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Energy Planning and Optimal Energy Provision

: A Retrospective Analysis of the Power Sector in Kenya

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Abstract

The challenges facing the power sector in Kenya have changed from the early 2000s when energy consumption was curtailed by insufficient power generation and unreliable power supply. One of the key challenges that has emerged in recent times is an anticipated energy surplus in the medium-term that could potentially increase electricity costs in the country.

The objective of this study is to quantitatively analyze the role that energy planning has played in guiding the development of policy and the achievement of government objectives pertaining to optimal energy provision in view of the challenges currently being faced by the sector. The study applies a retrospective optimization approach for its analysis using LEAP (Long-range Energy Alternatives Planning system) to build a model of Kenya's power sector from 2002 to 2017. Two scenarios, considered as possible development pathways to the historical development of the power sector during the study period, are built in the model in line with the objectives of the study.

The results of the analysis are compared in terms of installed capacity expansion, generation mix, carbon dioxide emissions, as well as costs in order to identify an alternative optimal energy supply strategy and therefore determine the significance of energy planning in energy policy formulation and optimal energy provision.

The key findings and policy recommendations of the study are as follows: first, optimal

power generation capacity expansion is instrumental in tackling the challenges of insufficient or surplus installed capacity in the system; hence, government capacity expansion programs should be advised by the planning process on the requisite capacity and expansion rate to minimize mismatches between supply and demand.

Second, optimal power generation plays a role in dealing with the challenges of idle installed capacity in the system. Thus, policy decisions regarding technologies to be used for power generation, which in turn influence energy resources development, should be guided by the energy planning process to lessen the share of idle capacity in system.

Third, optimal capacity expansion plays a part in managing electricity costs. Therefore, power system investment plans should be guided by the planning process in the selection of suitable generation technologies that can potentially contribute to least cost power generation.

Lastly, optimal power generation can contribute to the reduction of carbon dioxide emissions and as a result, can assist in the mitigation of climate change. Hence, capacity expansion programs as well as policies and strategies aimed at climate change mitigation, which in turn affect clean and renewable energy resources development, should be advised by the planning process in the selection of appropriate generation technologies.

Keywords: Energy planning, energy supply, LEAP model, retrospective optimization

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Chapter 1. Introduction

1.1 Study background

Energy is an essential ingredient of socioeconomic development given its versatile utilization in various sectors of the economy. Access to energy, particularly in developing countries, has positively influenced socioeconomic development through the enhancement of employment opportunities, improvement of health-care, raising literacy rates, and improvement of productivity (Trotter et al., 2017). A country's development agenda therefore ought to be supported by an energy plan developed from research on national energy demand, supply, prices, technologies, as well as social and environmental impacts (Prasad et al., 2014).

The development of energy plans entails identifying a set of energy sources and generation technologies that optimally meet energy needs. A comprehensive energy system analysis can conveniently be carried out using energy models which are simplified representations of real energy systems (Hiremath et al., 2007). The models play an important role in advising decisions pertaining to appropriate energy plans for the future through the analysis of existing energy supply systems and the development of strategies that consider various energy provision goals. These goals, which often tend to be in conflict with one another, include guaranteeing adequate supply to satisfy the national energy needs, minimizing energy supply costs, ensuring prudent exploitation of natural resources, and ensuring that energy supply does not negatively affect the population's health and lifestyle (Nagel, 2019).

1.2 Research problem

The attainment of economic growth and development targets in Kenya is dependent on, among others, optimal energy provision[1]. The government is cognizant of the importance of optimally supplying energy for the growth and development of the economy, as is evident from the energy policies and energy laws that have been developed over time. At the same time, the challenges facing the energy sector have continued to change. A decline in energy consumption was experienced in the 1980s, the 1990s, and the early 2000s because of decreasing economic growth and it has persisted in the 2000s despite a turnaround in the economy. The declining consumption was attributed partly to insufficient generation capacity and unreliable power supply.

The steps taken by the government to address the challenges and meet the objectives pertaining to optimal energy provision have included the development of national energy plans. However, challenges have emerged which concern the integration of energy planning in the development of electricity infrastructure with the political aspirations of various administrations influencing the energy plans as well as the procurement of power generation projects. The weaknesses in linking planning with implementation are likely to result in considerable energy surplus in the medium-term and an increase in electricity costs. A number of recommendations have been made to remedy the situation, including

[1]Optimal energy provision refers to adequate, reliable and affordable supply of energy to satisfy energy demand while protecting the environment

the renegotiation of power purchase agreements, the suspension of the procurement of additional intermittent capacity and delaying the construction of new geothermal power plants. The implementation of the recommendations is likely to bring about additional challenges particularly with regard to private investments in the sector. This study therefore seeks to analyze the role that energy planning has played in informing policy decisions aimed at achieving government objectives pertaining to optimal energy provision.

1.3 Research questions

The importance of optimal energy supply in meeting the country's economic growth and development targets in contrast to past energy consumption trends and the diverse challenges that the energy sector has faced over time raise the following questions that are of interest in this study:

i. What effects have policy decisions informed by factors other than quantitative energy planning had on the attainment of government objectives related to optimally supplying energy to promote economic growth and development?

ii. What role would energy planning have played in shaping policy decisions taken by the government to address the challenges that have been faced in the power sector and to guarantee adequate, reliable, and affordable energy supply?

1.4 Research objectives

The achievement of various goals with respect to energy provision is dependent on, among others, energy planning, which involves developing suitable plans through the analysis of the existing energy system and the proposal of appropriate supply strategies. The main objective of this study is to quantitatively analyze the importance of energy planning in guiding the making of energy policy in Kenya and in achieving government objectives pertaining to optimal energy provision. Specifically, the study aims at meeting the following objectives:

i. To investigate the impact of energy policy decisions on the achievement of government objectives pertaining to optimal energy provision.

ii. To assess the contribution of energy planning to policy-making and achievement of government objectives pertaining to optimal energy provision.

1.5 Methodology

The study is carried out by conducting an ex-post analysis of the evolution of the power sector in Kenya. The period chosen for the study, 2002 to 2017, observed the realization of economic growth as well as the implementation of a number of power sector reforms. The LEAP (Long-range Energy Alternatives Planning system) model is considered to be suitable for the analysis given the model's capabilities to allow for the representation of an energy system together with the creation and evaluation of different scenarios. The study therefore uses LEAP to create a model of the power sector in Kenya along with scenarios developed in line with the objectives of the study. The results of the analysis are compared and contrasted in terms of capacity expansion, generation mix, carbon dioxide emissions and costs.

1.6 Scope of the study

The study focuses on analyzing the historical evolution of the power sector in Kenya from 2002 to 2017 through the assessment of the actual energy consumption and the actual power generation over the period. It also compares the results of the historical evolution of the sector with the results of two scenarios, supply optimization scenario and ideal scenario, which are considered to be possible alternative development pathways to the historical evolution of the sector. The results are compared with regard to capacity expansion, power generation mix, costs (investment and power generation), and carbon dioxide emissions. The comparison is done in order to identify an alternative optimal energy supply strategy and to therefore analyze the significance of energy planning in optimal energy provision as well as in energy policy formulation.

1.7 Significance of the study

National energy planning in Kenya is done biennially and despite being faced with a number of challenges, the process has substantially contributed towards supporting the expansion of power generation capacity in the country. This study aims at quantitatively examining the contribution of the process in informing the formulation of energy policy and in attaining government targets regarding optimal energy provision. The results of the study will be useful in determining the importance of the energy planning process as an integral component of energy policy formulation and power generation capacity expansion. The results will also be useful in advising the development of future energy generation as well as energy consumption strategies that aim at collectively ensuring a balance between supply and demand.

1.8 Thesis structure

This thesis consists of six chapters. The second chapter elaborates on the power sector in Kenya. It explains the importance of energy in the context of socioeconomic development in the country. It describes the policy and institutional setup of the power sector as well as the national energy planning process. It also elaborates on the energy consumption trends observed in the country from the 1980s through the 2000s.

The third chapter reviews existing literature that is relevant to the study. It provides an understanding of the contribution made by the energy planning process in supplying energy, including a description of different energy system modelling tools and their applicability in analyzing various aspects of an energy system. It also provides a summary of a number of studies carried out with objectives that are similar to this study, the methodologies applied in the studies, and their findings.

The fourth chapter describes the methodology applied in carrying out the analysis including the model chosen for use in analyzing the data. It also explains the scenarios developed in keeping with the objectives of the study so as to assess the outcomes of different probable energy system development pathways compared to the historical evolution of the power sector. It further describes the data required for the study as well as the assumptions made in creating and analyzing the scenarios.

The fifth chapter explains the results obtained from the scenario analysis and the arising policy implications. It describes the analysis' results for each of the scenarios over the study period in detail and compares them with reference to capacity expansion, power generation mix, costs (investment and power generation), and carbon dioxide emissions. It also identifies key findings from the analysis' results and their implications in policy formulation.

The sixth chapter concludes the thesis and makes some policy recommendations as well as some suggestions for further study. It provides a summary of the study objectives, the approach used in carrying out the study and analysis results. It also makes a number of policy recommendations based on the findings of the study regarding capacity expansion, power generation mix, costs (investment and power generation), and carbon dioxide emissions. It further identifies some of the limitations encountered in carrying out the study and makes suggestions for further analysis.

Chapter 2. Overview of the Power Sector in Kenya

2.1 The role of energy in socioeconomic development in Kenya

The central role of energy in the country's socioeconomic development has been highlighted in its development blueprint, Kenya Vision 2030, which considers the importance of energy in achieving its objective of transforming Kenya into an industrialized country providing a high quality of life to its citizens by 2030. The blueprint is founded on economic, social and political pillars with the economic pillar specifically seeking to attain 10% of an annual GDP growth rate through implementation of development projects (Government of Kenya, 2007). The proposed development projects include industrial parks, standard gauge railway, light rail as well as iron and smelting industry. Implementation of the projects is expected to increase energy demand hence underscoring the importance of energy provision at relatively lower costs, enhanced efficiency in consumption as well as exploitation of new energy sources.

The importance of energy in facilitating socioeconomic development in the country has also been underscored in the government's five-year strategic agenda for the period between 2018 and 2022, the Big Four Action Plan. The Plan aims at stimulating economic growth and development through implementation of projects that will create jobs, improve health standards, enhance living conditions and lower the cost of living. Various projects have therefore been initiated by the government in line with the Plan's objective to, among others, promote value addition and increase the manufacturing sector's contribution to the country's GDP. Lowering electricity costs and improving electricity infrastructure will be helpful in attaining this objective and raising the competitiveness of locally manufactured goods (Parliamentary Budget Office, 2018).

2.2 The policy and institutional organization of the power sector in Kenya

The history of the country's power sector can be traced back to the formation of the East African Power and Lighting Company (EAP&L) in 1922. Its subsidiary, Kenya Power Company (KPC), was later established for the purpose of building electricity transmission lines between Nairobi and Tororo in Uganda to facilitate importation of power to Kenya. EAP&L was succeeded by state-owned Kenya Power and Lighting Company (KPLC) in 1983 (Ministry of Energy, 2011).

In terms of policy, the country's initial energy policy was developed in 1987 with the aim of mitigating the adverse effects of oil importation on the economy, guaranteeing security of supply, ensuring affordable pricing and advancing exploitation of indigenous resources. The 1990s saw the emergence of new challenges linked to economic liberalization including rising poverty, economic stagnation as well as electricity rationing and outages (Ministry of Energy, 2004). It was therefore necessary to review the policy in order to integrate it with broader policies for socioeconomic development and a subsequent policy, the Sessional Paper No. 4 of 2004 on Energy, was developed. This was in turn succeeded by the National Energy and Petroleum Policy of 2015 that was developed with the aim of ensuring adequate, sustainable and affordable supply to satisfy energy requirements at least cost while protecting the environment.

The structural adjustment program of the 1990s brought about power sector reforms as illustrated in figure 2.1. The reforms included enactment of the Electric Power Act of 1997, formation of state-owned Kenya Electricity Generating Company (KenGen) to undertake power generation, formation of the Energy Regulatory Board (ERB) to undertake sector regulation and continuation of KPLC's role in transmission and distribution (Ministry of Energy, 2011). Additional reforms in the sector were brought about by the Sessional Paper No. 4 of 2004 on Energy that provided for creation of the Geothermal Development Company (GDC) and the Kenya Electricity Transmission Company (KETRACO). The Energy Act of 2006 also reformed the sector through providing for creation of the Energy Regulatory Commission (ERC), that succeeded ERB, and the Rural Electrification Authority (REA) (Ministry of Energy, 2011). Other institutions in the sector are the Ministry of Energy (MoE) that is responsible for policy formulation and resource mobilization, the Kenya Nuclear Electricity Board (KNEB) that undertakes implementation of the country's nuclear power programme and independent power producers (IPPs) that take part in generation of bulk power for sale to KPLC (Ministry of Energy and Petroleum, 2015).

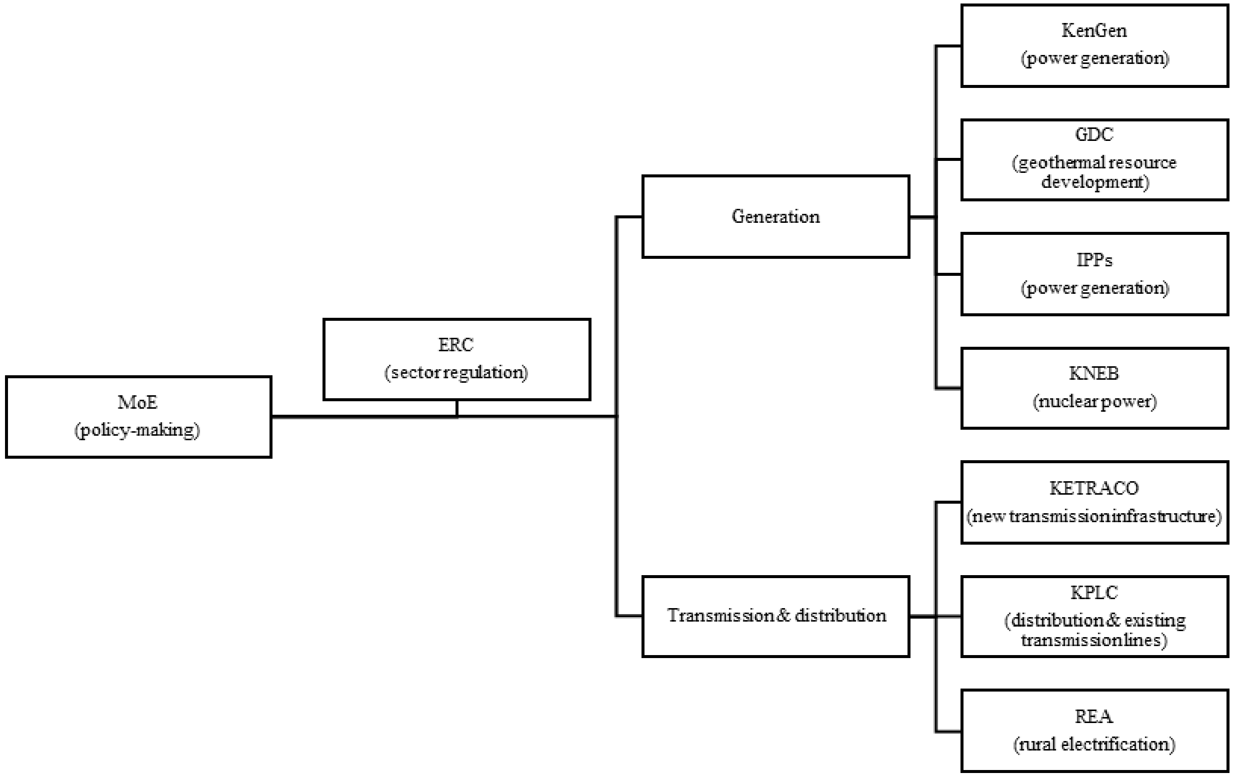

Figure 2.1. Institutional framework of the power sector in Kenya

2.3 National energy planning

The government's objectives regarding energy provision include: 1) increasing energy supply and guaranteeing security of supply; 2) ensuring reliable access to affordable energy, particularly electricity; 3) creating a supportive framework for private energy investments; and 4) limiting the environmental as well as social impacts of energy supply (Ministry of Energy and Petroleum, 2016). National energy planning plays a central role in achievement of these objectives. The Energy Act of 2006 assigned the responsibility for developing national energy plans to ERC which in turn established a committee in 2009 to develop and biennially update medium and long-term plans for the electricity sub-sector (Ministry of Energy and Petroleum, 2015). The national energy plans, which were last updated in 2016, forecast future demand, identify generation potential and estimate investments in transmission so as to satisfy demand at least cost.

Demand for energy in Kenya is met by biomass (69%), petroleum (22%) and electricity (9%) (Ministry of Energy and Petroleum, 2015). Electricity is generated using fossil fuels as well as renewable energy and these energy sources in 2017, as shown in table 2.1, contributed 34% and 66% respectively to the country's total installed capacity (Ministry of Energy, 2018). Electricity generation using fossil fuels relies on crude oil imported from Abu Dhabi, United Arab Emirates, and Saudi Arabia. The renewable energy sources available for exploitation include geothermal, hydro, wind, solar, biomass and biogas. The geothermal potential is estimated at 10,000 MW, large and small hydro potential is estimated at 6,000 MW and wind potential is estimated at 4,600 MW. The country also has considerable solar potential with 4 to 6 kWh/m^2/day insolation levels (Ministry of Energy, 2018). Cognizant of the importance of promoting generation of electricity using renewable energy, the government published a feed-in tariff policy for wind, small hydro and biomass electricity generation in 2008 and revised it in 2010 to also include geothermal, biogas and solar electricity generation (Ministry of Energy, 2012).

Table 2.1. Installed power generation capacity in 2017

Technology type	**Generation capacity (MW)**		**Energy purchased (GWh)**
	Installed	**Effective**	
Hydro	824	803	3,340.98
Geothermal	652	644	4,450.92
Thermal	803	762	2,164.86
Cogeneration	28	23.5	0.71
Solar	0.55	0.52	0.54
Wind	26	26	63.18
Imports	-	-	183.66
Total	2,333	2,259	10,204.85

Source: Ministry of Energy, 2018.

Despite playing a part in promoting expansion of the country's power generation capacity, the national energy planning process has faced a number of challenges. For example, there have been instances when conflicts have arisen between the technoeconomic national energy plans and political aspirations of different administrations which have tended to influence the plans to adopt overly optimistic assumptions regarding growth in energy demand as well as other factors (Godinho & Eberhard, 2019). In addition to the ambitious political targets pertaining to energy provision, weaknesses in linkages between planning and implementation also exist. Procurement of power generation projects in the country is largely connected with national energy planning but there have also been instances of it being politically influenced and this has undermined the energy planning process (Godinho & Eberhard, 2019).

2.4 Energy consumption trends in Kenya

A downward trend in economic growth in the 1980s, 1990s and early 2000s is said to have contributed to a decline in energy consumption at the time. Additionally, a low level of industrial development, high energy costs and limited investment in the transmission and distribution network also resulted in the declining consumption (Ministry of Energy, 2004). Stabilization of the macroeconomic environment in the 2000s led to growth in the economy but growth in energy consumption was hindered by shortages and disruptions in supply together with high costs. The electricity sub-sector has particularly faced problems relating to generation capacity, reliability of power supply and integration of planning in development of electricity infrastructure. Electricity access nationally at the time was approximately 15% and electricity consumption was reportedly 121 kWh per capita (Ministry of Energy, 2004). In order to deal with the problems, the government prioritized capacity expansion at the rate of economic growth as well as maintenance of an adequate reserve margin to ensure security of supply and by 2016, several power projects had been committed (Ministry of Energy and Petroleum, 2016). The government also, in a bid to expand capacity and guarantee supply, sought to increase the capacity in 2013 by at least 5,000 MW by 2017 and at the same time decrease the cost of generation to US$ 0.07 (Ministry of Energy and Petroleum, 2015). Furthermore, the government embarked on different national electrification projects targeting attainment of universal access to electricity by 2020 and the projects had raised the electricity access rate to 73.42% in 2018 (Kenya Power, 2018).

The capacity expansion is, however, likely to lead to a substantial energy surplus according to the long-term energy plan for the period between 2015 and 2035, resulting in an increase in the levelised cost of energy (LCOE) by up to 26% in the medium-term (Ministry of Energy and Petroleum, 2016). The challenges being faced in the power sector are mainly associated with stimulating demand for electricity and matching infrastructure to expected demand. Inadequate growth in demand has aggravated the challenges since the plans to increase power generation capacity lack corresponding plans to increase electricity consumption (Taneja, 2018). A subsequent medium-term update of the plan for the period between 2017 and 2022 recommends renegotiation of power purchase agreements for power plant projects with large capacities to incorporate operational flexibility; suspension of procurement of additional intermittent capacity through the feed-in tariff policy; and delaying the construction of new geothermal power plants to allow for growth in demand to match the supply (Ministry of Energy, 2018). Consequently, KPLC, the country's electricity retailer, is reported to have frozen signing new power purchase agreements indefinitely pending a review to determine the additional demand for electricity in the country.

Chapter 3. Literature Review

3.1 Review of role of energy planning in supply of energy

Energy typically refers to the ability to do work or produce heat. Energy is manifested in different forms including motive force, light, heat and chemical transformation. It can be exploited from different sources with varying degrees of ease or difficulty (Bhattacharyya, 2011). Demand for energy globally has continued to rise mainly due to industrial development and as a result, development of new and renewable energy has been prioritized in many countries. Electricity, which is probably the most versatile secondary energy source in the modern world associated with human and economic development, has particularly been increasing its share in the overall energy mix (Bazmi & Zahedi, 2011). The rise in energy demand generally, and electricity demand specifically, has brought to the fore concepts such as energy security, low emission energy generation and affordable energy supply (Thangavelu et al., 2015).

The provision of energy is guaranteed by an energy supply system that is made up of three sectors namely supply sector, energy transformation sector and energy consuming sector. The supply sector includes indigenous production, exports or imports of fuel; the energy transformation sector converts various primary energy forms to secondary energy forms; and the energy consuming sector utilizes different energy forms to satisfy lighting, heating, cooling and motive power needs (Bhattacharyya, 2011). The energy sector around the world is typically characterized by capital-intensive energy supply investments hence it is imperative for suitable investment decisions to be made considering issues such as rising demand, limited fossil fuel reserves and climate change. Energy projects typically have high initial investment requirements, long construction periods during which market conditions can change, long asset lifespans that increase uncertainty of future costs and benefits, large capacities to benefit from economies of scale and high degrees of specificity which render the assets unusable in other sectors of the economy (Bhattacharyya, 2011). It is therefore necessary to carry out long-term energy planning based on factors such as energy demand, energy generation technologies and their costs as well as fuel costs.

Energy planning involves identifying an optimal, normally least-cost, supply mix to satisfy a given energy demand. It involves determining an optimal combination of energy sources and energy generation technologies to meet energy demand. It is carried out using appropriate energy models to create an energy mix that optimizes performance parameters such as costs and emissions (Thangavelu et al., 2015). The process is a dynamic one, requiring periodic review considering changing conditions that make accurate forecasting of situations and trends difficult. Nonetheless, inaccurate plans are useful as opposed to no plans at all because more mistakes are made as a result of not attempting to plan ahead. Incorporating scenario analysis in energy planning can assist in improving forecasts through examination of probable events, tendencies and desirable situations by means of scenarios that are plausible, comprehensive and relevant (Bazan-Perkins & Fernandez-Zayas, 2008).

Policymakers often face a challenge in striking a balance between energy supply and demand which is a key feature of energy policy formulation and implementation. The energy planning process can assist in addressing this challenge. The ultimate objective of the process is to provide information to decisionmakers for, among others, formulation of appropriate government policies for development of the energy sector and preparation of capital investment programmes committing resources (financial and human) to the sector (Mougouei & Mortazavi, 2017; Wang & Min, 2000).

The challenges faced in energy planning include difficulties in estimating future demand for energy. Any errors in estimation could lead to either surpluses or shortages in energy generation capacity which is problematic particularly for electricity supply systems given the long lead times in building power plants and inability to store electricity (Soontornrangson et al., 2003). Problems of shortages in generation capacity due to demand forecasting errors cannot be solved in the short-term because of the long lead times required in construction of power plants. Shortages are disadvantageous especially for the productive sectors of the economy such as the industrial and commercial sectors since they decrease production which in turn decreases the country's gross domestic product (GDP). Problems of surpluses on the other hand can be solved by cancelling power plant projects or leaving existing power plants idle because of inadequate demand. Such measures are disadvantageous since repayment of the costs incurred in building and operating the power plants does not cease therefore leading to increased electricity costs for consumers.

Energy system modelling

Energy system models are useful in situations where policy makers need some insight into the ramifications of current investment and policy decisions on the development and performance of the energy system in the future. The models allow for the analysis of various energy demand and supply strategies through simulation of different expansion paths under different conditions to examine the possible implications of decisions policy instruments or technology evolution on the energy system (Gacitua et al., 2018). The models can therefore give insight into the changes that could be made to the system to enable optimal expansion under different conditions.

The long-term generation expansion planning problem is generally a mathematical problem formulated as a mixed integer nonlinear programming problem with several decision criteria and uncertainties (Trotter et al., 2019). Analysis of various kinds of energy-economy-environment planning and policy concerns has been conducted using energy system modelling tools such as general equilibrium simulation, system dynamics simulation as well as optimization models (Pandey, 2002). General equilibrium simulation and system dynamics simulation have been applied in analysis of long-term effects of macroeconomic policies such as market-based instruments as well as in analysis of effects of implications of privatization on utilities' behaviours in competitive markets. Optimization models on the other hand have been applied in tackling utilities' operational planning issues as well as in analysis of medium to long-term effects of energy system development features such as capacity expansion, emissions and costs.

Energy system models are grouped according to their representation of interactions between energy and economy into either bottom-up or top-down models. Bottom-up models are characterized by their detailed representation of energy resources, technologies and demand whereas top-down models are characterized by their sectoral aggregation and representation of energy system effects on, among others, trade and economic growth (Gargiulo & Gallachoir, 2013; Pandey, 2002). Optimization models are examples of bottom-up models that are used in evaluating technology and fuel options given exogenous structural constraints and assumptions about macroeconomic parameters such as prices and economic growth. General equilibrium simulation and system dynamics simulation models in contrast are examples of top-down models that are used in examining the macroeconomic implications of market-based instruments such as government regulatory policies as well as exogenous factors such as long-term technological progress.

3.2 Review of previous relevant studies

Energy planning is necessary in establishing an energy path that satisfies the society's demand for final energy services and facilitates attainment of national development objectives (Lee et al., 2018). A number of studies have been carried out in different countries to examine the contribution made by energy planning in development of energy policies and resolving power sector challenges such as energy crises. The studies have been motivated by, among others, problems arising from generation capacity expansion, consideration of proposals for dealing with energy crises and analysis of benefits that are likely to be realized by carrying out energy planning.

Spain

The progression of Spain's power sector was examined taking into consideration conventional and renewable technologies as well as sustainability and energy security in a study that was motivated by the problems that had resulted from expansion in the country's generation capacity. The study also sought to draw lessons from its results on the importance of quantitative energy planning as a prerequisite for policy-making. The study used LEAP (Long-range Energy Alternatives Planning system) to model different scenarios of Spain's power sector and calculate the cost of not doing energy planning as well as the unforeseen economic crisis that occurred in the country. The results of the analysis pointed to excess installed capacity, surplus investment, higher electricity generation cost, no significant improvement in the country's stance with regard to its global obligations in renewable energy share and maintenance of energy independence with no unfavourable effects on energy affordability with proper energy planning. The study concluded that energy planning requires committed policy-making to succeed since the analysis showed that following an imperfect plan is less costly than not following any plan at all (Gomez, Dopazo, & Fueyo, 2016).

Iran

A similar study was carried out in Iran to investigate the role which commitment to energy planning guidelines could have played in averting the challenges faced in the power sector and the benefits that could have been realized. The paper used MESSAGE (Model for Energy Supply Strategy Alternatives and their General Environmental Impacts) to conduct an ex-post analysis by modelling two scenarios of the evolution of the country's power sector. The results of the analysis pointed to a possibility to reduce cumulative total system costs because of lower fuels costs of more efficient and less emitting technologies considered in the cost-optimal scenarios that optimized the supply-side and included demand management. The results also indicated that it was possible to lower total carbon dioxide emissions in the cost-optimal scenarios compared with an actual scenario that modelled the historical development of the sector. Consequently, the study recommended inclusion of renewable energy technologies in the medium to long-term generation mix and implementation of demand-side strategies through, among other things, energy price reform (Manzoor & Aryanpur, 2017).

Pakistan

A study was also carried out in Pakistan to review the status of the energy and electricity sector in the country and recommend a way out of the energy crisis in the country through energy planning. It considered previous planning studies that had been carried in the country as well as the policies that had been formulated. The study applied qualitative data analysis to identify strengths and weaknesses in the energy and electricity sector with respect to planning and formulation of policy. The study found that Pakistan was unable to appropriately harness its indigenous energy resources during its severe energy crisis partly due to development of irrational energy policies that disregarded various energy planning studies that were carried out at the time with international support. It recommended formulation of energy policies informed by comprehensive integrated energy planning to advise policymakers regarding effects of implementing different energy plans (Mirjat et al., 2017).

Kingdom of Saudi Arabia

A study with similar focus on energy planning was carried out in the Kingdom of Saudi Arabia to analyze progression of its power market over a period of 10 years taking into consideration cost and environmental impact minimization. The study found that consideration of cost minimization only resulted in international fuel prices causing a rise in energy efficiency and introduction of renewable energy sources in the expansion plan in contrast to domestic fuel prices. The study also found a similar result for a scenario considering minimization of environmental impact because the effect of cost on the expansion plan was negligible given the reduced environmental impact (Groissbock & Pickl, 2016).

3.3 Research implications

The literature reviewed indicates that energy planning is useful in optimally supplying energy at least-cost because the process takes into account factors such as energy demand, energy generation technologies and their costs as well as fuel costs in order to identify an optimal combination that satisfies energy demand. Energy system modelling tools allow for assessment of different energy demand and supply strategies under given conditions. Periodic reviews of energy plans are necessary since accurate forecasting of situations and trends is made difficult by changing conditions. Scenario analysis, which involves examining possible events, tendencies and desirable situations using scenarios, can also assist in improving forecasts. The information obtained from the energy planning process can particularly be useful for decisionmakers in formulation of policies for energy sector development. The studies carried out in various countries to assess the role of energy planning in development of energy policies and resolution of power sector challenges have shown that an imperfect plan is less costly than not following any plan at all as in the case of Spain and Pakistan. The studies have also shown that optimal energy provision can assist in reducing total power system costs and carbon dioxide emissions as in the case of Iran and the Kingdom of Saudi Arabia.

Chapter 4. Methodology

4.1 Analysis approach and modelling

This study adopts a retrospective optimization approach for its analysis and achievement of its objectives. The approach to analysis of power sector development has been applied in examining progression of the power sector in Spain considering quantitative energy planning as a prerequisite for policy-making (Gomez, Dopazo, & Fueyo, 2016) and in investigating the potential role which energy planning could have played in averting the challenges faced by the power sector in Iran (Manzoor & Aryanpur, 2017). Similarly, this study uses the approach to analyze the significance of energy planning in guiding the development of energy policy and achievement of government objectives pertaining to optimal energy provision in Kenya.

The analysis in this study is carried out using the Long-range Energy Alternatives Planning (LEAP) system model which is an energy planning model that covers both the demand and supply sides of an energy system (Heaps, 2016). The model follows an accounting framework approach to give a consistent view of energy demand and supply based on an energy system's physical description (Bhattacharyya, 2011). It has been utilized extensively in energy policy analysis because of its suitability in tracking energy consumption, production and resource extraction in various sectors of the economy. The model also allows for creation of probable pathways for development of an energy system using a scenario approach. It therefore makes it possible to represent different energy systems with different data structures enabling energy policy analysts to create and evaluate different scenarios based on aspects such as energy requirements, social costs and benefits as well as environmental impacts.

4.2 Scenario development

This study is carried out by creating a model of the power sector in Kenya from 2002 to 2017 using the LEAP model. The model consists of two scenarios, namely supply optimization scenario and ideal scenario as shown in table 4.1, that are developed in line with the objectives of this study. The outcomes of the scenarios are analyzed in regard to capacity expansion, power generation mix, costs (investment and power generation) and carbon dioxide emissions with the aim of determining the importance of energy planning in development of the power sector in Kenya.

Table 4.1. Summary of the scenarios created in the study

	Supply optimization scenario	Ideal scenario
Scenario basis	Models optimal expansion of generation capacity and energy mix to meet actual demand	Models combined application of supply optimization and DSM with aim of achieving efficiency
Scenario creation	Created using actual consumption data with energy generation being optimized in LEAP given actual resources used in power generation	Created same way as supply optimization scenario and extended to incorporate effect of EEC measures on consumption
Applicability	Useful in examining importance of long-term least cost energy planning in developing supply-side strategies	Useful in assessing potential benefits of synchronized implementation of supply-side optimization and DSM strategies
Input data	Input data similar with that used to model the historical evolution of the power sector	Input data similar with that in supply optimization scenario with adjusted consumption (EEC measures)

Historical evolution of the power sector

This scenario is representative of the historical development of the power sector during the study period. It is created using actual energy production and consumption data to obtain results which form a basis for comparison with the results of the other scenarios in terms of capacity expansion, power generation mix, costs (investment and power generation) and carbon dioxide emissions. The input data includes actual energy demand, actual transmission and distribution losses, actual energy generation, actual costs (capital cost, fixed and variable operation and maintenance costs, fuel cost) and actual energy resources used for power generation.

Supply optimization scenario

This scenario models the development of the power sector taking into account optimization of energy production to satisfy the energy requirements during the study period. It is created using actual energy consumption data and energy generation is optimized in LEAP given the actual energy resources used for power generation to identify an optimal expansion path during the period. The results of the scenario are useful in examining the importance of long-term least cost energy planning in developing supply-side strategies that effectively and efficiently meet energy demand. The input data is similar with the data used to model the historical evolution of the power sector.

Ideal scenario

This scenario models the development of the power sector considering a combined application of supply-side optimization and demand-side management to attain efficiency in energy production and consumption. It is created using energy consumption data that is adjusted to factor in implementation of energy efficiency and conservation (EEC) measures during the period and energy generation is optimized in LEAP given the actual energy resources used for power generation as in the supply optimization scenario. It is assumed that EEC measures implemented during the period were likely to progressively decrease energy consumption by up to 20% at the end of period. This assumption is based on an estimated primary energy wastage in 2005 of between 10% and 30% (Ministry of Energy and Petroleum, 2015). The results are useful in assessing the potential benefits of implementing an energy supply strategy that optimizes the supply-side of the energy system while achieving efficiency in the demand-side. The input data for this scenario is similar with the data for the supply optimization save for the adjusted energy demand.

4.3 Data requirements and assumptions

The data required for this study broadly consists of energy consumption, energy generation and energy resources. The data is obtained for the period between 2002 and 2017. An annual discount rate of 8% is assumed for cost calculations in the study (Kenya National Bureau of Statistics, 2018). Additionally, a planning reserve margin of 25% in excess of the peak demand is assumed based on the margin applied in previous energy planning studies (Ministry of Energy, 2011; Ministry of Energy and Petroleum, 2013).

Energy consumption

The historical evolution of the power sector and the supply optimization scenario are created using historical energy consumption data as shown in table 4.2. The data is grouped into four consumer categories as approved in the *2018 Schedule of Tariffs* by the sector regulator, Energy Regulatory Commission, and which are used by the national electricity retailer, Kenya Power and Lighting Company, for billing purposes. The domestic consumer group is representative of household consumption that is capped at 15 MWh per month (or 180 MWh annually) per household at low voltage level (240 or 415 volts). The small commercial consumer group is representative of non-domestic consumers whose consumption is similarly capped at 15 MWh per month (or 180 MWh annually) per connection at low voltage level (240 or 415 volts). The domestic and small commercial consumer groups are distinguished by, among others, their specific consumption with the latter having a higher specific consumption. The large commercial and industrial tariff group is representative of consumers whose consumption either exceeds 15 MWh per month (or 180 MWh annually) per connection at low voltage level (415 volts) or whose supply is metered at medium to high voltage levels (between 11 and 132 kilovolts). The street lighting consumer category is representative of consumption by public lamps (street lights) whose supply is metered at low voltage level (240 or 415 volts).

Fluctuations in demand are taken into account in all the scenarios by means of a representative annual load shape and load duration curve as illustrated in figure 4.1 and figure 4.2 respectively. Annual load curves obtained for the period between 2008 and 2015 did not show significant variations from year to year in terms of shape despite an overall increase in load (demand) during the period (Ministry of Energy and Petroleum, 2016). Similarly, the load curve in any given year did not show significant variations within the year with only one peak occurring towards the end of the year in either November or December (Ministry of Energy and Petroleum, 2016). The load curve in 2008 is therefore used to represent the annual fluctuations in demand over the study period.

Table 4.2. Annual energy consumption (2002 – 2017)

Year	Energy consumption by tariff group (GWh)								Total energy consumption (GWh)
	Domestic	**Share (%)**	**Street lighting**	**Share (%)**	**Small commercial**	**Share (%)**	**Large commercial & industrial**	**Share (%)**	
2002	945	25.5	6	0.2	498	13.4	2,257	60.9	3,707
2003	1,013	25.7	7	0.2	516	13.1	2,399	61.0	3,936
2004	1,079	25.6	7	0.2	556	13.2	2,574	61.1	4,216
2005	1,157	25.9	8	0.2	586	13.1	2,716	60.8	4,467
2006	1,257	26.3	10	0.2	611	12.8	2,907	60.8	4,785
2007	1,407	27.4	12	0.2	646	12.6	3,071	59.8	5,135
2008	1,488	27.9	14	0.3	776	14.5	3,062	57.3	5,340
2009	1,507	27.4	16	0.3	892	16.2	3,086	56.1	5,502

Year	Energy consumption by tariff group (GWh)								Total energy consumption (GWh)
	Domestic	Share (%)	Street lighting	Share (%)	Small commercial	Share (%)	Large commercial & industrial	Share (%)	
2010	1,616	27.7	17	0.3	935	16.0	3,276	56.1	5,844
2011	1,749	28.2	17	0.3	1,020	16.5	3,409	55.0	6,195
2012	1,863	29.0	20	0.3	1,089	16.9	3,452	53.7	6,423
2013	2,047	29.7	22	0.3	1,156	16.8	3,658	53.1	6,882
2014	2,112	28.7	28	0.4	1,293	17.6	3,935	53.4	7,367
2015	2,284	29.6	38	0.5	1,309	17.0	4,074	52.9	7,705
2016	2,452	30.6	49	0.6	1,326	16.5	4,189	52.3	8,016
2017	2,597	30.8	60	0.7	1,386	16.4	4,389	52.1	8,431

Source: Ministry of Energy and Petroleum, 2016.

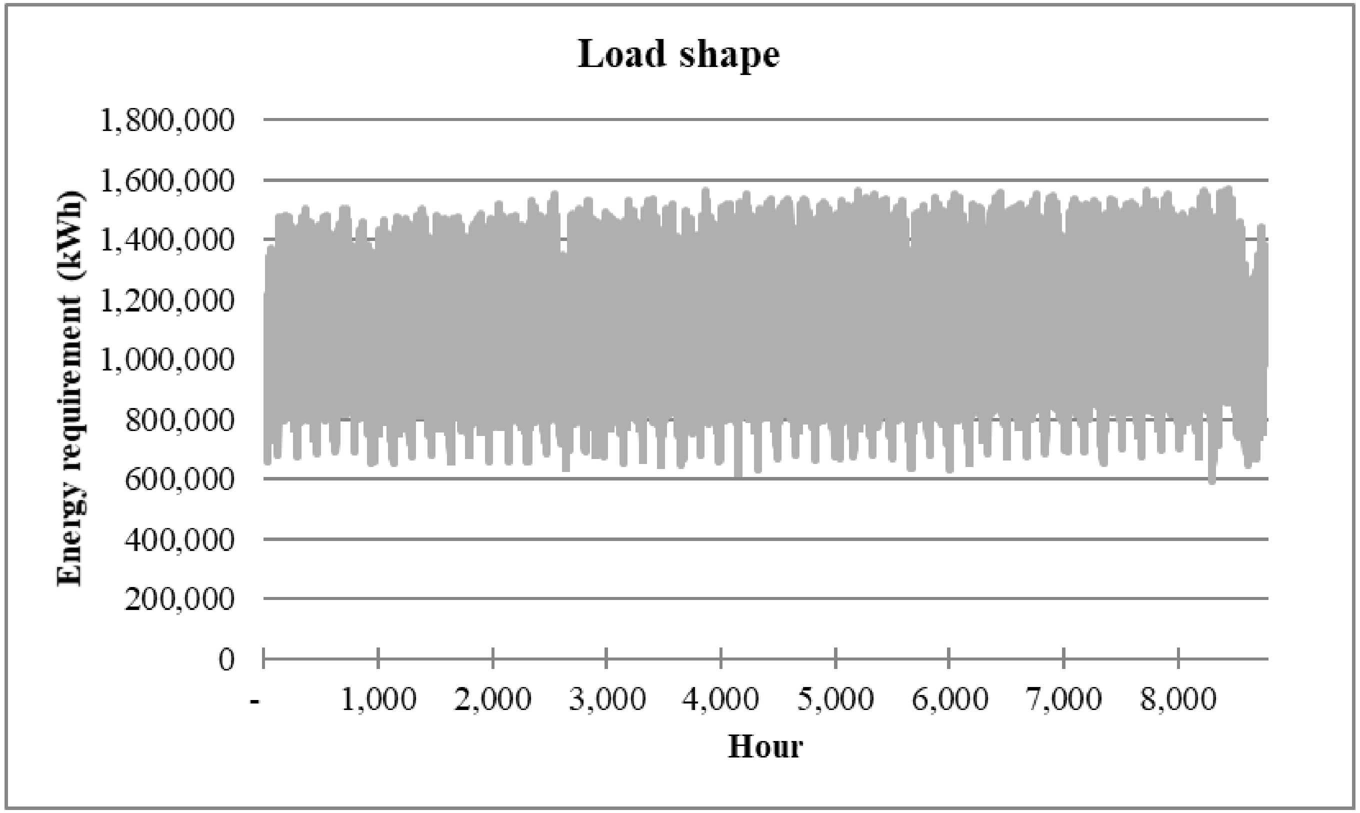

Figure 4.1. Load shape in 2008 (Ministry of Energy and Petroleum, 2016)

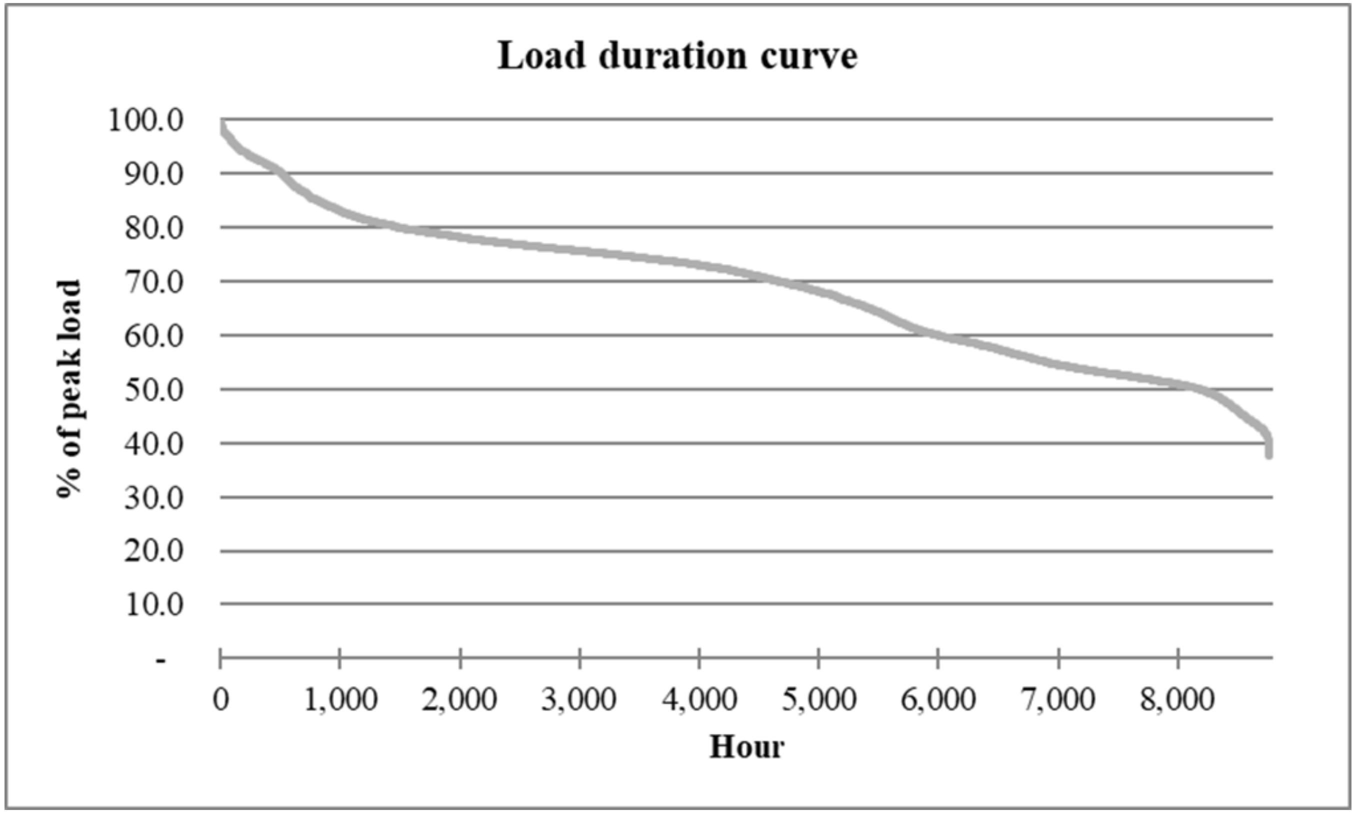

Figure 4.2. Load duration curve in 2008 (Ministry of Energy and Petroleum, 2016)

Energy generation

The scenarios in this study are created using historical installed capacity data. Additionally, the historical evolution of the power sector uses actual energy generation data. The data for the scenarios also includes maximum availability which is the maximum percentage of energy generated in a specific period by a given technology, process efficiency which is the percentage of energy output from energy input for a given technology, merit order (base or peak load) of a given technology, capital cost as well as fixed and variable operation and maintenance costs. Table 4.3 shows the installed capacity and energy generation data during the study period and table 4.4 shows the technoeconomic data for the different power generation technologies.

The power generation technologies that the country utilized over the study period were hydro, thermal, geothermal, wind and cogeneration power generation technologies. The country's hydro power generation potential is estimated to be up to 6,000 MW of which 806 MW had already been exploited over the study period (Ministry of Energy, 2011). The installed capacity consisted mainly of large hydro power plants with capacities ranging from 20 MW to 225 MW. Thermal power plants in the country had a total installed capacity of 772 MW by the end of the study period and they utilized heavy fuel oil (residual fuel oil) for power generation that was until 2013 refined and processed in the country from crude oil imported from the United Arab Emirates and Saudi Arabia and thereafter imported as a refined product (Ministry of Energy and Petroleum, 2016). The country's geothermal power generation potential has been estimated to be up to 12,000

MW of which 623 MW had been exploited by the end of the study period (Ministry of Energy and Petroleum, 2016). The country's wind power generation potential is estimated to be up to 4,600 MW (Ministry of Energy and Petroleum, 2016). Cogeneration power plants in the country, operated by two sugar milling companies, use biomass (bagasse) to generate steam for use in the companies' processes and for generation of electricity that is exported to the national grid (Ministry of Energy and Petroleum, 2016). The power generation potentials of hydro, geothermal and wind energy sources are taken into account in the simulations to ensure that expansion of the generation capacity from these sources is realistic.

Table 4.3. Installed capacity by technology and energy generation (2002 – 2017)

Year	Hydro		Thermal		Geothermal		Wind		Cogeneration	
	Capacity (MW)	Generation (GWh)	Capacity (MW)	Generation (GWh)	Capacity (MW)	Generation (GWh)	Capacity (MW)	Generation (GWh)	Capacity (MW)	Generation (GWh)
2002	725	2,757	235	1,258	93	433	-	-	-	-
2003	725	3,189	235	911	198	584	-	-	-	-
2004	725	3,066	288	1,067	198	910	-	-	-	-
2005	725	2,946	288	1,481	198	1,019	-	-	-	-
2006	725	3,150	288	1,741	198	1,007	-	-	-	-
2007	725	3,381	288	1,817	198	1,016	-	-	-	-
2008	785	3,172	318	2,087	198	1,099	5	0	22	7
2009	785	2,513	408	2,711	198	1,258	5	8	22	51

Year	Hydro		Thermal		Geothermal		Wind		Cogeneration	
	Capacity (MW)	Generation (GWh)	Capacity (MW)	Generation (GWh)	Capacity (MW)	Generation (GWh)	Capacity (MW)	Generation (GWh)	Capacity (MW)	Generation (GWh)
2010	785	2,792	408	2,662	198	1,364	5	17	22	93
2011	785	3,438	528	2,426	198	1,443	5	16	22	93
2012	806	3,870	528	2,317	201	1,548	5	15	22	86
2013	806	4,123	528	2,375	201	1,801	5	16	22	64
2014	806	3,629	695	2,224	543	3,203	5	28	22	36
2015	806	3,544	772	1,501	623	4,331	26	47	32	7
2016	806	3,564	772	1,685	623	4,530	26	60	32	0
2017	806	3,281	772	2,139	623	4,749	26	55	32	2

Source: Ministry of Energy and Petroleum, 2016.

Table 4.4. Technoeconomic parameters of power generation technologies

Technology type	Process efficiency* (%)	Capacity factor (%)	Capacity credit (%)	Capital cost (US$2015/kW)	Operation & maintenance costs	
					Fixed (US$2015/kW)	Variable (US$2015/MWh)
Hydro	95	51	79	3,430	27.4	0.5
Thermal	42	65	100	1,729	31.5	8.8
Geothermal	15	89	100	3,365	151.9	0.0
Wind	35	33	22	2,030	76.1	0.0
Cogeneration	35	50	50	3,000	150.0	8.5

*Source: *EURELECTRIC & VGB, 2003; Ministry of Energy and Petroleum, 2016.*

Transmission and distribution losses data, which is calculated using the difference between the amount of electricity injected into the grid and the amount supplied to consumers, is factored in creating the scenarios. Table 4.5 shows the historical transmission and distribution losses as percentages of annual energy generation during the study period.

Table 4.5. Transmission and distribution losses (2002 – 2017)

Year	**Transmission & distribution losses (%)**
2002	20.27
2003	19.40
2004	18.49
2005	18.89
2006	18.79
2007	17.36
2008	16.52
2009	16.15
2010	16.09
2011	16.81
2012	18.05
2013	18.36

Year	Transmission & distribution losses (%)
2014	17.90
2015	18.59
2016	19.29
2017	19.05

Source: Ministry of Energy and Petroleum, 2016.

Energy resources

The scenarios created in this study use both primary (domestic) and secondary (imported) resources for power generation. The primary resources are hydro, geothermal, wind and biomass (bagasse). The imported resource is heavy fuel oil for thermal power generation and table 4.6 illustrates the international oil prices during the study period.

Table 4.6. International oil prices of imported oil (2002 – 2017)

Year	Fuel cost	
	US$/bbl	**US$2015/bbl**
2002	27.7	298.45
2003	28.36	45.84
2004	36.93	51.90
2005	53.65	109.71

Year	Fuel cost	
	US$/bbl	US$2015/bbl
2006	64.9	83.48
2007	72.46	89.30
2008	97.86	64.72
2009	62.65	53.93
2010	79.16	379.51
2011	110.6	102.71
2012	112.97	120.68
2013	110.1	213.39
2014	99.45	123.48
2015	52.53	52.53
2016	44.18	79.76
2017	54.91	51.95

Source: Kenya National Bureau of Statistics, 2018.

Chapter 5. Analysis Results and Discussion

5.1 Analysis results

Actual energy demand and supply data was used to model the historical evolution of the power sector in Kenya from 2002 to 2017 as an initial step in analysis of data. The subsequent step involved creating two scenarios, namely the supply optimization scenario and ideal scenario, to aid in assessing the significance of energy planning in development of the sector during the study period. The results of the analysis for the scenarios were obtained with reference to capacity expansion, power generation mix, costs[2] (investment and power generation) and carbon dioxide emissions.

Historical evolution of the power sector

Energy consumption

Energy consumption in the base year was 3,706 GWh with the large commercial and industrial customers having the largest share in consumption at 60.9%. At the end of the study period, consumption had increased to 8,429 GWh with the large commercial and industrial customers still having the largest share in consumption at 52.0%. The other tariff groups, unlike the large commercial and industrial customers, increased their energy consumption shares over the period with the domestic customers increasing their share from 25.5% in 2002 to 30.9% in 2017, the small commercial customers increasing their

[2]All costs are reported in 2015 real prices

share from 13.4% to 16.4% and the street lighting increasing its share from 0.2% to 0.7%. Figure 5.1 illustrates the annual growth in energy consumption by the different tariff groups over the period.

Installed capacity

Installed capacity in the base year was 1,053 MW with hydro power plants having the largest capacity share at 68.9% with 725 MW. At the end of the study period, the installed capacity had increased to 2,259 MW with hydro power plants still having the largest capacity share at 35.7% with 806 MW. The other power generation technologies similarly increased their capacities over the period: thermal power plants' capacity increased from 235 MW (15.6%) in 2002 to 772 MW (34.2%) in 2017 and geothermal power plants' capacity increased from 93 MW (6.2%) to 623 MW (27.6%). Wind and cogeneration power plants were commissioned in 2008 with capacities of 5 MW and 22 MW respectively. At the end of the period, wind power plants' capacity share was 1.2% with 26 MW and cogeneration power plants' capacity share was 1.4% with 32 MW. Figure 5.2 illustrates the historical capacity expansion with the different technologies over the period.

Power generation

Power generation from the various technologies also had grown over the study period from a total of 4,648 GWh at the beginning in 2002 to a total of 10,424 GWh at the end in 2017 as illustrated in figure 5.3. The power generation mix was dominated by hydro power generation followed by geothermal power generation. Thermal power generation also contributed to the mix substantially. The results also showed that the 8,284 GWh of electricity generated in 2013 needed to be supplemented with an import of 145 GWh.

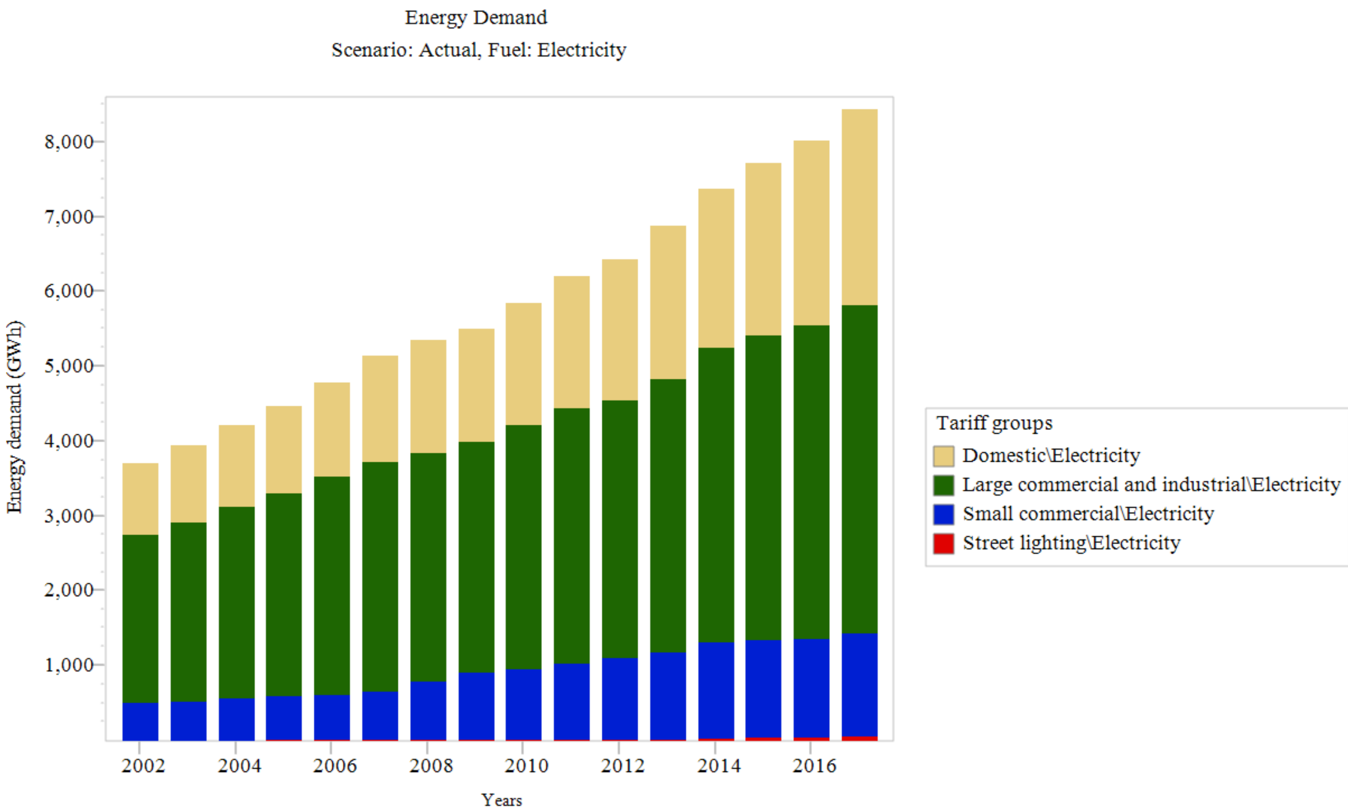

Figure 5.1. Annual energy demand by tariff group (historical evolution of the power sector)

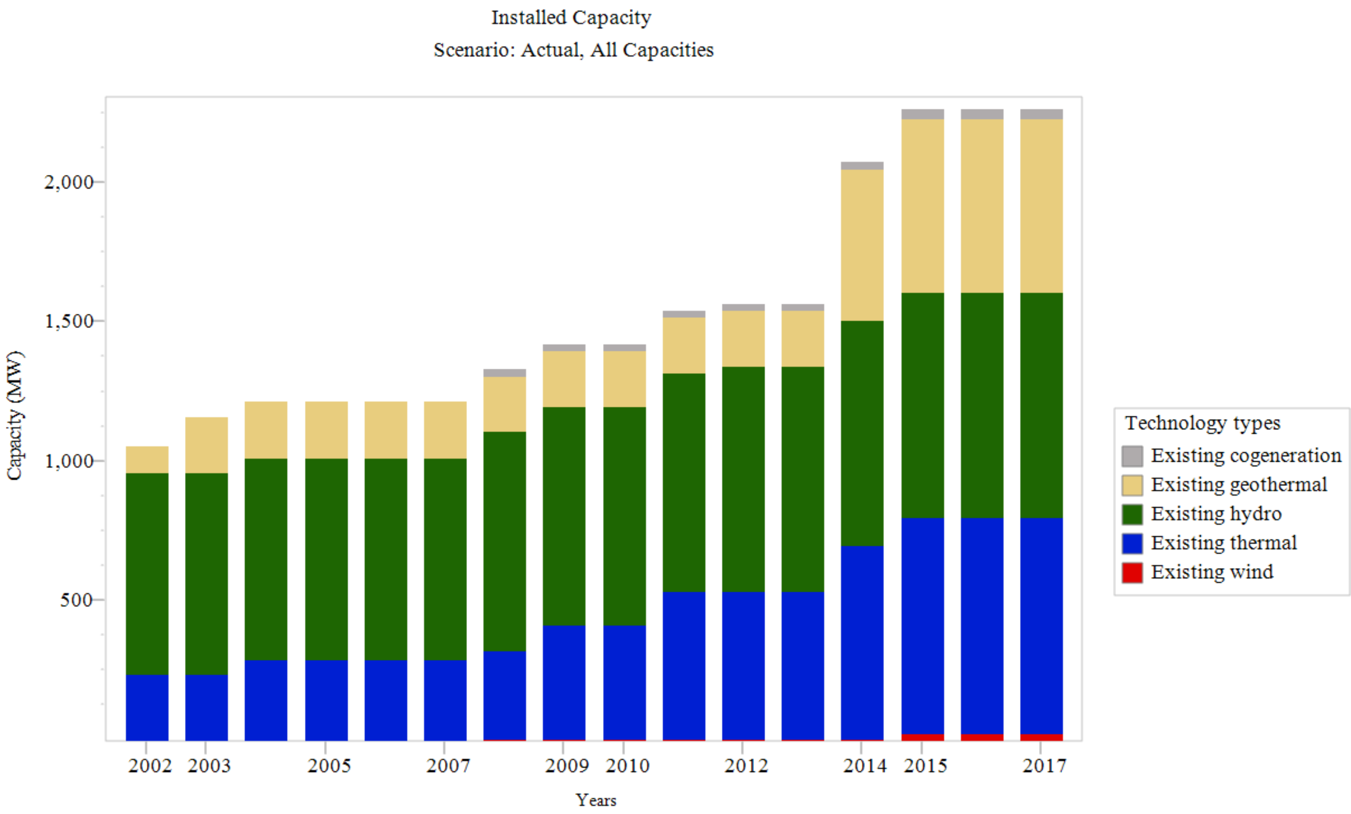

Figure 5.2. Annual capacity expansion (historical evolution of the power sector)

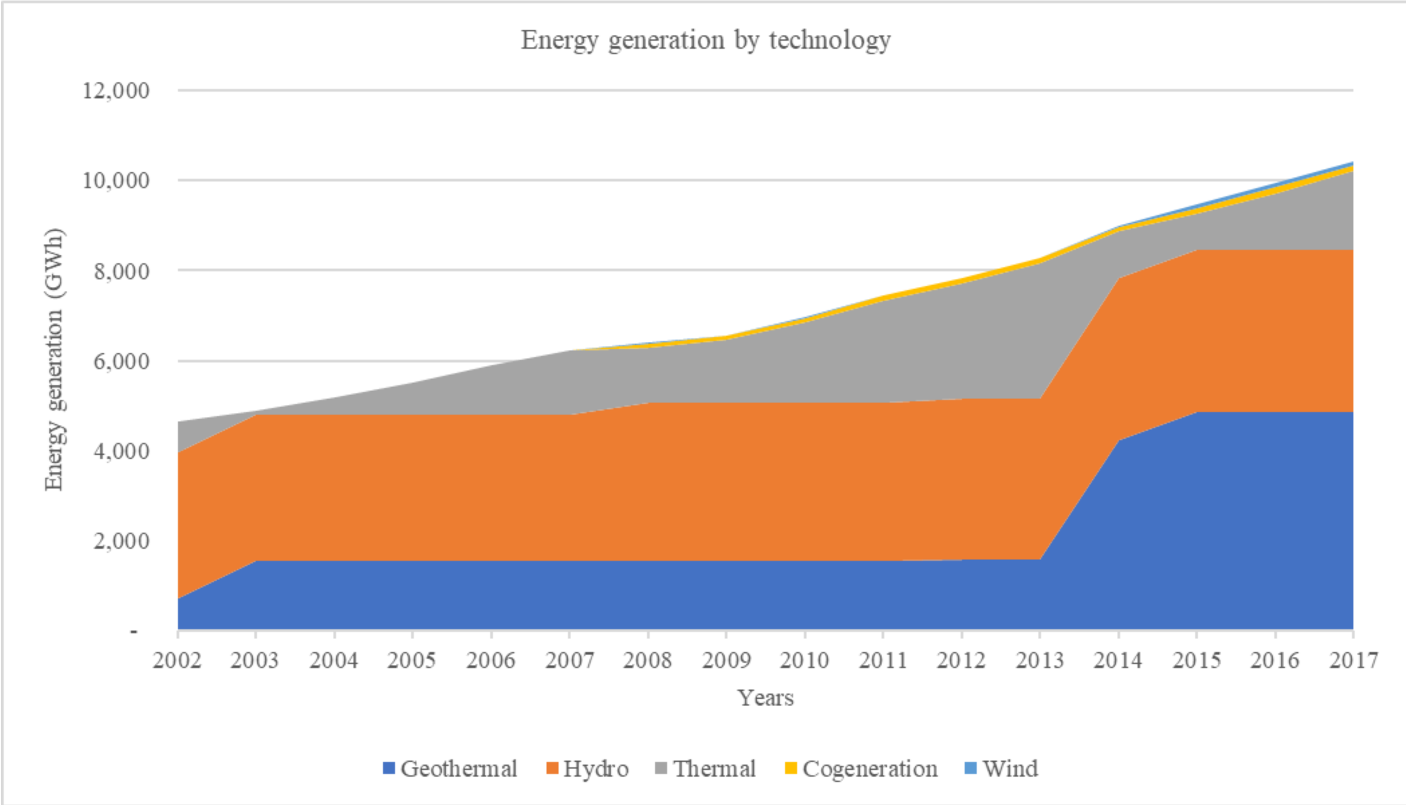

Figure 5.3. Annual energy generation by technology (historical evolution of the power sector)

Investment and power generation costs

The annual investments costs over the period were calculated using the capacities of the different technologies added in a particular year and their capital costs (see tables 4.3 and 4.4 respectively in the previous chapter). The capacity expansion over the period necessitated an investment totaling US$ 3,121 million. The investment costs were incurred specifically in 8 years for different power generation technologies: US$ 353.3 million was invested in 2003 in geothermal power plants; US$ 91.6 million was invested in 2004 in thermal power plants; US$ 333.8 million was invested in 2008 in hydro, thermal, wind and cogeneration power plants; US$ 155.6 million was invested in 2009 in thermal power plants; US$ 207.5 million was invested in 2011 in thermal power plants; US$ 82.1 million was invested in 2012 in hydro and geothermal power plants; US$ 1,439.6 million was invested in 2014 in thermal and geothermal power plants; and US$ 459.2 million was invested in 2015 in thermal, geothermal, wind and cogeneration power plants. Table 5.1 shows the annual investment costs for the different technologies over the period. The result of an approximation of the capital cost over the period pointed to the unit cost of implementation being 2,588 US$/kW.

Table 5.1. Annual investment costs (historical evolution of the power sector)

Year	Investment costs by technology (million US$2015)					Total annual costs (million US$2015)
	Hydro	Thermal	Geothermal	Wind	Cogeneration	
2002	-	-	-	-	-	-

Year	Investment costs by technology (million US$2015)					Total annual costs (million US$2015)
	Hydro	Thermal	Geothermal	Wind	Cogeneration	
2003	-	-	353.3	-	-	353.3
2004	-	91.6	-	-	-	91.6
2005	-	-	-	-	-	-
2006	-	-	-	-	-	-
2007	-	-	-	-	-	-
2008	205.8	51.9	-	10.2	66.0	333.8
2009	-	155.6	-	-	-	155.6
2010	-	-	-	-	-	-
2011	-	207.5	-	-	-	207.5
2012	72.0	-	10.1	-	-	82.1
2013	-	-	-	-	-	-
2014	-	288.7	1,150.8	-	-	1,439.6
2015	-	128.1	259.0	41.0	28.9	457.0
2016	-	-	-	-	-	-
2017	-	-	-	-	-	-

The levelized cost of electricity (LCOE) was calculated using the total costs incurred in implementing the scenario as illustrated in table 5.2 and the total energy generated over the period as illustrated in figure 5.3. The LCOE obtained was 65.35 US$/MWh.

Table 5.2. Annual cost of production (historical evolution of the power sector)

Year	Cost of production (million US$2015)				Total annual costs
	Capital cost	Fixed O&M cost	Variable O&M cost	Fuel cost	
2002	33.10	41.39	7.64	295.33	344.37
2003	42.43	57.34	2.49	6.59	99.53
2004	42.43	59.01	5.05	29.25	135.75
2005	42.43	59.01	8.00	115.00	224.44
2006	42.43	59.01	11.38	133.97	246.80
2007	42.43	59.01	14.22	185.00	300.67
2008	72.19	65.28	13.44	115.63	266.55
2009	88.04	68.12	14.88	109.13	280.17
2010	88.04	68.12	18.44	990.22	1,164.82
2011	109.17	71.90	22.68	342.82	546.57
2012	116.16	72.93	25.14	427.65	641.88
2013	116.16	72.93	29.06	953.93	1,172.09
2014	253.38	130.14	11.73	195.28	590.53
2015	277.14	142.23	9.63	52.55	481.55

Year	Cost of production (million US$2015)				Total annual costs
	Capital cost	Fixed O&M cost	Variable O&M cost	Fuel cost	
2016	256.61	131.70	12.59	116.39	517.28
2017	237.60	121.94	15.17	103.28	477.99

Supply optimization scenario

Energy consumption

Actual energy consumption data was used to create this scenario hence the energy consumption results are similar with the results in the historical evolution of the power sector with consumption increasing from 3,706 GWh in 2002 to 8,429 GWh in 2017. Likewise, historical existing capacity data in the base year was used to create the scenario with the generation expansion path being optimized.

Installed capacity

The results showed that the installed capacity would have increased from 1,053 MW in the base year to 2,110 MW at the end of the period. The installed capacity would have been made up of hydro, thermal and geothermal power plants. Table 5.3 illustrates the optimized capacity expansion with the different technologies over the period.

Power generation

Power generation from the various technologies would have grown over the study period as in the historical evolution of the power sector from a total of 4,648 GWh at the beginning in 2002 to a total of 10,424 GWh at the end in 2017 as illustrated in figure 5.4. The power generation mix in this scenario would have been dominated by hydro power generation followed by geothermal power generation. Thermal power generation would have been significantly reduced compared to the historical evolution of the sector.

Table 5.3. Annual capacity expansion (supply optimization scenario)

Year	Installed capacity by technology (MW)					Total installed capacity (MW)
	Hydro	Thermal	Geothermal	Wind	Cogeneration	
2002	725	235	93	-	-	1,053
2003	725	235	198	-	-	1,158
2004	725	235	241	-	-	1,201
2005	725	235	295	-	-	1,255
2006	725	235	338	-	-	1,298
2007	725	235	379	-	-	1,339
2008	725	235	401	-	-	1,361
2009	726	235	417	-	-	1,378
2010	785	235	465	-	-	1,485

Year	Installed capacity by technology (MW)					Total installed capacity (MW)
	Hydro	Thermal	Geothermal	Wind	Cogeneration	
2011	856	235	470	-	-	1,561
2012	913	235	488	-	-	1,637
2013	1,000	235	521	-	-	1,756
2014	1,081	235	540	-	-	1,856
2015	1,153	235	540	-	-	1,928
2016	1,221	235	568	-	-	2,024
2017	1,292	235	583	-	-	2,110

Investment and power generation costs

The annual investments costs over the period were calculated using the capacities of the different technologies added in a particular year and their capital costs (see table 4.4 in the previous chapter). The optimized capacity expansion would have necessitated an investment totaling US$ 3,497 million over the period. The investment costs would have been incurred annually from 2003 to 2017 for hydro and geothermal power plants. Table 5.4 shows the annual investment costs for the different technologies over the period. The result of an approximation of the capital cost over the period pointed to the unit cost of implementing the scenario as being 3,309 US$/kW.

The levelized cost of electricity (LCOE) was calculated using the total costs incurred in implementing the scenario as illustrated in table 5.5 and the total energy generated over the period as illustrated in figure 5.4. The LCOE obtained was 35.40 US$/MWh.

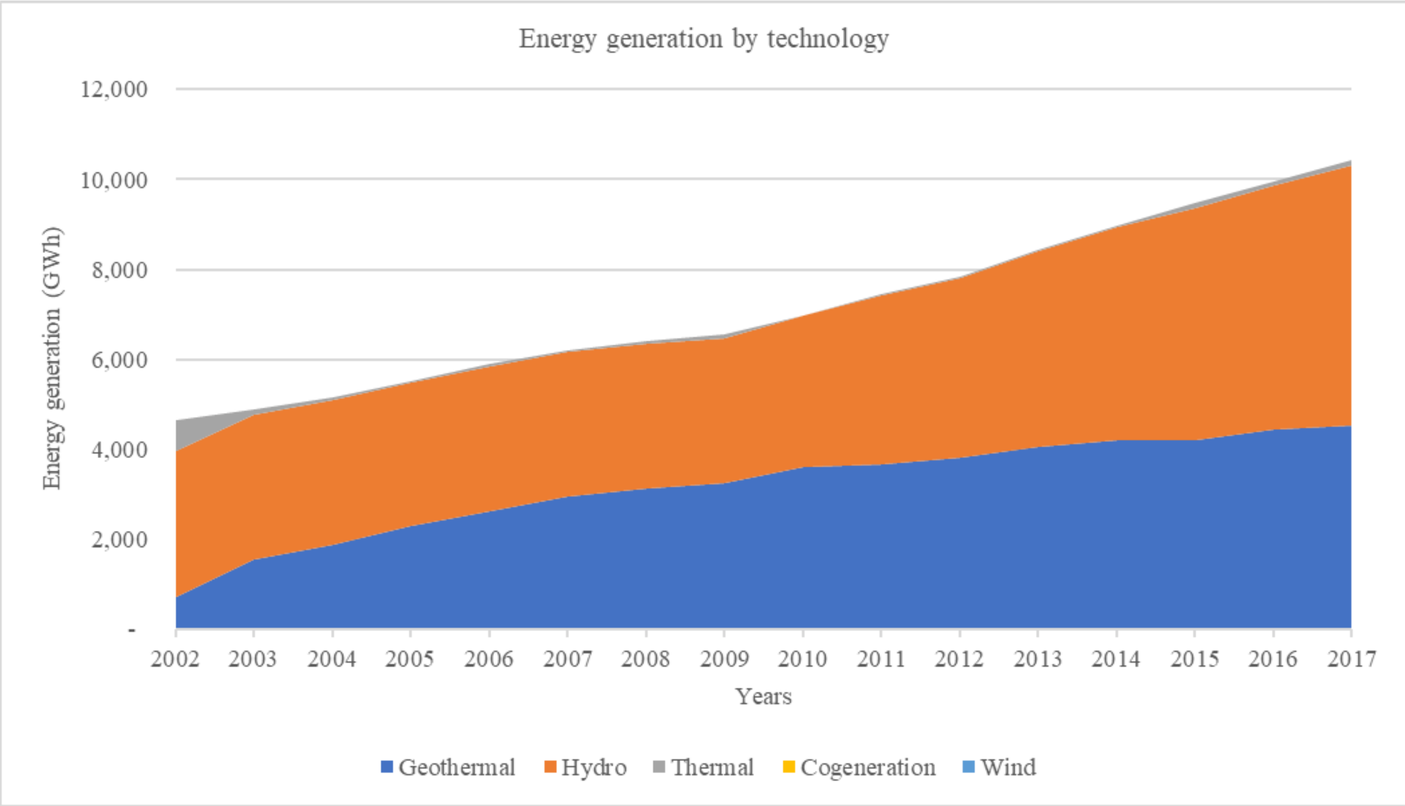

Figure 5.4. Annual energy generation by technology (supply optimization scenario)

Table 5.4. Annual investment costs (supply optimization scenario)

Year	Investment costs by technology (million US$2015)					Total annual costs (million US$2015)
	Hydro	Thermal	Geothermal	Wind	Cogeneration	
2002	-	-	-	-	-	-
2003	-	-	354.3	-	-	354.3
2004	-	-	144.1	-	-	144.1
2005	-	-	181.8	-	-	181.8
2006	-	-	144.9	-	-	144.9
2007	-	-	138.9	-	-	138.9
2008	-	-	71.6	-	-	71.6
2009	4.2	-	53.5	-	-	57.7
2010	203.1	-	161.2	-	-	364.2
2011	242.4	-	19.4	-	-	261.7
2012	196.3	-	60.9	-	-	257.2
2013	297.0	-	109.5	-	-	406.5
2014	277.3	-	64.1	-	-	341.4
2015	237.4	-	-	-	-	237.4
2016	209.3	-	85.1	-	-	294.4
2017	201.1	-	39.8	-	-	240.9

Table 5.5. Annual cost of production (supply optimization scenario)

Year	Cost of production (million US$2015)				Total annual costs
	Capital cost	Fixed O&M cost	Variable O&M cost	Fuel cost	
2002	-	41.39	7.64	295.33	344.37
2003	33.19	57.39	2.47	6.44	99.50
2004	46.69	63.89	2.16	4.62	117.36
2005	63.72	72.10	1.78	3.30	140.89
2006	77.29	78.64	1.99	5.29	163.20
2007	90.30	84.91	2.01	5.97	183.19
2008	97.01	88.14	2.10	5.18	192.42
2009	102.37	90.59	2.30	6.09	201.34
2010	134.49	99.48	1.69	0.96	236.63
2011	156.63	102.29	2.12	4.21	265.26
2012	178.80	106.61	2.25	4.72	292.38
2013	213.96	113.93	2.34	6.03	336.26
2014	243.22	119.03	2.65	6.11	371.01
2015	244.36	116.43	3.15	8.11	372.41
2016	250.82	113.32	3.09	7.91	375.14
2017	252.05	108.33	3.27	7.32	370.92

Ideal scenario

Energy consumption

The energy consumption data used to create this scenario considered implementation of energy efficiency and conservation measures to achieve savings in consumption over the period. The results showed that energy consumption would have increased from 3,706 GWh in 2002 to 7,765 GWh in 2017 as illustrated in figure 5.5. The capacity expansion simulation used in the scenario was the same as that used in the supply optimization scenario in which the generation expansion path was optimized.

Installed capacity

The results showed that the installed capacity increased from 1,053 MW at the beginning of the period to 1,954 MW at the end of the period. The installed capacity would have comprised hydro, thermal and geothermal power plants. Table 5.6 illustrates the optimized capacity expansion with the different technologies over the period.

Power generation

Power generation from the various technologies would also have increased over the study period from a total of 4,648 GWh at the beginning in 2002 to a total of 9,603 GWh at the end in 2017 as illustrated in figure 5.6. The power generation mix in this scenario, similar to the supply optimization scenario, would have been dominated by hydro power generation followed by geothermal power generation.

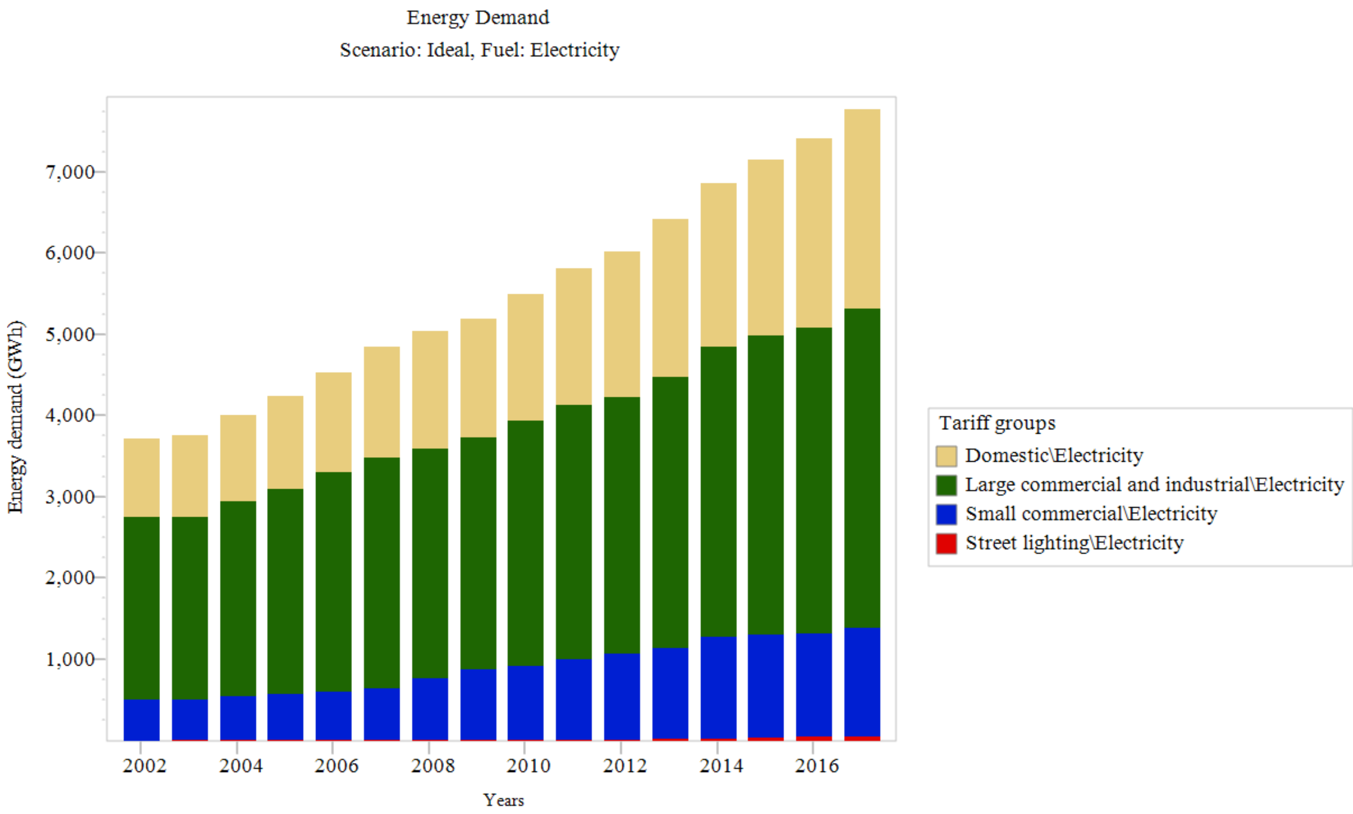

Figure 5.5. Annual energy demand by tariff group (ideal scenario)

Table 5.6. Annual capacity expansion (ideal scenario)

Year	Installed capacity by technology (MW)					Total installed capacity (MW)
	Hydro	Thermal	Geothermal	Wind	Cogeneration	
2002	725	235	93	-	-	1,053
2003	725	235	172	-	-	1,132
2004	725	235	208	-	-	1,168
2005	725	235	258	-	-	1,218
2006	725	235	297	-	-	1,257
2007	725	235	334	-	-	1,294
2008	725	235	355	-	-	1,315
2009	725	235	369	-	-	1,329
2010	725	235	444	-	-	1,404
2011	788	235	449	-	-	1,473
2012	840	235	466	-	-	1,541
2013	918	235	495	-	-	1,648
2014	989	235	512	-	-	1,736
2015	1,052	235	512	-	-	1,799
2016	1,111	235	536	-	-	1,882
2017	1,172	235	547	-	-	1,954

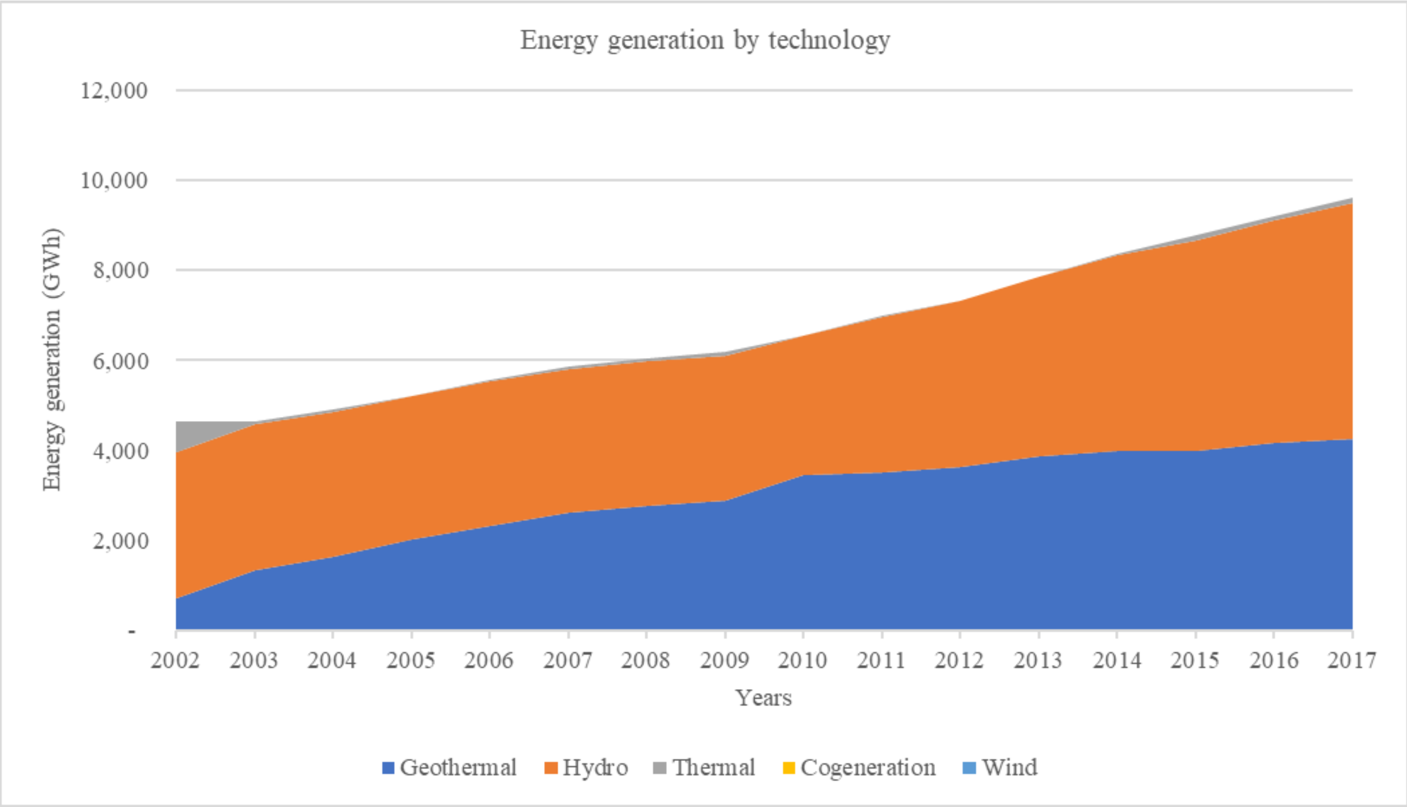

Figure 5.6. Annual energy generation by technology (ideal scenario)

Investment and power generation costs

The annual investments costs over the period were calculated using the capacities of the different technologies added in a particular year and their capital costs (see table 4.4 in the previous chapter). The optimized capacity expansion would have necessitated an investment totaling US$ 2,980 million over the period. The investment costs would have been incurred annually from 2003 to 2017 for hydro and geothermal power plants. Table 5.7 shows the annual investment costs for the different technologies over the period. The result of an approximation of the capital cost over the period pointed to the unit cost of implementing the scenario as being 3,306 US$/kW.

Table 5.7. Annual investment costs (ideal scenario)

Year	Investment costs by technology (million US$2015)					Total annual costs (million US$2015)
	Hydro	Thermal	Geothermal	Wind	Cogeneration	
2002	-	-	-	-	-	-
2003	-	-	267.3	-	-	267.3
2004	-	-	121.0	-	-	121.0
2005	-	-	167.1	-	-	167.1
2006	-	-	130.7	-	-	130.7
2007	-	-	125.7	-	-	125.7
2008	-	-	68.3	-	-	68.3

Year	Investment costs by technology (million US$2015)					Total annual costs (million US$2015)
	Hydro	Thermal	Geothermal	Wind	Cogeneration	
2009	-	-	50.2	-	-	50.2
2010	-	-	250.9	-	-	250.9
2011	217.1	-	18.0	-	-	235.1
2012	177.5	-	55.1	-	-	232.6
2013	267.0	-	99.1	-	-	366.1
2014	245.3	-	55.7	-	-	301.0
2015	207.3	-	-	-	-	207.3
2016	181.0	-	71.5	-	-	252.6
2017	171.2	-	32.5	-	-	203.8

The levelized cost of electricity (LCOE) was calculated using the total costs incurred in implementing the scenario as illustrated in table 5.8 and the total energy generated over the period as illustrated in figure 5.6. The LCOE obtained was 33.62 US$/MWh.

Table 5.8. Annual cost of production (ideal scenario)

Year	Cost of production (million US$2015)				Total annual costs
	Capital cost	Fixed O&M cost	Variable O&M cost	Fuel cost	
2002	-	41.39	7.64	295.33	344.37

Year	Cost of production (million US$2015)				Total annual costs
	Capital cost	Fixed O&M cost	Variable O&M cost	Fuel cost	
2003	25.04	53.46	2.23	4.60	85.33
2004	36.38	58.93	2.13	4.39	101.83
2005	52.04	66.47	1.77	3.12	123.39
2006	64.28	72.37	1.97	5.00	143.62
2007	76.06	78.04	1.99	5.63	161.72
2008	82.46	81.13	2.07	4.89	170.54
2009	87.16	83.39	2.26	5.74	178.55
2010	110.66	94.72	1.56	0.91	207.84
2011	130.55	97.27	1.96	3.95	233.73
2012	150.60	101.17	2.07	4.42	258.27
2013	182.28	107.78	2.15	5.63	297.83
2014	208.06	112.25	2.43	5.68	328.43
2015	209.38	109.67	3.16	7.05	329.27
2016	214.92	106.22	2.82	7.31	331.28
2017	215.75	101.19	2.98	6.74	326.67

5.2 Discussion

Capacity expansion

The results of the annual capacity expansion over the period for the scenarios are summarized in table 5.9. In the historical evolution of the power sector, the installed capacity at the end of the period in 2017 was 2,259 MW. The largest contribution to the capacity was from hydro power plants but their share decreased over the period. Geothermal and thermal power plants on the hand had their capacity shares considerably increased. Wind and cogeneration power plants were also included in the capacity from 2008 but their shares were minimal.

The installed capacity in the supply optimization scenario, which assumed that expansion of generation capacity was optimal in meeting energy demand, would have been 2,110 MW at the end of the period. The capacity, which would have been 149 MW (7%) less than that in the historical evolution of the sector, would have comprised hydro (61%), geothermal (28%) and thermal (11%) power plants. The capacity share of geothermal power plants would have been approximately the same as that in the historical evolution of the sector. However, the capacity share of hydro power plants would have increased considerably to substitute thermal power generation. Wind and cogeneration power plants would also not have contributed to the capacity.

In the ideal scenario, which assumed that energy efficiency and conservation measures were implemented alongside optimal expansion of generation capacity to meet the reduced energy demand, the installed capacity at the end of the period would have been 1,954 MW. The capacity, which would have been 305 MW (14%) less than in the historical evolution of the sector, would have had a similar composition as in the supply optimization scenario with hydro (60%), geothermal (28%), and thermal (12%) power plants. Similarly, no wind and cogeneration power plants would have been added to the installed capacity.

Table 5.9. Annual capacity expansion by scenario

Year	Installed capacity by scenario (MW)		
	Actual	**Supply optimization**	**Ideal**
2002	1,053	1,053	1,053
2003	1,158	1,158	1,132
2004	1,211	1,201	1,168
2005	1,211	1,255	1,218
2006	1,211	1,298	1,257
2007	1,211	1,339	1,294
2008	1,328	1,361	1,315
2009	1,418	1,378	1,329
2010	1,418	1,485	1,404
2011	1,538	1,561	1,473
2012	1,562	1,637	1,541

Year	Installed capacity by scenario (MW)		
	Actual	Supply optimization	Ideal
2013	1,562	1,756	1,648
2014	2,071	1,856	1,739
2015	2,259	1,928	1,799
2016	2,259	2,024	1,882
2017	2,259	2,110	1,954

The resulting reserve margins over the period for the different scenarios are illustrated in figure 5.7. The reserve margin, which is a percentage of the power generation capacity in the system above the peak demand and is useful in gauging the capability of the system to meet demand, can influence the overall system cost (Reimers et al., 2019). Although a high reserve margin increases the reliability of the system, it also tends to increase its overall cost. A planning reserve margin of 25% was used in creating the model for the study and the results obtained for the different scenarios showed that the actual reserve margin at the beginning of the period was 76% which was considerably higher than the planning reserve margin of 25%.

In the historical evolution of the power sector, the results showed that the reserve margin ranged between 68% and 29% over the period. In the supply optimization scenario, the reserve margin would have decreased to 25% in 2009 and it would have been maintained until the end of the period. Similarly, the margin in the ideal scenario would have decreased to 25% in 2010 and it would have been maintained until 2017.

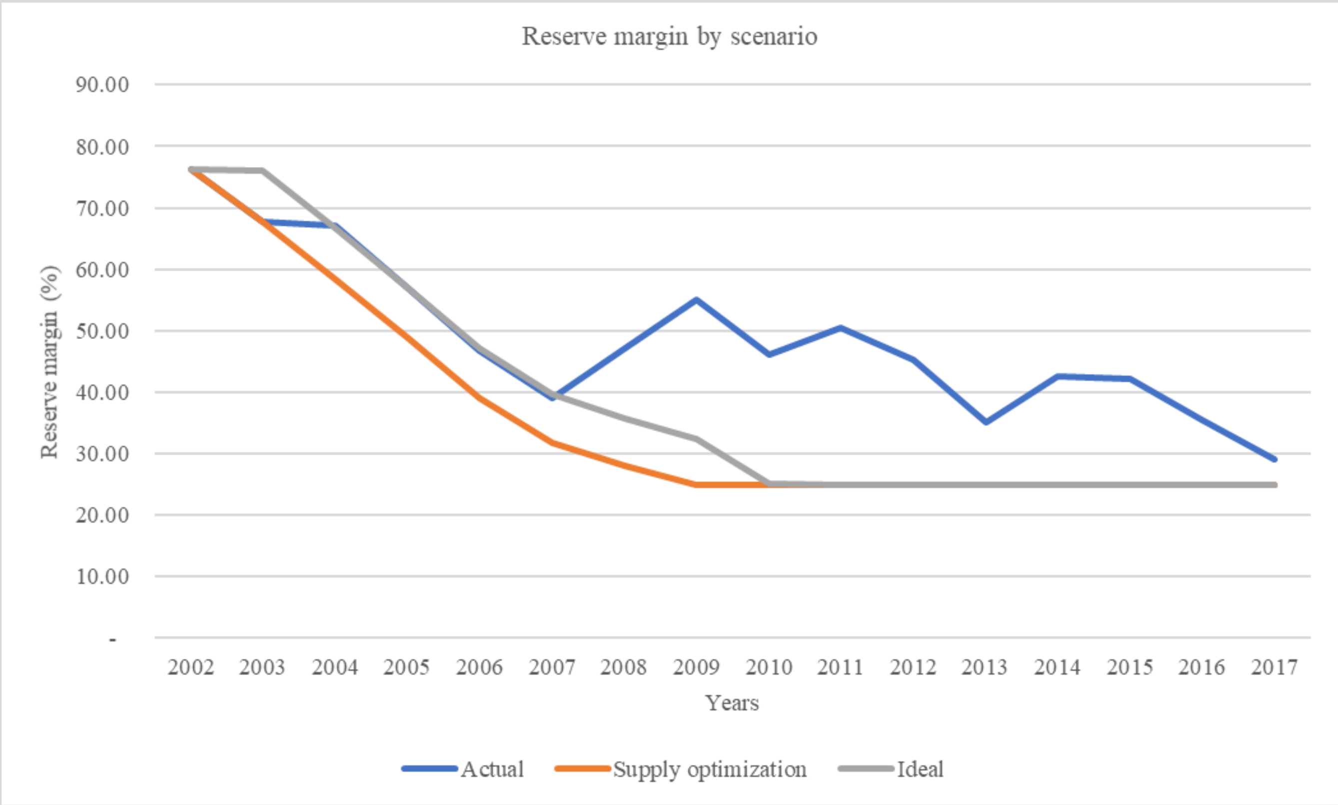

Figure 5.7. Reserve margin by scenario

Power generation mix

The power generation mix of the different technologies in each of the scenarios at the beginning and end of the study period are summarized in table 5.10. The total power generated at the beginning of the period was 4,648 GWh with 3,239 GWh (69.7%) being produced from hydro, 725 GWh (15.6%) from geothermal and 684 GWh (14.7%) from thermal power plants. The generation mix fully utilized hydro and geothermal power plants up to their capacity factors (51% and 89% respectively). However, the utilization of thermal power plants was slightly more than half of their capacity factor (65%) implying that close to half of the installed capacity was idle.

At the end of the period in 2017, the 10,424 GWh generated in the historical evolution of the power sector consisted of 4,857 GWh (47%) from geothermal, 3,601 GWh (35%) from hydro, 1,750 GWh (17%) from thermal, 75 GWh (0.7%) from wind and 140 GWh (1.3%) from cogeneration power plants. The power generation mix, in the same way as in the base year, fully utilized hydro and geothermal as well as the additional capacity from wind and cogeneration power plants up to their capacity factors. The utilization of thermal power plants decreased to less than half of their capacity factor implying that more than half of the installed capacity was idle.

The two scenarios, supply optimization and ideal scenarios, in contrast with the historical evolution of the sector would have had a power generation of 10,424 GWh and 9,603 GWh in 2017 dominated by hydro power generation at 55% and 54% respectively. Power generation from geothermal and thermal power plants would have contributed

44% and 1% respectively to the energy mix in the supply optimization and ideal scenarios. Similar to the historical evolution of the sector, geothermal and hydro power plants would have been fully utilized while the utilization of thermal power plants would have been decreased substantially to less than a quarter in both scenarios.

Table 5.10. Power generation mix in 2002 and 2017 by scenario

Scenario	Power generation mix in 2002 (%)					Power generation mix in 2017 (%)				
	Hydro	Thermal	Geothermal	Wind	Cogeneration	Hydro	Thermal	Geothermal	Wind	Cogeneration
Actual	69.7	14.7	15.6	-	-	34.5	16.8	46.6	0.7	1.3
Supply optimization	69.7	14.7	15.6	-	-	55.2	1.2	43.6	-	-
Ideal	69.7	14.7	15.6	-	-	54.4	1.2	44.4	-	-

Investment (capital) costs

The total investment requirements for the different power generation technologies in each of the scenarios over the study period are summarized in figure 5.8. The total investment requirement for the capacity expansion in the historical evolution of the power sector was estimated at US$ 3,121 million over the study period. The investment shares that were allocated to the different power generation technologies were 8.9% for hydro, 29.6% for thermal, 56.8% for geothermal, 1.6% for wind and 3.0% for cogeneration power plants.

The total investment requirement in the supply optimization scenario compared to the historical evolution of the sector would have increased by approximately 12% to US$ 3,497 million over the period. The investment would have been allocated to hydro (53%) and geothermal (47%) power plants. The share of investment allocated to hydro power plants in the scenario would have increased substantially compared with the investment share in the historical evolution of the sector. On the other hand, the investment share that would have been allocated to geothermal power plants would have slightly reduced. There would also have been no investment in thermal, wind and cogeneration power plants implying that their capacity would have been substituted with the increased investment in hydro power plants.

In the ideal scenario, the total investment requirement over the period would have decreased by approximately 5% to US$ 2,980 million. The investment, like in the supply optimization scenario, would have been allocated to hydro (49%) and geothermal (51%)

power plants with no investment in thermal, wind and cogeneration power plants. In comparison with the historical evolution of the sector, the investment share allocated to hydro power plants would have increased substantially while the share allocated to geothermal power plants would have slightly decreased. The implication is that the increased investment in hydro power plants in the scenario would also have been to substitute the capacity from thermal, wind and cogeneration power plants.

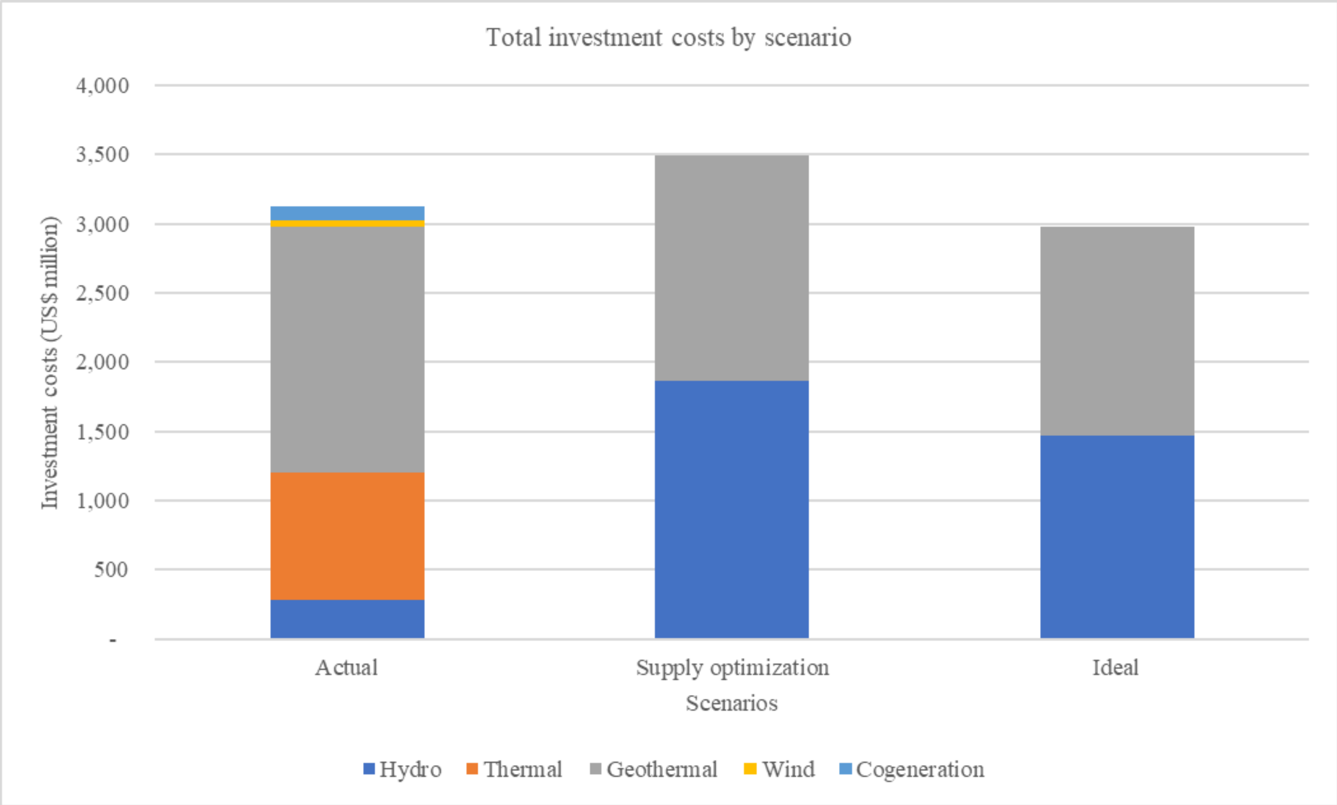

Figure 5.8. Total investment costs by scenario

Power generation costs

The total cost of power generation comprising investment (capital), fixed operation and maintenance (O&M), variable O&M and fuel costs for each of the scenarios over the study period are summarized in figure 5.9. The total power generation cost in the evolution of the power sector was estimated at US$ 7,491 million over the study period. Fuel costs made up a substantial share of the cost at 56%. The shares of the other components of the cost were 24% for capital costs, 17% for fixed O&M costs and 3% for variable O&M costs. The levelized cost of electricity (LCOE) was estimated at 65.35 US$/MWh.

The total power generation cost in supply optimization scenario would have been reduced by close to half compared to the historical evolution of the sector with the cost being estimated at US$ 4,062 million over the period. In contrast with the historical evolution of the sector, capital costs would have made up a substantial share of the cost at 54%. The shares of the other components of the cost would have been 36% for fixed O&M costs, 9% for fuel costs and 1% for variable O&M costs. Compared to the historical evolution of the sector, the increased share of capital costs is due to investment in relatively capital-intensive hydro and geothermal power plants while the decreased share of fuel costs is due to reduced thermal power generation. The LCOE would have been 35.40 US$/MWh implying that optimal power generation would have reduced the cost by approximately 46%.

In the ideal scenario, the power generation cost would also have been reduced by approximately close to half compared to the historical evolution of the sector with the cost being estimated at US$ 3,623 million over the period. Similar to the supply optimization scenario, capital costs would have made up a substantial share of the cost at 51%. The shares of the other components of the cost would have been 38% for fixed O&M costs, 10% for fuel costs and 1% for variable O&M costs. Likewise, investment in relatively capital-intensive hydro and geothermal power plants increased the share of capital costs while reduced thermal power generation decreased the share of fuel costs. The LCOE would have been 33.62 US$/MWh implying that a 6% decrease in energy demand alongside optimal power generation would have reduced the cost by approximately 49% compared to the historical evolution of the sector.

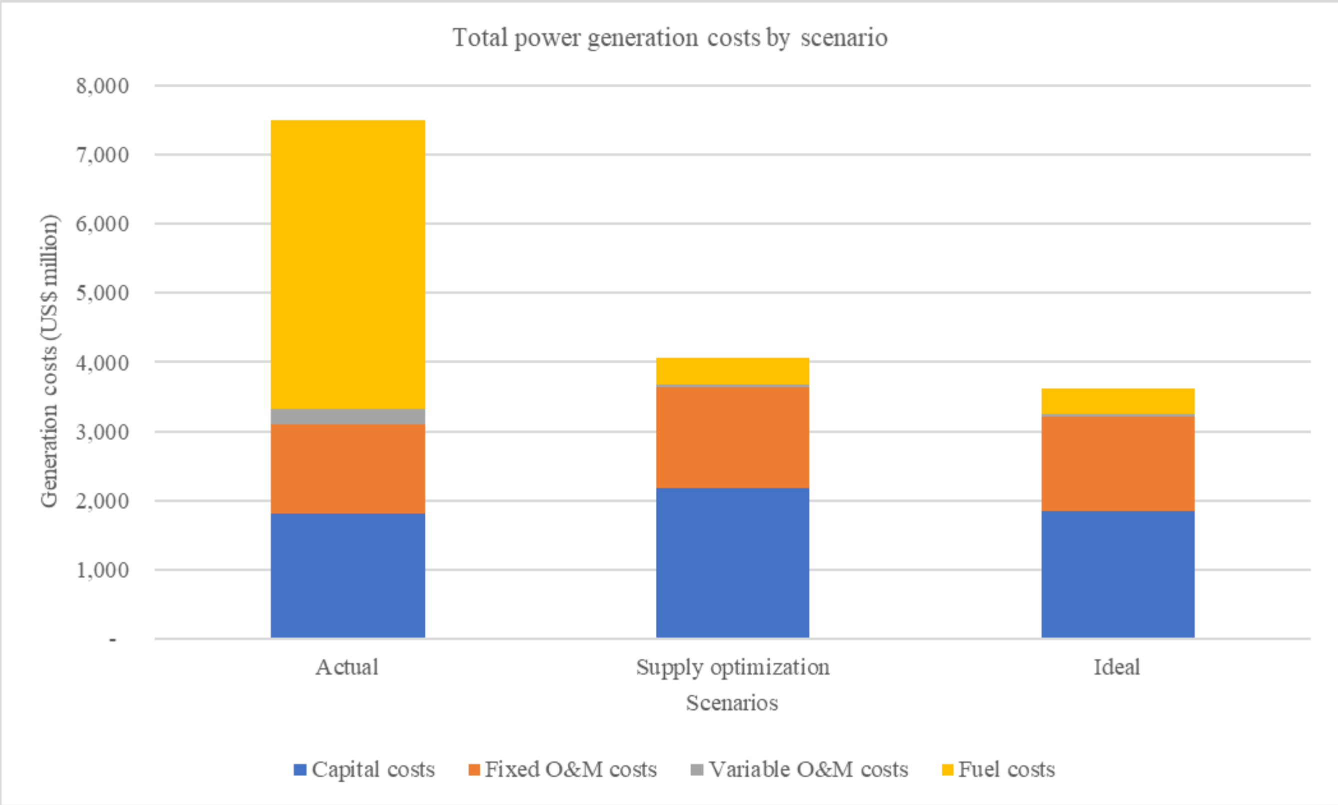

Figure 5.9. Total power generation costs by scenario

Carbon dioxide emissions

The total carbon dioxide (CO_2) emissions over the study period for each of the scenarios are summarized in figure 5.10. The total CO_2 emissions from the historical evolution of the power sector were estimated at 13.74 million tonnes over the period attributed to considerable thermal power generation. The specific CO_2 emissions were estimated at 119.90 kg CO_2/MWh.

The total CO_2 emissions in the supply optimization scenario, compared to the historical evolution of the sector, would have been substantially reduced to 0.97 million tonnes over the period due to a substantial decrease in thermal power generation. The specific CO_2 emissions would have been approximately 8.49 kg CO_2/MWh.

In the ideal scenario, the total CO_2 emissions would have similarly been substantially reduced compared to the historical evolution of the sector to 0.92 million tonnes over the period as a result of substantially decreased thermal power generation. The specific CO_2 emissions would have been approximately 8.54 kg CO_2/MWh.

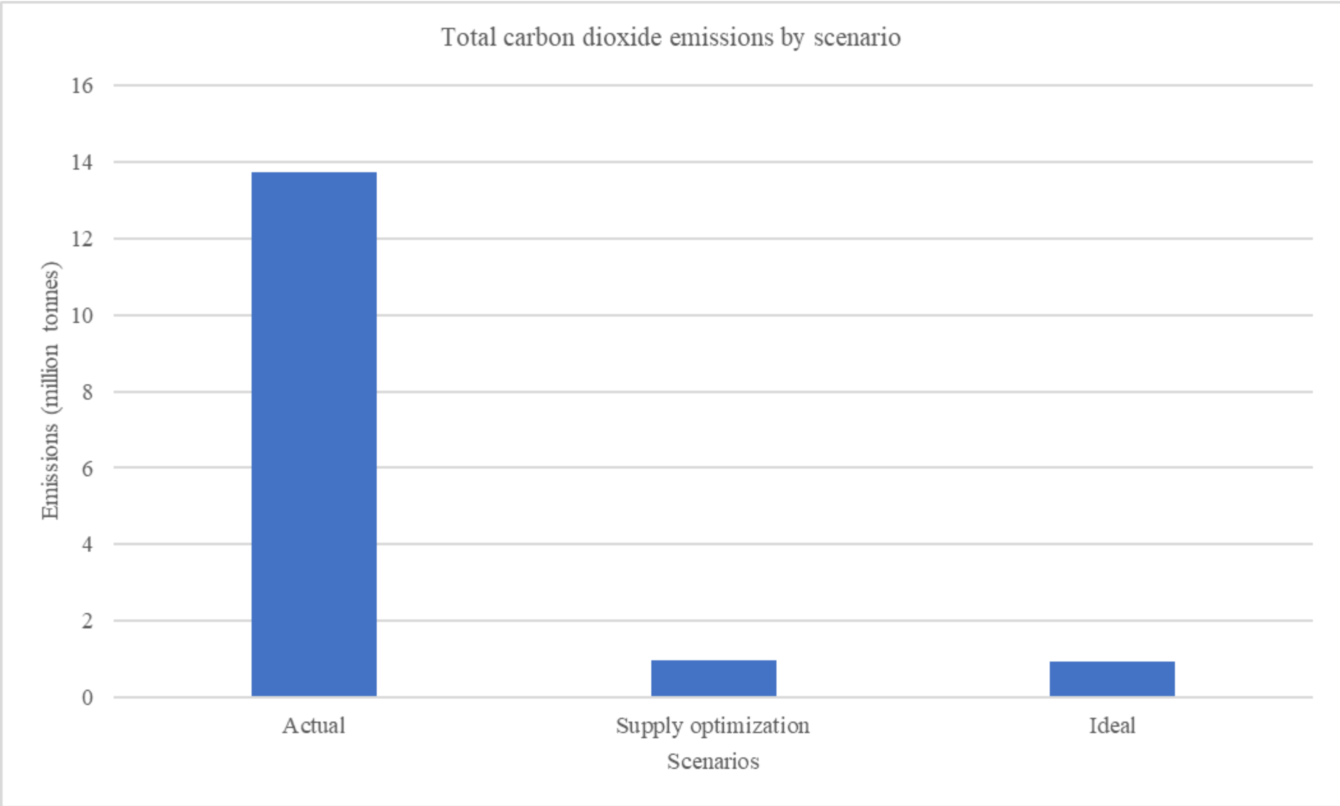

Figure 5.10. Total carbon dioxide emissions by scenario

5.3 Key findings and policy implications

The key findings from the analysis and their policy implications are as follows:

First, optimization of the capacity expansion path over the study period would have resulted in a reduction of the installed capacity required to satisfy the demand. Energy demand in the historical evolution of the power sector and the supply optimization scenario was the same but for the latter, a lesser installed capacity would have been sufficient to meet the demand. Reduction in energy demand because of achievement of efficiency in consumption would have further decreased the installed capacity. Implementation of EEC measures coupled with optimized expansion of power generation capacity would have generally resulted in a reduction of between 7% and 14% in the country's installed capacity by the end of the study period in 2017.

Second, an optimized expansion path over the period would have resulted in a comparatively reliable system with potentially lower overall system costs. Although the reserve margin in the historical evolution of the sector was considerably higher than the planning reserve margin over the period, the system's reliability would have similarly been achieved with lesser capacity as in the optimal expansion paths in the supply optimization and ideal scenarios. The high reserve margin in the historical evolution of the sector implies that the system could have possibly been oversupplied. On the other hand, optimization of the expansion path would have been helpful in determining the requisite capacity to efficiently maintain the planning reserve margin.

Third, optimization of the power generation mix would have resulted in higher utilization of hydro and geothermal power plants with the contribution of thermal power plants to the mix being considerably reduced. Despite the power generated in the historical evolution of the sector and the supply optimization scenario being the same, the mix in the latter would have consisted mainly of hydro and geothermal power plants with generation using thermal power plants being lowered. In addition, cogeneration and wind power plants would not have been included in the mix as was the case in the historical evolution of the sector. The composition of the power generation mix in the ideal scenario would have been similar to that in the supply optimization scenario. An optimal power generation mix would have therefore resulted in more hydro and geothermal power plants being brought online to substitute the generation from thermal, cogeneration and wind power plants.

Fourth, optimization of the power generation capacity over the study period would have necessitated investment in comparatively capital-intensive technologies with lower operation and maintenance costs. The installed capacities in the three optimized scenarios in this study would have had hydro and geothermal power plants making up a bigger share of the capacities with no additional investment in thermal power plants. The investment in capacity expansion over the period would have been 12% higher if the expansion path was optimal and 5% lower if energy consumption was efficient and supply was optimized.

Fifth, optimization of the power generation mix would have considerably reduced the cost of power generation. In comparison to the historical evolution of the sector, an optimized energy mix would have reduced the LCOE by between 43% and 49%. The components of the LCOE include capital, operation and maintenance (fixed and variable) and fuels costs. The capital cost and fuel cost components arguably tend to have the largest shares in the LCOE and substantial changes in the components potentially change the LCOE. The high capital costs incurred in expansion of the power generation capacity in the two scenarios would have been compensated with low generation costs mainly due to low fuels costs. On the other hand, despite the capital cost in the historical evolution of the sector being low, the LCOE was high largely due to high fuel costs incurred from high utilization of thermal power plants. The choice of power generation technologies therefore needs to take into consideration the effects of the different cost components on the LCOE.

Lastly, optimization of the power generation capacity over the period would have substantially reduced the CO_2 emission levels mainly by decreasing the use of thermal power plants for power generation and increasing the use of hydro and geothermal power plants. The partial substitution of thermal power generation with hydro and geothermal power generation would have lowered the CO_2 emission levels from approximately 119.90 kg CO_2/MWh to 8.43 kg CO_2/MWh on average. Optimization of the power generation capacity would have therefore contributed positively to the government's objective of limiting the environmental impacts of energy supply.

Chapter 6. Conclusion and Policy Recommendations

6.1 Conclusion

The power sector in Kenya has faced various challenges over time including declining energy consumption, because of decreasing economic growth, insufficient generation capacity, as well as unreliable power supply and a considerable energy surplus in the medium-term because of weaknesses in integrating energy planning in the development of electricity infrastructure. This study therefore sought to quantitatively examine the importance of energy planning in guiding energy policy development in Kenya first, by investigating the impact of energy policy decisions on the achievement of government objectives pertaining to optimal energy provision and second, by investigating the contribution of energy planning to energy policy development for optimal energy provision.

The study outlined the contribution of energy in the achievement of the country's development objective of transforming Kenya into an industrialized country and the government's five-year strategic agenda that aims at stimulating economic growth and development. The study also outlined the various policies that have been developed to address different challenges such as mitigating the adverse effects of oil importation on the economy in the 1980s, economic stagnation and electricity rationing and outages in the 1990s, and guaranteeing adequate, sustainable and affordable supply in the 2000s.

The study further reviewed the national energy planning process in the country which is carried out biennially, to update future energy demand forecasts, generation potential, and investments in transmission resulting in medium and long-term energy plans that satisfy demand at the least cost.

The key findings from the different scenarios are summed up as follows: in the historical evolution of the power sector, energy consumption grew from 3,706 GWh in 2002 to 8,429 GWh in 2017 with the installed capacity also growing from 1,053 MW to 2,259 MW to satisfy the demand. Hydro and geothermal power plants dominated the power generation mix that also included thermal, cogeneration, and wind power plants. The expansion of power generation capacity required a total investment of US$ 3,121 million over the study period translating to a specific capital cost of approximately 2,588 US$/kW. The LCOE for this scenario was estimated at 65.35 US$/MWh and specific CO_2 emissions were approximately 119.90 kg CO_2/MWh.

In the supply optimization scenario, the growth in energy consumption over the period was the same as in the historical evolution of the power sector but the installed capacity would have decreased to 2,110 MW at the end of the period in 2017 due to optimization of the expansion path. Hydro and geothermal power plants would have, to a larger extent, dominated the power generation mix that would have also included thermal power plants with a lowered contribution to the mix. The expansion of the power generation capacity would have required a total investment of US$ 3,497 million translating to a specific capital cost of approximately 3,309 US$/kW. The LCOE for this scenario would have been approximately 35.40 US$/MWh and specific CO_2 emissions would have been approximately 8.49 kg CO_2/MWh.

In the ideal scenario, energy consumption would have increased from 3,706 GWh in 2002 to 7,765 GWh in 2017. Energy consumption would have been decreased compared to the historical evolution of the sector as a result of EEC measures assumed to have been implemented progressively over the period in order to reduce consumption. The power generation mix would also have included hydro, geothermal, and thermal power plants as in the supply optimization scenario. The expansion of power generation capacity would have required a total investment of US$ 2,980 million translating to a specific capital cost of 3,306 US$/kW. The LCOE for this scenario would have been approximately 33.62 US$/MWh and specific CO_2 emissions would have been approximately 8.54 kg CO_2/MWh.

6.2 Policy recommendations

This study makes the following policy recommendations based on its analysis:

First, the optimization of capacity expansion through an energy planning process can potentially help in ensuring that the challenge of having excess (or inadequate) installed capacity in the power system at any given point in time is mitigated. By carrying out energy planning, it is possible to come up with proposals regarding the amount of power generation capacity that can sufficiently satisfy demand. It is also possible to simulate how changes in energy demand due to various reasons will affect the amount of power generation capacity needed in the system. Integration of energy planning proposals in the government's capacity expansion programs is therefore recommended to provide guidance on the amount of power generation capacity required at different points in time and the rate at which the expansion should occur. This will help in ensuring that energy supply can match the demand, and the challenges of demand-supply mismatch are therefore minimized.

Second, the optimization of power generation capacity through energy planning can help in guaranteeing that the different power generation technologies installed in the power system are fully utilized to their capacity. This is important in dealing with the challenge of having idle installed capacity in the system which also tends to have an impact on electricity costs. By adopting energy planning, it is possible to simulate the extent to which different power generation technologies included in the system will be used in meeting energy demand and to create proposals of different combinations of base load and peak power generation technologies that can efficiently meet demand. The incorporation of energy planning proposals in decision-making regarding the power generation technologies to be used for power generation in the country will, by extension, affect decisions regarding the exploration and the exploitation of different energy sources in the country.

Third, optimizing the expansion of power generation capacity requires careful consideration of all the different cost components of power generation technologies because they eventually tend to have an impact on the cost of electricity. For instance, power generation technologies with a high fuel cost component will tend to increase the electricity cost. By adopting energy planning, it is possible to comprehensively analyze the cost of implementing different expansion paths and identify which cost components have the largest impact on electricity cost. Hence, it is possible to create proposals of expansion paths that can be implemented to ensure that the resulting electricity cost is the least possible cost. The inclusion of energy planning proposals in the government's investment plans for the energy sector would therefore provide guidance on suitable power generation technologies that can potentially help in lowering the cost of electricity in the country.

Lastly, optimizing the power generation mix can help in dealing with the problem of CO_2 emissions and hence help in achieving national targets with regard to lowering of emission levels and combating climate change. By adopting energy planning, it is possible to identify the contribution of different power generation technologies to the overall CO_2 emission levels of the power system and create proposals of suitable technologies that can substitute power generation from the emitting technologies, hence assisting in bringing down the emission levels. The incorporation of energy planning proposals in the government's capacity expansion programs as well as policies and strategies with regard to addressing the challenge of climate change in the energy sector will also, by extension, have an impact on the policies and strategies aimed at promoting clean and renewable energy sources.

6.3 Limitations of the study and suggestions for further study

Despite achieving its objective of analyzing the importance of energy planning in guiding energy policy and achieving optimal energy provision, this study has some limitations. One of the limitations of the study is the assumption made regarding the implementation of EEC measures in developing the ideal scenario. It was assumed that implementing the measures to attain a reduction in energy consumption would not necessitate additional costs to be incurred. However, it is plausible that the measures would require some level of investment, for example, in the installation of efficient electrical appliances. The cost data associated with the implementation of the measures was not obtained in the course of the study; the information would nonetheless be useful in determining the effect of implementing the measures on the total costs associated with the scenario.

The study was also limited by the omission of environmental externality costs associated with CO_2 emissions. The historical evolution of the sector and the two scenarios were developed taking into consideration the CO_2 emission levels of the polluting technologies in the different expansion paths, but the externality costs of CO_2 emissions were not included in the calculations of the total power generation costs of the scenarios. The information on the externality costs of CO_2 emissions would be useful in the formulation of climate change mitigation policies and strategies such as the levy of carbon taxes, the development of regulations for CO_2 emissions, and the creation of a carbon emissions trading system. Further studies may therefore take into consideration the cost estimates for CO_2 emissions in order to determine the true costs of power generation and enhance the policies and strategies aimed at combating climate change.

Bibliography

Akinlo, A. E. (2008). Energy consumption and economic growth: Evidence from 11 Sub-Sahara African countries. *Energy Economics, 30*(5), 2391-2400.

Bazan-Perkins, S. D., & Fernandez-Zayas, J. L. (2008). Evaluation of Mexico's 1975 – 2000 energy plan. *Energy Economics, 30*(5), 2569-2586.

Bazmi, A. A., & Zahedi, G. (2011). Sustainable energy systems: Role of optimization modeling techniques in power generation and supply–A review. *Renewable and Sustainable Energy Reviews, 15*(8), 3480-3500.

Bhattacharyya, S. C. (2011). Energy economics: concepts, issues, markets and governance: Springer Science & Business Media.

Esso, L. J. (2010). Threshold cointegration and causality relationship between energy use and growth in seven African countries. *Energy Economics, 32*(6), 1383-1391.

EURELECTRIC & VGB (2003). *Efficiency in electricity generation*. Brussels/Essen: EURELECTRIC/VGB.

Gacitua, L., Gallegos, P., Henriquez-Auba, R., Lorca, A., Negrete-Pincetic, M., Olivares, D., Valenzuela, A., & Wenzel, G. (2018). A comprehensive review on expansion planning: Models and tools for energy policy analysis. *Renewable and Sustainable Energy Reviews, 98*, 346-360. doi:https://doi.org/10.1016/j.rser.2018.08.043

Gargiulo, M., & Gallachoir, B. O. (2013). Long-term energy models: Principles, characteristics, focus, and limitations. *Wiley Interdisciplinary Reviews: Energy and Environment, 2*(2), 158-177.

Godinho, C., & Eberhard, A. (2019). Learning from Power Sector Reform: The Case of Kenya. Policy Research Working Paper Series 8819, The World Bank. https://ideas.repec.org/p/wbk/wbrwps/8819.html

Gomez, A., Dopazo, C., & Fueyo, N. (2016). The "cost of not doing" energy planning: The Spanish energy bubble. *Energy, 101*, 434-446.

Government of Kenya. (2007). *Kenya vision 2030: The popular version*. Nairobi: Government of Kenya.

Groissbock, M., & Pickl, M. J. (2016). An analysis of the power market in Saudi Arabia: Retrospective cost and environmental optimization. *Applied energy, 165,* 548-558.

Heaps, C. G. (2016). *Long-range Energy Alternatives Planning (LEAP) system*. [Software version: 2018.1.32] Stockholm Environment Institute. Somerville, MA, USA. https://www.energycommunity.org

Hiremath, R. B., Shikha, S., & Ravindranath, N. H. (2007). Decentralized energy planning; modeling and application–a review. *Renewable and Sustainable Energy Reviews, 11*(5), 729-752. doi:https://doi.org/10.1016/j.rser.2005.07.005

Kenya National Bureau of Statistics. (2018). *Economic survey 2018*. Nairobi: Kenya National Bureau of Statistics.

Kenya Power. (2018, May 8). Kenya leads East Africa peers in access to electricity. Retrieved from https://www.kplc.co.ke/content/item/2485/kenya-leads-east-africa-peers-in-access-to-electricity

Lee, N. C., Leal, V. M. S., & Dias, L. C. (2018). Identification of objectives for national energy planning in developing countries. *Energy Strategy Reviews, 21*, 218-232. doi:https://doi.org/10.1016/j.esr.2018.05.004

Manzoor, D., & Aryanpur, V. (2017). Power sector development in Iran: A retrospective optimization approach. *Energy, 140*, 330-339.

Ministry of Energy. (2004). *Sessional paper no. 4 on energy*. Nairobi: Ministry of Energy.

Ministry of Energy. (2011). *Updated least cost power development plan*. Nairobi: Ministry of Energy.

Ministry of Energy. (2012). *Feed-in-tariffs policy on wind, biomass, small-hydro, geothermal, biogas and solar resource generated electricity*. Nairobi: Ministry of Energy.

Ministry of Energy. (2018). *Updated least cost power development plan*. Nairobi: Ministry of Energy.

Ministry of Energy and Petroleum. (2013). *Updated least cost power development plan*. Nairobi: Ministry of Energy and Petroleum.

Ministry of Energy and Petroleum. (2015). *Draft national energy and petroleum policy*. Nairobi: Ministry of Energy and Petroleum.

Ministry of Energy and Petroleum. (2016). *Power generation and transmission master plan, Kenya: Long term plan (main report)*. Nairobi: Ministry of Energy and Petroleum.

Mirjat, N. H., Uqaili, M. A., Harijan, K., Valasai, G. D., Shaikh, F., & Waris, M. (2017). A review of energy and power planning and policies of Pakistan. *Renewable and Sustainable Energy Reviews, 79*, 110-127.

Mougouei, F. R., & Mortazavi, M.-S. (2017). Effective approaches to energy planning and classification of energy systems models. *International journal of energy economics and policy, 7*(2), 127-131.

Nagel, J. (2019). Optimization of Energy Supply Systems: Modelling, Programming and Analysis (Vol. 69): Springer.

Odhiambo, N. M. (2010). Energy consumption, prices and economic growth in three SSA countries: A comparative study. *Energy Policy, 38*(5), 2463-2469.

Pandey, R. (2002). Energy policy modelling: agenda for developing countries. *Energy Policy, 30*(2), 97-106.

Parliamentary Budget Office. (2018). *Eye on the big four: Budget watch for 2018/19 and the medium term*. Nairobi: Parliamentary Budget Office.

Prasad, R. D., Bansal, R. C., & Raturi, A. (2014). Multi-faceted energy planning: A review. *Renewable and Sustainable Energy Reviews, 38*, 686-699. doi:https://doi.org/10.1016/j.rser.2014.07.021

Reimers, A., Cole, W., & Frew, B. (2019). The impact of planning reserve margins in long-term planning models of the electricity sector. *Energy Policy, 125*, 1-8. doi:https://doi.org/10.1016/j.enpol.2018.10.025

Soontornrangson, W., Evans, D., Fuller, R. J., & Stewart, D. (2003). Scenario planning for electricity supply. *Energy Policy, 31*(15), 1647-1659.

Taneja, J. (2018). If you build it, will they consume? Key challenges for universal, reliable, and low-cost electricity delivery in Kenya. *Center for Global Development Working Paper* (491).

Thangavelu, S. R., Khambadkone, A. M., & Karimi, I. A. (2015). Long-term optimal energy mix planning towards high energy security and low GHG emission. *Applied energy, 154,* 959-969.

Trotter, P. A., Cooper, N. J., & Wilson, P. R. (2019). A multi-criteria, long-term energy planning optimization model with integrated on-grid and off-grid electrification – The case of Uganda. *Applied energy, 243*, 288-312. doi:https://doi.org/10.1016/j.apenergy.2019.03.178

Trotter, P. A., McManus, M. C., & Maconachie, R. (2017). Electricity planning and implementation in sub-Saharan Africa: A systematic review. *Renewable and Sustainable Energy Reviews, 74*, 1189-1209.

Wang, C.-H., & Min, K. J. (2000). Generation planning with quantified outage costs. *Electric Power Systems Research, 54*(1), 37-46.

Wolde-Rufael, Y. (2009). Energy consumption and economic growth: the experience of African countries revisited. *Energy Economics, 31*(2), 217-224.

Abstract (Korean)

케냐 전력 부문이 직면하고 있는 도전 과제는 2000년대 초 불충분한 발전량과 안정적이지 않은 전력 공급으로 에너지 소비가 축소되었던 상황으로부터 변화했다. 최근 들어 나타난 주요 과제 중 하나는 중기 에너지 잉여로 인해 국내 전기요금이 증가할 수 있다는 것이다. 본 연구의 목적은 현재 직면하고 있는 과제의 관점에서 에너지 계획이 최적 에너지 공급과 관련된 정책 개발 및 정부 목표 달성을 위해 수행한 역할을 정량적으로 분석하는 것이다. 본 연구는 2002년부터 2017년까지의 케냐 전력 부문 모형을 구축하기 위해 LEAP(장기 에너지 계획 시스템)를 이용한 후향적 최적화 접근법을 적용한다. 본 연구의 목적을 고려하여, 연구 기간 동안 전력 부문의 역사적 개발에 대해 가능한 개발 경로로 간주되는 두 가지 시나리오를 모형에 구축하였다. 에너지 정책 도출 및 최적 에너지 공급에 있어 에너지 계획의 중요성을 확인하기 위하여, 분석 결과는 설치용량 확장, 발전 믹스, 이산화탄소 배출, 그리고 비용 측면에서 비교되었다. 분석 결과, 최적 발전용량 확장은 시스템에 부족하거나 남아도는 설치용량 문제를 해결하는 데 중요한 역할을 하므로, 정부의 용량 확대 프로그램은 수요과 공급의 불일치를 최소화하기 위해 필수 용량 및 확장률에 대한 계획 프로세스의 조언을 구하여야 하는 것으로 나타났다. 최적 전력 발전은 시스템 내 유휴 용량으로 인한 문제를 처리하는 데 주요한 역할을 한다. 따라서, 에너지 자원 개발에 영향을 미치는 발전 기술에 관한 정책 결정은 에너지

계획 프로세스에 의해 시스템 내 유휴 용량을 감소시킬 수 있는 방향으로 유도 되어야 한다. 또한, 분석 결과는 최적 용량 확장이 전력 비용 관리에 있어서도 그 역할을 한다는 것을 보여준다. 따라서 전력 시스템 투자 계획 역시 최저 비용 발전에 잠재적으로 기여할 수 있는 적절한 발전 기술을 선택하는 에너지 계획 프로세스에 의해 인도 되어야 한다. 게다가, 최적 전력 발전은 이산화탄소 배출 감소에 기여할 수 있고, 결과적으로 기후 변화를 완화하는 데 도움이 될 수 있는 것으로 나타났다. 따라서, 청정하고 재생 가능한 에너지 자원 개발에 영향을 미치는 용량 확장 프로그램뿐만 아니라 기후 변화 완화 정책과 전략 역시 적절한 발전 기술을 선정하기 위해 에너지 계획 프로세스를 참조하여야 한다.

주요어 : 에너지 계획, 에너지 공급, LEAP 모형, 후향적 최적화
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