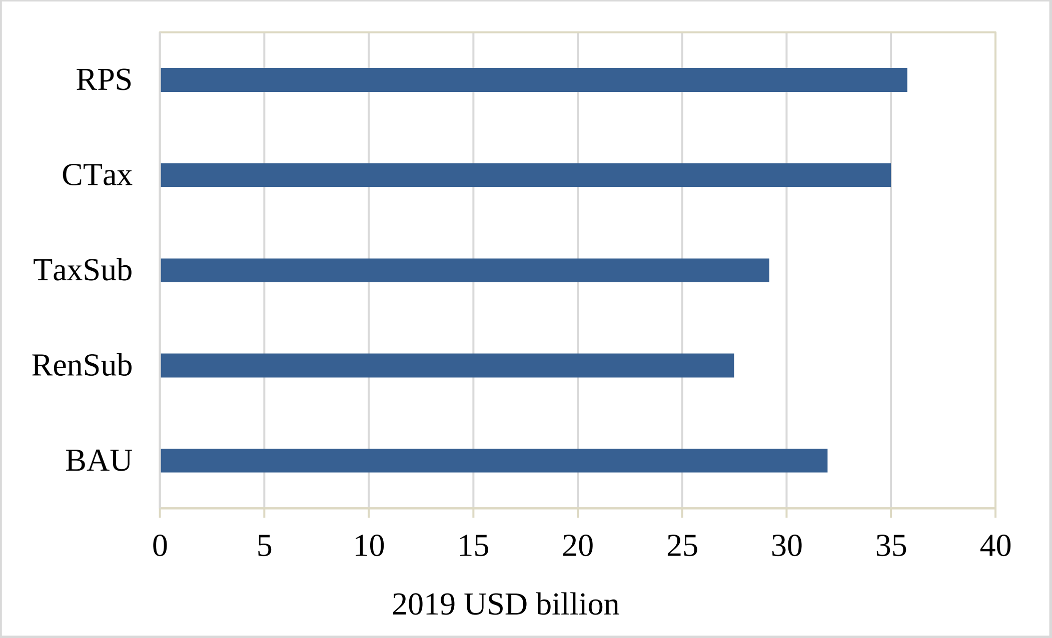

Figure 13: Total discounted system cost for the five scenarios in 2019 USD billion.

The total system cost breakdown accounts for the non-discounted annual investment (INV), fixed operation and maintenance (FIX), and variable investment (VAR) costs. The non-discounted system cost breakdown compares the costs incurred in the same years under the different scenarios. The base year VAR cost is the highest among all the scenarios. The base year's high VAR results from the fuel cost required to run the diesel generators, which comprises 10% of the generated energy in that year. Since the model is not constrained to utilize diesel plants after 2020, the model does not consider diesel generation beyond 2020 because of fuel cost. The low-carbon development scenarios have higher INV and FIX costs but a lower VAR cost than the BAU scenario from 2045 (see Figure 11). There is an increased share of solar capacity in the low-carbon scenarios beginning in 2045. For instance, in 2050, the RPS scenario has 26 GW of solar power, TaxSub has 25 GW, RenSub has 12 GW, CTax has 11 GW, and BAU has zero. Therefore, the high INV cost relates to the higher installed capacity required, considering solar power's low capacity factor, to meet power demand when the model prioritizes solar in the low-carbon development scenarios. Contrarily, the low VAR cost associated with solar power generation accounts for the low variable cost in the low-carbon development scenarios.

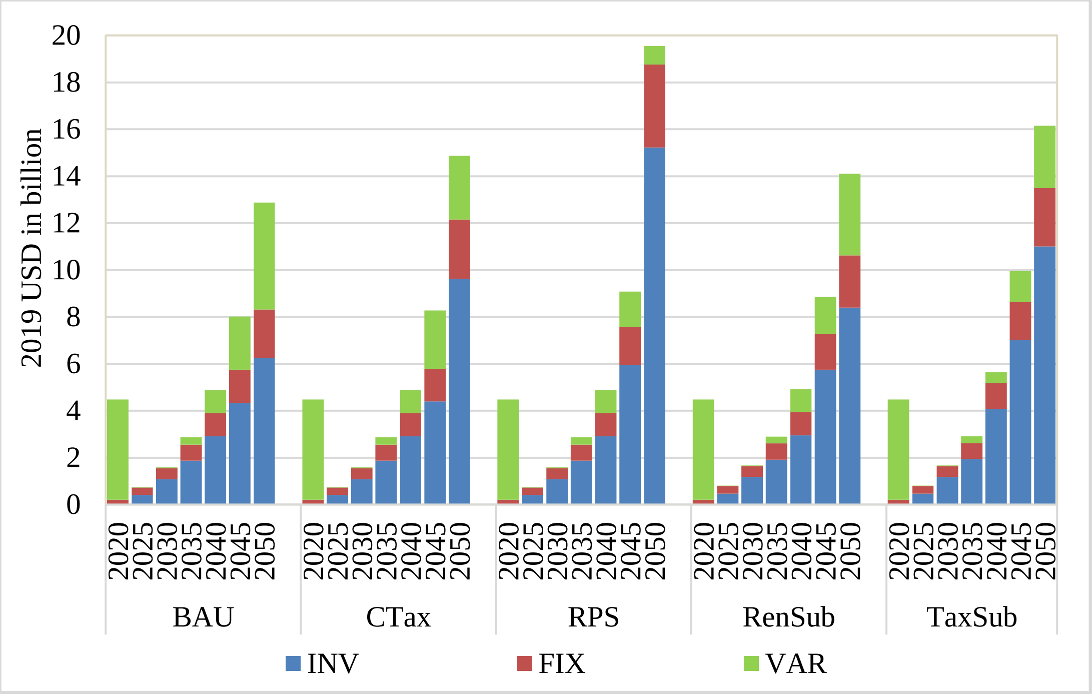

Figure 14: The undiscounted total system cost breakdown for the five scenarios.

The cost of unit electricity in the current study is presented using the marginal electricity price at the distribution point. Marginal electricity price is the cost incurred to generate an extra unit of electricity and includes the capital cost, fixed cost, and variable cost (58). There is a general drop in marginal prices after 2020 across the scenarios (see Figure 12). This drop relates to the removal of diesel generators from the power generation mix. The subsidy component accounts for the relatively more considerable reduction seen in the RenSub and TaxSub scenarios. The general increase in marginal prices after 2030 in the BAU, CTax, and TaxSub scenarios is accounted for by coal capacity, which comes onto the grid in 2035. The carbon tax element in the CTax and TaxSub scenarios accounts for the further increase in prices contrary to the BAU. Combined with the lower investment and fixed cost resulting from the subsidy, the TaxSub marginal prices are slightly below the CTax scenario. The marginal prices in the TaxSub scenario are higher than BAU because marginal prices are significantly affected by variable costs, for example, the carbon tax levied on GHG emissions resulting from generated power. The rise in marginal prices in the RPS scenario from 2040 onwards relates to the increased share of solar power. The RenSub has the least marginal prices among the five scenarios. A subsidy value, a cost shouldered by the government, keeps prices low in this scenario.

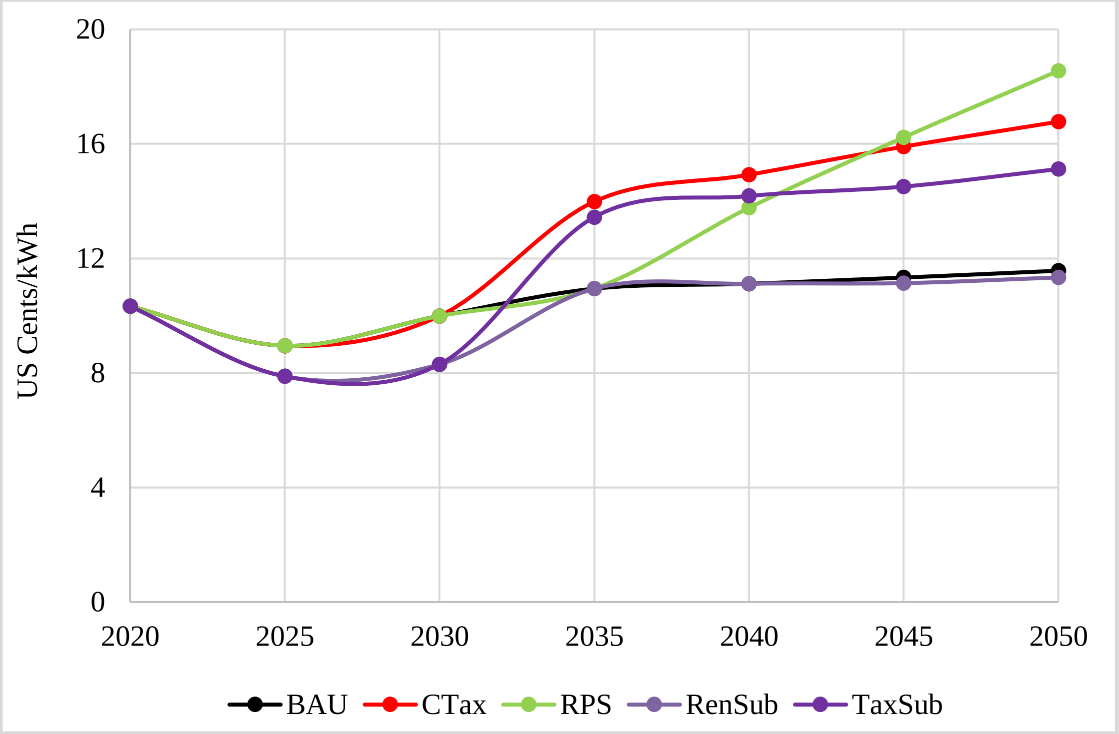

Figure 15: Marginal electricity prices in the five scenarios.

5. Discussion

With the risks associated with climate change, low-carbon development pathways are increasingly considered a promising approach to mitigating GHG emissions related to the heat and electricity sector. Governments and energy stakeholders worldwide seek to reduce power sector-related GHG emissions by implementing strategies to guide a low-carbon power generation expansion path (59). Such strategies include energy policies that are simulated, evaluated, and implemented using policy instruments. On the other hand, the SSA governments are challenged to provide universal access to secure, reliable, and affordable energy for its growing population while limiting GHG emissions. Using Kenya as a case study, we evaluate low-carbon strategies for SSA's power generation expansion.

The current study uses an advanced and refined version of the Kenya-TIMES model to appraise the impact of low-carbon policy instruments on Kenya's power generation expansion. The improvements in the current model include using twelve time-slices instead of the four in the earlier Kenya-TIMES version. The twelve time-slices allow for a more refined representation of the intermittent renewables' capacity factors. For instance, the wind capacity factor for day, peak, and night times is separately accounted, while solar has night and day capacity factors. Further, the current model applies the peaking reserve constraint, which provides a time-sliced dependent peaking reserve factor. This factor ensures optimum reserve capacity to protect the power system against intermittency or other contingency. The accounting of technology learning curves for generation technologies reflects the real-world technology price evolution. Lastly, the current Kenya-TIMES version includes biomass resources and imported electricity from Ethiopia. Therefore, the model has been significantly improved from the previous version and represents the actual system more significantly.

The current study establishes that the cost-competitive nature of geothermal, hydropower, and wind presents them as prime candidates for power generation expansion for Kenya in all the scenarios. As a result, the low-carbon development strategies significantly impact the generation technology mix after 2035 once the prime candidates' potential has been exhausted.

With the peaking reserve constraint, there is a concurrency in increasing the percentage of the intermittent renewable sources in the generation mix with the intermediate and peaking capacity. In 2050, for instance, the TaxSub scenario has 25 GW of solar capacity compared to zero in the BAU and 13 GW in the RenSub. To counterbalance the high level of the intermittent solar capacity, TaxSub has 1.9 GW biomass capacity in 2050 compared to zero in the BAU and RenSub in the same year. Further, the hydropower capacity (intermediate load capacity) is 17.65% more in TaxSub than BAU and RenSub in 2050, while the gas capacity (peak load capacity) is 61% and 8.8% more than the BAU and RenSub scenarios, respectively, in 2050. These dynamics also show the role a renewable subsidy or a hybrid of renewable subsidy and carbon tax could play in expediting the development of wind and solar resources in Kenya's power sector in the short to medium term.

The energy generation in RPS, like BAU, is 100% renewable from the base year until 2035. Resultantly, the impact of the RPS targets is seen after 2035. Significant changes are realized starting in 2045 as the energy system aims to attain 100% renewable generation in 2050. Unlike in the TaxSub and RenSub scenarios, the increase in solar capacity in the RPS case is not commensurate with accelerated gas capacity development. For example, despite the 26 GW of solar in 2050 in the RPS scenario, it adopts 257 MW of gas. The RPS power generation mix in 2050 goes contrary to a practical, real-life situation. In this scenario, the last coal capacity is developed in 2040. Coal plants have an economic lifetime of 30 years, yet, in 2050, there is no power generation expected from the coal plants as the model keeps 100% renewable generation. This results in 1.9 GW of idle capacity. Further, without storage but 100% renewable generation requirement, the gas plants cannot be used to balance the intermittency associated with solar and wind. Such a system would be impractical in a real-life case. Besides RPS in 2050, TaxSub has the lowest coal generation among the low-carbon scenarios in the 2040-2050 period. These low capacities indicate that a carbon tax and subsidy hybrid could be more feasible in reducing the share of fossil fuel in Kenya's power generation mix in the long term.

The GHG emission reduction under the low-carbon scenarios indicates that coupled energy and climate policy instruments can be used to regulate Kenya's power sector-related GHG emissions. Moreover, the variability in emission reduction levels shows that the policy instruments could be adjusted to achieve targeted emission reduction. The renewable subsidy does not guarantee the NDC's emission reduction target in 2050, while the high emission reduction in the RPS in 2050 is infeasible in the absence of storage, as explained in the preceding paragraph. High GHG emission cuts in the low-carbon scenarios correlate with the higher development of solar and biomass resources instead of coal. This replacement indicates the central role of solar and biomass resources in decarbonizing Kenya's future power sector. On the other hand, emissions from 2020 to 2035 are below the government's NDC projection by 87%. The NDC emission projection is based on the government's generation forecast, envisaging a significant share of fossil fuel generation as early as 2020. However, in the current study, geothermal, hydropower, and wind power generation dominate the 2020-2035 period. The low emissions in 2020 to 2035 suggest that the Kenyan government can avert coal development and the large-scale absorption of the expensive solar and, biomass if it harnesses geothermal and hydropower to their full sustainable potential in the short to medium term. Different studies put Kenya's geothermal potential between 7 GW and 10 GW and wind potential between 4 GW and 6 GW (20) (60). However, the current study uses a conservative value of 4 GW for geothermal and the 2.3 GW economically feasible hydropower potential.

The energy system cost is higher in the RPS and CTax scenarios because of the additional investment and fixed operation and maintenance costs. The cost differences are because of the large installed capacities of solar resources. However, it is not easy to effectively forecast the cost of solar technology from 2020 to 2050. The rapid development of solar resources may significantly decrease the costs, contrary to what is applied in this study. Furthermore, the deployment of storage technologies could substantially alter the system costs in the RPS and CTax scenarios. On the other hand, the RenSub and TaxSub scenarios show a lower energy system cost than BAU. A subsidy of 18% on the unit capital cost of any additional GW of solar and wind starting in 2022 guarantees reduced capital cost earlier in the modeling period and a significant reduction in the total system cost. However, the government shoulders the cost of the subsidy, which results in a 5 billion USD revenue loss for the entire modeling period. An evaluation of the ability of the government budget to absorb the revenue losses would provide an insight into the feasibility of this policy instrument regarding the government's budget. Alternatively, the government can let the subsidy cost be financed by a subsidy surcharge, which would be added to the final electricity tariff, as has been the case in Spain and Germany (61).

In all the scenarios, marginal electricity price trends relate similarly to the total system cost except the TaxSub scenario. Unlike total system cost, marginal cost is significantly influenced by the variation in variable cost. Therefore, even though the BAU's total system cost is higher than the TaxSub scenario, levying a carbon tax on any extra unit of electricity generated increases the marginal electricity prices in the TaxSub, contrary to the BAU. The assumption in the TaxSub is that the carbon tax levied on unit production is used to subsidize additional wind or solar units. This design removes the subsidy burden from the government's shoulders, and discourages fossil fuel consumption while providing an option for renewable capacity development. This observation relates to such policy instrument application's results in Germany, Britain, and Spain (57) (61). The introduction of storage could substantially alter the marginal prices associated with the low-carbon scenarios.

Based on the assumptions in the current study, the overall analysis indicates that a hybrid of renewable subsidy and carbon tax presents a comparatively feasible low-carbon development pathway for Kenya's future power development. The TaxSub achieves feasible GHG emission cuts, i.e., below the NDC allowable levels. Secondly, the TaxSub attains solar adoption and accelerated uptake of wind resources earlier in the modeling horizon. Furthermore, TaxSub has the second-lowest total system cost and the third-lowest marginal electricity prices. Lastly, the scenario protects the government from revenue losses provided the accrued subsidy cost does not exceed the levied carbon tax.

The results in this study apply to the extent of the assumptions and the modeling framework used herein. The Kenya-TIMES model framework and assumption refinement have improved the current results compared to the earlier Kenya-TIMES model results in Musonye et al. (12) and the government's LCPDP econometric model results (20). The detailed representation of the time-slices and wind capacity factor resulted in the increased competitiveness of wind resources to the same level as geothermal and hydropower. Resultantly, wind capacity development occurred concurrently with the geothermal and hydropower development. The competitiveness of wind resources and the inclusion of biomass options deterred the adoption of nuclear capacity under low-carbon policy strategies in the current model, unlike the other two models. Lastly, the refined intermittent renewable resources' capacity factors and the peaking reserve equation optimized peaking capacity share, reducing the total system cost. This observation indicates that a more advanced energy-planning tool could inform effective and efficient energy planning decisions for the SSA countries.

This research shares similar features with two recent studies that used TIMES modeling framework for South Africa (11) and the entire African continent (13). The three studies assess policy implications on future GHG emission reduction in SSA. The strength of the South

African TIMES (SATIMES) study (11) arises from the use of an integrated SATIMES modeling framework with the South African General Equilibrium model (SAGE) via a recursive dynamic process. This linking accounts for the secondary impact of shocks, for instance, change in electricity demand regarding prices. Such changes are fed back into the SATIMES to adjust generation. The TIAM-ECN (13) strength is that it assesses GHG emissions from the five economic sectors ─ waste, agriculture, power sector, land use, transportation, and industrial processes. On the other hand, the merit of Kenya-TIMES is that it evaluates more detailed low-carbon strategies at the national level accounting for the local assumptions as much as possible. The SATIMES only evaluates the carbon tax, while the TIAM-ECEN evaluates the carbon tax, carbon emission cap, and atmospheric radiative forcing cap strategies. Further, the regional scale of the TIAM-ECN can easily obscure critical country-specific assumptions and details. The three studies indicate the significance of using advanced optimization-based energy planning tools to guide decision-making for low-carbon power pathways and the role of policy instruments in reducing GHG emissions in SSA. The evaluation of the low-carbon strategies in detail at the national level in Kenya-TIMES hopefully sets a new benchmark for studies dedicated to low-carbon strategies at the national level for the SSA countries.

Future studies can address the shortcomings related to the assumptions and the modeling framework in the current study. The limitations include evaluating the short-term operational constraints resulting from the increased share of variable sources on the long-term power planning and the impact of storage on the overall system cost, considering the high percentage of solar power in the low-carbon pathways. Further, there is a need for a multi-criteria analysis to rank the low-carbon policy instruments based on energy security, reliability, costs, accrued revenue loss and gain by the government, affordability, and environmental benignity. The current model can be used to evaluate other SSA countries' low-carbon strategies by using country-specific input parameters and assumptions. Such country-specific models can be expanded into a regional energy system model accounting for an interconnected low-carbon power market in the East African power pool and farther to the other SSA power pools using the TIMES modeling framework's trade function like the one developed for the European countries (62).

6. Conclusion

The SSA is one of the regions in the world whose forecasted population and economic growth are expected to increase its energy demand significantly. As the high-income economies implement strategies to reduce energy-related GHG emissions, the SSA countries face the challenge of meeting their present and future energy needs while limiting GHG emissions. Kenya is one of the SSA countries whose ambitious economic development plan is projected to increase energy demand exponentially.

This study developed an optimization-based national scale bottom-up energy system planning model called the Kenya-TIMES. The model is used to appraise the impact of low-carbon strategies on Kenya's power generation expansion. The study used the most recent energy data and advanced TIMES framework features, including twelve time slices, technology learning curves, peaking reserve constraint, and time-slice-related capacity factors for the intermittent sources. The results indicate that, apart from the renewable subsidy, the low-carbon policy instruments can cut GHG emissions below the NDC's targeted reduction level by 2050. Even though the renewable portfolio standard achieves the highest emission cuts by 2050, it does so at the highest cost, and without storage, it is infeasible in 2050. Based on the assumption in this study, the TaxSub scenario could provide an effective and efficient low-carbon pathway for Kenya's power sector generation expansion. The government can also achieve low GHG emissions at a lower cost if it prioritizes developing the maximum geothermal and hydropower potential.

This study further indicates that advanced energy planning tools could be more efficient in informing low-carbon energy planning decisions in SSA. The results can help improve the understanding of the implications of low-carbon policy instruments on Kenya's future power development, helping educate the nation's low-carbon development strategy. The current Kenya-TIMES model could be further refined to account for storage and the short-term operational constraints in generation expansion. Such accounting is critical for short to medium-term planning.

The detailed evaluation of the low-carbon strategies at the national level using advanced optimization-based energy planning tools hopefully sets a benchmark for similar studies for other SSA countries. The current model can be expanded using the TIMES framework's trade function to build a regional model to assess the feasibility of the low-carbon energy market and trading in the SSA power pools.

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5. Summary and conclusions

5.1 Summary

Climate change, primarily caused by emitting GHG into the atmosphere, is a growing global concern. As a result, through the Paris Agreement, the international community has committed to reducing GHG emissions related to the various sectors of the economy through the NDCs. Energy production and consumption account for the highest GHG emissions from a single sector. Nevertheless, energy is critical in addressing the challenges being addressed by the 17 SDGs. Furthermore, energy production and consumption will increase as demand grows and countries strive to achieve universal access to modern energy services. SSA is one of the regions with the highest energy poverty globally. Some of the reasons hindering universal access are the high cost of connection, low annual investment in generation expansion, inefficient and ineffective planning, and politically driven decisions without reference to holistic data-driven analysis. The forecasted population and economic growth will significantly increase the SSA's energy demand. The SSA countries are challenged to meet their energy needs at an affordable cost while limiting GHG emissions. The prerequisite to universal energy access is effective and efficient energy planning. Kenya is one of the SSA countries yet to achieve universal access to electricity. Moreover, its energy demand is projected to grow exponentially considering its ambitious Vision 2030 economic expansion plan.

The study described in this thesis contributes to the development of pathways toward access to secure, affordable, and sustainable energy services in Kenya by developing an optimization-based model of Kenya's energy system. The model's foundation and selection of the appropriate modeling platform were established in Chapter II, which involved a scoping review of existing integrated energy modeling studies for the SSA region at a national or regional level. In Chapter III, a national-scale bottom-up optimization-based model, Kenya-TIMES, was developed. The techno-economic and environmental assessment for the power system's generation expansion for the Kenyan government's forecasted three demand levels were analyzed using the model. In Chapter IV, using Kenya as the case study, an evaluation of the low-carbon development strategies for power generation expansion for SSA was carried out using a more refined version of the Kenya-TIMES model.

Paper I seeks to address the question, "what are the existing integrated energy modeling studies for Sub-Saharan Africa?" The question is addressed by conducting a scoping review of 30 integrated energy modeling studies. The reviewed modeling studies use top-down simulation, bottom-up optimization, or hybrid modeling tools. The studies are either at a national or regional scale, evaluating various energy themes based on different assumptions. The studies, however, inadequately assess some critical energy system elements because of the assumptions used in the studies or the modeling tools' limited capability. The existing modeling studies also indicate that European-based institutions are the main drivers of modeling-based energy planning studies done for the SSA region. This study, therefore, recommends that the SSA countries develop national-scale power expansion plans that comprehensively incorporate low-carbon policy assessment using the existing energy planning tools. Once a national-scale demand-supply foundation has been established, the results of the national models could be interlinked within a power pool, a regional demand-supply balance based on a regional electricity market assessed, and the national models adjusted accordingly.

A cyclic approach could be adopted to develop the national and regional models, adjusting the national and regional levels' model inputs to achieve equilibrium between the national and regional objectives. The objectives should be guided by meeting the demand, achieving universal access to modern energy services, ensuring affordability, and limiting GHG emissions. The SSA governments should collaborate with other energy stakeholders to provide reliable and transparent data required to build these models. There is also a need for the SSA governments to work with academic institutions and build local energy modeling and planning capacity, which will allow for timely data updates in these models for the real-time accounting of changes in local socio-economic conditions.

Paper II addresses the question, "can an optimization-based model be used to guide Kenya's energy system planning?" The study uses the technology-rich, bottom-up optimization-based TIMES modeling framework to develop the national-scale Kenya-TIMES energy model. To address the question, the Kenya-TIMES model was calibrated using real-world data from Kenya's energy sector and used to assess the techno-economic and environmental impacts of meeting the projected demand under a business as usual and carbon cap scenario guided by the NDC targets. The comparison between the Kenya-TIMES results and the other energy modeling studies done for Kenya shows the variation in the modeling outcomes. The Kenya-TIMES shows improved results regarding meeting the GHG emission reduction and cost optimization. The Kenya-TIMES modeling study demonstrates how a bottom-up optimization energy model could best guide energy policy decisions to achieve national objectives regarding energy security, energy system costs and electricity prices, and GHG emission reduction for Kenya's energy system. This study recommends evaluating low-carbon policy strategies for Kenya's energy system using the Kenya-TIMES model.

In paper III, the study develops the Kenya-TIMES model further. It addresses the question, "what are the implications of low-carbon policies on Kenya's energy system when assessed under an optimization-based model?" The study demonstrates the practicality of the Kenya-TIMES model to guide low-carbon goals by assessing the impact of low-carbon policy instruments on Kenya's energy system. The evaluated themes include generation technology expansion, GHG emission reduction driven by Kenya's NDCs, and the energy system cost and electricity prices associated with these policy instruments. The results indicate that the low-carbon policies increase the share of renewable energy sources in the energy mix and reduce GHG emissions, but at a higher cost. The study further shows the need to leverage energy storage to curb overcapacity associated with the increased intermittent sources' share in the low-carbon development pathways. The study recommends the adoption of advanced bottom-up optimization-based energy modeling in Kenya's energy planning to guide low-carbon energy development pathways while accounting for energy security and affordability.

5.2 Contribution to knowledge

The main subject of this study is optimization-based modeling of Kenya's energy system for pathways towards access to secure, affordable, and sustainable energy services. This study contributes to knowledge academically and practically. Academically, the scoping review of the integrated energy modeling studies done for Sub-Saharan Africa provides a database for researchers and energy stakeholders by summarizing the model features, policy themes, the contribution from the Sub-Saharan Africa region's institutions, and research gaps in Sub-Saharan Africa's existing modeling studies. Further, the analysis of the power generation expansion for the different demand levels for Kenya using the Kenya-TIMES model elaborates the disparities in the energy systems' generation expansion results relating to the type of energy planning tool used. This disparity is revealed in comparing the generation technology mix and related GHG emissions under the bottom-up optimization-based Kenya-TIMES model and the econometric model used for energy planning by the Kenyan government.

The development of the Kenya-TIMES model, its use in evaluating the different aspects of Kenya's energy system, and the possibility of its use by decision-makers provide a practical contribution for guidance towards energy decisions required for sustainable economic development for Kenya. The Kenya-TIMES model presents a new national-scale optimization-based energy system model, which can be further developed and used by Kenya's energy decision-makers to do various energy-related studies to improve access to energy services sustainably. The study provides the steps, hence a benchmark, that can be used by the other Sub-Saharan countries to develop national-scale energy system planning models to evaluate optimal low-carbon policy instruments using advanced energy planning tools.

The practical advice that could be drawn from this research is that the Kenyan and other SSA governments should establish detailed demand-supply databanks for country-specific energy sectors. These databanks should include the past energy trends and projected demand-supply drivers. The database should be available to researchers and energy stakeholders to enable energy planning studies and modeling. Furthermore, there is a need to establish a centralized energy panning department in Kenya and any other SSA country yet to establish such a department. This department could be hosted in the Ministry of Energy and should comprise energy statisticians, scientists, and engineers trained in energy modeling and simulation. Lastly, the TIMES modeling framework could be recommended to guide national energy planning objectives for the SSA countries. It is also notable that other energy modeling frameworks could guide national energy objectives.

5.3 Future work

The limitations of this study's results are defined by the scope and assumptions of research and the limitations of the TIMES modeling framework. The shortcomings arising from assumptions and scope include the exclusion of storage assessment and its implication on the generation expansion under low-carbon policies. Further, the study does not evaluate the impact of short-term operational constraints, such as the ramp rates and minimum up and downtime for the baseload generation, on the level of variable renewable energy uptake and energy system cost. Based on the TIMES's framework shortcomings, the study does not firmly recommend one low-carbon policy that could be implemented in Kenya's context. The TIMES framework cannot carry out a multi-criterion decision analysis. A multi-criterion decision analysis could rank the policies based on different criteria for energy security, GHG emission levels, and affordability. As a result, we recommend future work as follows.

Future studies could evaluate the implication of storage on the generation expansion of Kenya's energy system. Kenya has a peak demand that begins at 6 pm and ends at 10 pm. On the other hand, solar insolation is high from 8 am to 4 pm, and wind has a higher time-slice capacity factor from 8 am to 5 pm and 10 pm to 7 am. The low-carbon policy scenarios have a higher percentage share of the intermittent wind and solar power generation, resulting in a higher level of installed capacity because of the mismatch in the timing of the demand and supply peaks. The inclusion of storage will account for the mismatch between demand and generation from the intermittent sources, address overcapacity and provide insights into the cost of using storage to tackle the mismatch between the peak demand and intermittent sources generation. The TIMES framework can account for hourly demand-supply profiles for a selected number of days in a year, providing a refined and reliable modeling platform for evaluating storage in future studies using the Kenya-TIMES model.

Kenya’s current baseload comprises hydropower and geothermal generation. The model results indicate that coal power could be included for baseload generation with increased demand. Further, there is a share of gas capacity related to the percentage of intermittent sources’ generation, which accounts for the peaking reserve. Increased share of variable sources’ power generation in the low-carbon policy scenarios necessitates, for example, frequent ramp-up and ramp-down of the baseload and peaking reserve generations to match the intermittency. The periodic ramp rates have a cost implication, particularly for geothermal, coal, and gas power plants whose technical parameters limit their use as intermediate or peaking plants. The cost is associated with, for instance, the wear and tear, start-up costs in cases where the power plant was shut, loss of efficiency, and human resources. Therefore, future studies could account for the daily operational constraints in the long-term energy planning model. The study could define constraints accounting for the technically and economically feasible start-up times, ramp rates, minimum up and downtime, and minimum load level in the long-term energy generation expansion model. The Unit Commitment feature of the TIMES modeling framework enables the use of Kenya-TIMES for this study.

The diversity, vastness, and geographical distribution of the energy resources in the SSA region provide an excellent opportunity for an integrated regional electricity market. For instance, there is a high hydropower potential on the River Nile in Uganda and Congo River in the Democratic Republic of Congo, gas reserves in Tanzania, and high geothermal potential in Kenya and Ethiopia. Therefore, future studies could further develop the Kenya-TIMES model and use the trade function in the TIMES framework to assess the feasibility of an interconnected low-carbon power market for the East Africa regional power pool. The regional electricity market evaluation could be implemented by including the national-scale energy data of countries in this pool in the Kenya-TIMES model. Such a study could provide insights into the benefits of collaborative generation expansion regarding costs, power system stability and quality of energy services, and carbon emission reduction at the regional level. This study could also be extended to the other Sub-Saharan Africa regional power pools.

Lastly, a multi-criterion decision analysis could be done to rank the low-carbon policy instruments. Long-term energy planning and decision-making are subject to multiple decision variables that might present conflicting trends. For instance, environmental benignity could mean a high percentage of renewable sources in the energy mix, increasing energy system costs. A multi-criteria decision analysis could compare the low-carbon policies based on a combination of energy security, reliability, costs, accrued revenue loss and gain by the government, energy affordability, and environmental benignity. Such assessment could rank the effectiveness of the low-carbon policies based on a combination of the multi-criterion decisions. The evaluation can be done using output from the TIMES model in combination with other decision support tools.

5.4 Overall Conclusions

Overall, energy system planning, analysis, and policymaking have become intertwined aspects of achieving the SDGs and combating climate change. Governments worldwide have committed to reducing fossil-fuel-based energy supply in their national energy mix. The governments have adopted an approach of gradual reduction over time. So far, no country has shown how to industrialize using low-carbon fossil fuels or leapfrog from fossil fuel-based energy generation to low-carbon fuels. However, the global community and the SSA governments could leverage the energy poverty and the high potential of renewable energy resources in SSA to rail the SSA's generation expansion from the conventional fossil-fuel-dominated pathway followed by the developed economies. Proper energy systems analysis and planning will be critical in establishing such a relatively complex supply-demand power system efficiently and effectively.

Studies from developed economies indicate that efficient energy planning is a precursor to addressing energy challenges. Energy planning modeling frameworks have been developed and used to effectively guide energy objectives of intricate national energy systems and address energy challenges in these economies. Such planning has addressed energy poverty and costs, energy security, and reduced GHG emissions.

Kenya has vast energy resource potential, including coal reserves, gas, solar, wind, hydropower, biomass, and geothermal. The Kenyan government aims to address the high cost of energy and energy poverty challenges while limiting GHG emissions as it strives to attain an industrializing country status. The state of Kenya's energy system and future objectives presents a complex situation that is ideal for the analysis presented in this study.

This study has developed a national-scale energy-planning model using an optimization-based planning tool to evaluate pathways towards access to affordable and sustainable energy services for Kenya. The study documents the model development process from reviewing existing modeling works in the SSA region to low-carbon policy evaluation for Kenya's energy system. The study has successfully assessed low-carbon policies for Kenya's power generation expansion under the Vision demand growth. The results indicate that advanced energy planning tools can improve energy decisions to meet national energy objectives while accounting for the global GHG emission reduction efforts. The insights generated by this study can guide better decision-making in energy system planning for Kenya and other countries faced with similar energy challenges to the Kenyan ones.

This thesis shows how an optimal energy system that meets SDG-7 and countries' committed NDCs can be addressed through a research and policy perspective. It elaborates on the relevance of national energy planning capacity, reliable national energy data, and energy planning driven by the country-specific energy objectives in guiding national energy decisions. This study shows that research-based capacity building could address the energy planning expertise gap alongside assessing national energy objectives and policies required to meet the NDCs and SDG-7 in developing economies. Therefore, in a collaborative effort to combat climate change, the global community should leverage expertise in developed economies to build energy planning capacity in developing economies.

The thesis further presents the importance of using advanced energy planning tools to guide national and regional energy systems' objectives. The thesis shows that advanced energy planning tools can concurrently account for various energy themes required to address the SDG-7 and NDCs. The relevance of these tools in evaluating locally-driven policy targets, for instance, the share of renewable energy in the energy mix and globally-driven targets, for example, carbon pricing, is illustrated. This study shows that advanced bottom-up optimization-based modeling tools can be helpful for the long-term planning of energy systems. The thesis demonstrates that energy planning decisions could be improved by using bottom-up optimization-based energy modeling tools to guide national energy decisions in SSA countries, as shown by the analysis done for Kenya's energy system. Therefore, addressing energy challenges in SSA will require a paradigm shift in energy planning strategy by the region’s countries.

The TIMES framework enables for representation of different national-scale energy systems connected with trade links. Therefore, leveraging on the more or less similar economic, social and technological setups of the SSA countries and the flexible TIMES framework, the developed Kenya-TIMES model could be adopted in other SSA countries by adjusting the reference energy system’s input data and the energy demand drivers to fit the chosen country’s conditions. Furthermore, the Kenya-TIMES can be expanded using the TIMES trade function to evaluate a low-carbon energy market in the regional SSA power pools. Based on this research, it is recommended that the SSA countries adopt advanced energy planning tools to guide their generation expansion decisions to address their energy access challenges. Developing the Kenya-TIMES model to assess and guide low-carbon national energy decisions and objectives in the current study will hopefully set a benchmark for similar studies for other SSA countries and the region.

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