RENEWABLE ELECTRICITY IN KENYA

Master Thesis

DETAILS

12-09-2017

22,194 words

Utrecht University

Sustainable Development

Track: Energy and Materials

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Summary

In Kenya, the current generated electricity is largely based on renewables, and is thus relatively low carbon. However, if it is up to the Kenyan Electricity Sector Partners, the share of renewables will decrease and make place for large scale central fossil fuelled electricity plants and a large share of imports. Making Kenya more dependent of Ethiopia for its electricity supply, increasing the transmission needs and increasing the GHG emissions from its electricity generation. Therefore, a more regional renewable electricity generation system is proposed in this study.

This is done by forecasting the electricity demand towards 2030 and making a BAU and alternative low carbon scenario for generation technologies to fulfil that demand. The BAU scenario is based on existing plans from the Kenya Electric Power Sector and the low carbon scenario is based on renewable electricity generated as close as possible to the end-user. These scenarios were compared based on costs, GHG emission potential and resulting transmission and distribution losses.

This study shows that there are enough resources in the country to provide the Kenyans with almost 100% renewable electricity, at a lower costs than with partly fossil fuelled generation, even in the high demand forecast scenario. Moreover, this would mean no need for a large share of imported electricity which reduces Kenya’s dependence on Ethiopia drastically. Furthermore, there are significant amounts of resources available within most counties to supply a part of their own electricity needs, decreasing the need for transmission and therefore reducing the high transmission and distribution losses Kenya is facing. This will save more electricity and therewith emissions and costs. This study therefore indicates that regional renewable electricity generation in Kenya has the potential to abate GHG emissions and save costs, while securing the availability of electricity.

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List of Abbreviations

BAU	business as usual
CO_2e	carbon dioxide equivalent
CSP	Concentrated Solar Power
DNI	Direct Normal Irradiance
ERC	Energy Regulatory Commission
GDC	Geothermal Development Company
GDP	gross domestic product
GHG	greenhouse gas
GHI	Global Horizontal Irradiance
GIZ	German Agency for International
GW	gigawatt
GWh	gigawatt hour
IEA	International Energy Agency
IPCC	Intergovernmental Panel on Climate Change
IPP	independent power producers
ISWA	International Solid Waste Association
IRENA	International Renewable Energy Agency
KenGen	Kenya Electricity Generating Company
KETRACO	Kenya Electricity Transmission Company
Kg	kilogram
KNBS	Kenya National Bureau of Statistics
KPLC	Kenya Power and Lighting Company
kWh	kilowatt hour
LCOE	levelized cost of electricity
MACC	Marginal Abatement Costs Curve
MOEP	Ministry of Energy and Petroleum
MSD	medium-speed diesel
MSW	municipal solid waste
Mt	million tonnes
MW	megawatt
NEMA	National Environment Management Authority, Kenya
NREL	National Renewable Energy Laboratory
PV	photovoltaic|
REA	Rural Electrification Authority
SWERA	Solar and Wind Energy Resource Assessment
TJ	terajoule
UDLCPDP	Updated Least Cost Power Development Plan

Introduction

Worldwide there are 1.2 billion people lacking access to electricity (IEA, 2016). The region with the lowest electrification rate is Sub Saharan Africa. Only 35.5% of the population has access to electricity (World Bank, 2017). It is undisputed that access to modern energy such as electricity is essential for development. It is strongly correlated with higher education, better health and poverty reduction. Moreover, access to and thus use of sustainable modern energy also contributes to the alleviation of environmental concerns associated with traditional solid fuel use (o.a. Pachauri et al., 2011; World Bank, 2008; Kanagawa & Nagata, 2008; Kirubi et al., 2008). As former United Nations Secretary-General Ban Ki-moon stated; "[renewable energy is] the golden thread that connects economic growth, social equity, and environmental sustainability" (UN Foundation, 2017). The United Nations acknowledge the necessity of access to sustainable modern energy for all for strengthening economies, protecting ecosystems and achieving equity. The 7th Sustainable Development Goal therefore is 'Ensure access to affordable, reliable, sustainable and modern energy for all'.

In Kenya, only 23% of the total population has access to electricity in 2012. This number is higher in urban areas, namely 58.2%. While only 6.7% of the rural population has access to electricity. This makes Kenya among the twenty countries with the lowest electrification rate worldwide. (World Bank, 2017b) Both the electrification rate and the average per capita electricity consumption of estimated 150 kWh lie below the average of developing countries (MOEP, 2012). Electricity contributes about 5% of Kenya's final energy consumption with the remainder from solid biomass (71%) on which rural households are mostly relying, oil products (22%) and coal (2%) (IEA, 2017c).

To be able to provide Kenyan citizens with electricity, production should be increased and the grid should be expanded. The current electricity mix is relatively climate friendly; more than 80% of the electricity production in 2014 is from renewable sources (IEA, 2017c). However, the national energy and petroleum policy states that the recently discovered coal resources are expected to play a greater role in electricity production towards 2030 (MOEP, 2015). Moreover, In the Updated Least Cost Power Development Plan (UDLCPDP), a guide to how the electricity sector can be developed up to 2030 at the least costs also includes new gas and coal and diesel plants (Electric Power Sector Kenya, 2011). Up to 2030 the electricity mix is planned to change from more than 80% renewables towards 58% renewables, off which 19% is nuclear (ibid.). The generation plants are not planned close to the users, resulting in long transmission and distribution lines. More than 1/3 of the installed capacity is generated in a different province than were the demand is (ibid.). These long distances between generation and users result in high transmission losses.

Fossil fuel combustion and especially coal combustion produces greenhouse gas (GHG) emissions, leading to human induced climate change. In a baseline scenario, the global average surface temperature is projected to rise over the 21st century and is likely to surpass 3 degrees Celsius this century, with some areas of the world expected to warm even more. Moreover, precipitation patterns are expected to change, posing huge impact on regional water and food security (IPCC, 2014). The poorest and most vulnerable people are being affected the most, among them the inhabitants of Kenya itself. Sustainable Development Goal 13 addresses this global challenge; Take urgent action to combat climate change and its impacts (UN, 2017). Building and investing in new fossil fuelled power generation projects would work against this goal. Instead the path of low carbon development of the electricity sector could be beneficial.

Kenya offers rich resources for sustainable electricity generation. It has a significant amount of annual sunlight hours with a high irradiation, the potential for wind energy is proven to be viable in various regions, the availability of biomass seems promising and the majority of the installed capacity is currently geothermal and hydropower. According to Kiplagat et al., Kenya has harnessed only about 30% of its hydropower sources, approximately 4% of the potential geothermal resources and much smaller proportions of proven wind and solar power potentials. They also state that a large potential exists for the development of biomass based energy such as biogas, biodiesel and power generation form sugarcane waste; bagasse (Kiplagat et al., 2011).

Authors consider distributed generation to have potential for energy savings, increased reliability and it will decrease the costs of upgrading the electricity grid and provide benefits for health, environment and land use burden (o.a. Pepermans et al., 2003; Strachan & Farrell, 2005; Alanne & Saari, 2006; Akorede et al., 2010). Distributed generation is defined in various ways by various authors. The definition used in this study is power generation close to the end users. With the high losses in Kenya and the costs of infrastructure, local generation might be cheaper and more sustainable than central generation.

Renewable power generation, combined with generation closer to the end users would lead to lower transmission losses and thus GHG emissions. Feasibility of these options should be studied. Apart from the UDLCPDP, another long-term development report has been written by ECN together with International Institute for Sustainable Development (IISD). This report presents a low carbon development pathway using sustainable sources (Cameron et al., 2012). However, this report also analyses the country as a whole, not taking into account renewable electricity production on a regional scale; close to users. Moreover, the ECN report does not consider transmission and distribution losses. There are no studies available that look at regional RE potentials and take into account transmission and distribution losses.

The aim of this study is two-fold; studying the potential of a low carbon electricity future for Kenya as compared to the business as usual in which more fossil fuel based technologies will be used, and researching the feasibility to generate this renewable energy as close to the end-user as possible, therewith reducing transmission and distribution losses. Kenya's vision is to transform Kenya into a newly industrializing, middle-income country providing a high quality of life to all its citizens in a clean and secure environment by 2030 (Government of Kenya, 2007). In this vision, renewable electricity generation could play a major positive role. By taking 2030 as the end-year for this study, it will be relevant for policy making about the development of the electricity system within this vision. Moreover, this thesis could contribute to the debate about the feasibility of local generation versus central generation. This leads to the research question; *To what extent can regional renewable electricity production in Kenya contribute to a lower GHG emissions scenario towards 2030 as compared to a business-as-usual scenario based on central electricity production?* An analysis for the demand, potential and cost of regional sustainable electricity production.

1. Theoretical background

1.1 Renewable energy

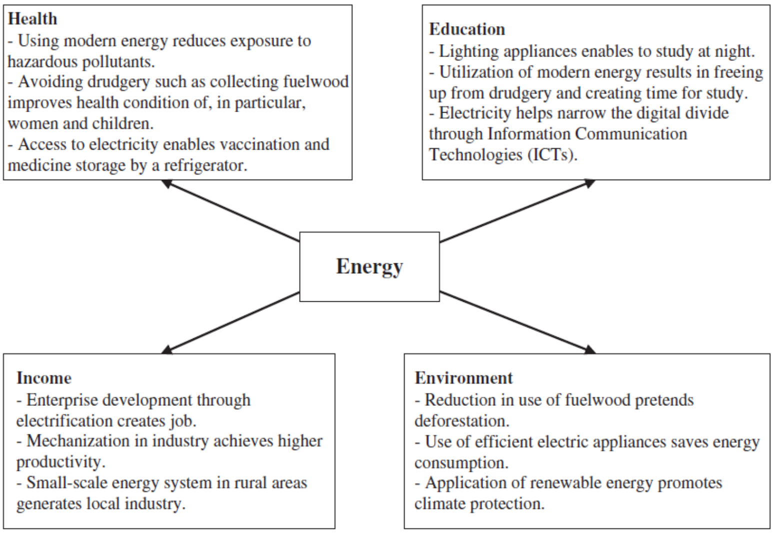
The IEA defines renewable energy as; “Energy derived from natural processes (e.g. sunlight and wind) that are replenished at a faster rate than they are consumed” (IEA, 2017b). Solar, wind, geothermal, hydro, and some forms of biomass are common sources of renewable energy. The emissions from energy generation from renewable sources are therefore assumed to be nihil, depending on the source. The potential for renewable energy resources is enormous, because it technically is an endless source. The IPCC sates that economic development has been strongly correlated with growth of energy use and increasing GHG emissions. Renewable energy could provide the growth in energy without increasing GHG emissions, contributing to sustainable development (IPCC, 2012). Also, according to Dincer & Rosen, renewable energy resources, technologies and their utilization are a key component of sustainable development (2012).

1.2 Sustainable Development

A renewable electricity mix in Kenya thus contributes to sustainable development and the sustainable development goals. But what is sustainable development? Sustainable development is defined in the Brundtland report as “development that meets the needs of the present without compromising the ability of future generations to meet their own needs” (Brundtland, 1987). Furthermore, sustainability can be broken down into three main components: social, environmental, and economic capital (Dyllick and Hockerts, 2002). These aspects are often referenced as the 3P’s: people, planet, profit coined by Elkingtonne (1994). This division is part of the theory of the Triple Bottom Line (TBL) (Elkington, 1994; Elkington, 1999).

Social aspects

As discussed in the introduction, access to electricity enhances development in various areas. It contributes to improved productivity and directly and indirectly influences poverty reduction, better health and improved education (o.a. Pachauri et al., 2011; World Bank, 2008). Kanagawa & Nagata have listed the main benefits in a matrix below (Kanagawa & Nagata, 2008).



Health
- Using modern energy reduces exposure to hazardous pollutants.
- Avoiding drudgery such as collecting fuelwood improves health condition of, in particular, women and children.
- Access to electricity enables vaccination and medicine storage by a refrigerator.

Education
- Lighting appliances enables to study at night.
- Utilization of modern energy results in freeing up from drudgery and creating time for study.
- Electricity helps narrow the digital divide through Information Communication Technologies (ICTs).

Income
- Enterprise development through electrification creates job.
- Mechanization in industry achieves higher productivity.
- Small-scale energy system in rural areas generates local industry.

Environment
- Reduction in use of fuelwood pretends deforestation.
- Use of efficient electric appliances saves energy consumption.
- Application of renewable energy promotes climate protection.

Figure 1, Kanagawa, M., & Nakata, T. (2008). Assessment of access to electricity and the socio-economic impacts in rural areas of developing countries. Energy Policy, 36(6), 2016-2029.

Evidence from Kenya provides an insight in the benefits of a community micro-grid. Access to electricity enables SME’s to work with electrical tools, thus improving the productivity per worker and increasing the revenue of the SME’s. “Moreover, access to electricity enables and improves the delivery of social and business services from a wide range of village-level infrastructure such as schools, financial institutions, and farming tools. Increased productivity and growth in revenues within the context of better delivery of social and business support services contribute to achieving higher social and economic benefits for rural communities” (Kirubi et al., 2008). The social aspects are therefore assumed to be positively impacted by a regional renewable electricity system, but are however not taken into account in this study.

Environmental aspects

Electricity generation can have impacts both on the global climate system through GHG emissions and on the local ecology. The latter is however very site-specific and will therefore be excluded from this study.

Human interference with the climate system causes risks for all natural systems and humans themselves. The greatest contributors in this interference are greenhouse gas emissions, of which CO2 is the most prominent (IPCC, 2014). Emissions are caused by transport, production, land-use change and a large amount comes from energy use. Moreover, 40% of all energy related CO2 emissions are due to electricity generation (IEA, 2017a). The main resources for electricity generation are coal, gas, nuclear and renewables including hydro, geothermal, wind and solar. Reducing the amount of fossil fuels in the electricity mix will reduce greenhouse gas emissions.

Furthermore, decentralised power generation, or power generation close to the user is currently increasing in popularity due to the positive effect on emissions due to higher efficiency and fewer losses in transmission and distribution (Pepermans et al., 2003; Alanne & Saari, 2006; Akorede et al., 2010).

Economical aspects

Economical aspects are considered a driving factor when it comes to approving an investment or project. Costs should be charted accurately over the total lifetime of a project to enable accurate decision-making (Munns et al., 1996). According to Blok (2016), costs should be divided into two main sections:

- Investments,
- Operation and maintenance costs.

Investments are non-recurring costs, mainly composed of equipment costs, installation, and training (ibid.). Recurring costs cover operating and maintenance costs. To be fully comprehensive, a life-cycle costs (LCC) analysis should be done. An LCC includes not only the costs of raw materials, construction of the project and the operation phase, it also includes the costs in the end-of-life phase (Schau et al., 2011). Renewable energy sources often have lower operation costs because there is no need for the purchase of feedstock in most cases. Furthermore, a regional electricity generation system could result in avoided investments in transmissions and distribution capacity and it could bypass costs for transmission and distribution.

1.3 Regional Generation

As discussed, regional generation, thus generation close to the end users, could lower GHG emissions and costs through less losses from transmission distribution. In this study, regional generation is defined as power generation close to the end user, meaning that the demand of each county in Kenya will be generated within that county when possible. Kenya has 47 counties, ranging from 70,691 km2 to 229.7 km2, thus showing a large difference in size. Narrowing down electricity generation for regions within counties is however not possible since there is not enough data on a smaller scale.

Figure 2, Counties in Kenya

1.4 Renewable electricity technologies

This section provides a summary of relevant renewable electricity technologies for electricity generation and their potential in Kenya, based on previous studies and reports.

Hydropower

Kenya’s drainage system consists of five major basins: Lake Victoria; Rift Valley; Athi River; Tana River; and Ewaso Ngiro North River. These basins contain the main part of the country’s hydro resources for power generation. Kenya’s total installed large hydropower capacity is 785.8 MW (KPLC, 2016). The potential for small, mini and micro-hydro system (with capacities of less than 10MW each) is estimated at 3,000MW nationwide (Kiplagat et al., 2012). However, hydropower generation is vulnerable to large variations in rainfall and climate change. Kenya’s electricity generation is more than 50% based on hydro. This has proved to be a big challenge, currently and in the recent past with the failure of long rains that resulted in power and electricity shortfalls (Government of Kenya, 2012; Obulutsa, 2017). Moreover, there are also negative social and environmental impacts related to the hydro projects. Multiple big hydro projects were cancelled to mitigate the social impacts of relocation (Government of Kenya, 2012).

Geothermal power

Geothermal energy is the second largest resource for electricity generation in Kenya. In 2015 the total effective installed capacity was 485MW, a sharp increase since the last 5 years (KPLC, 2016). The Government through the Ministry of Energy, GDC, KenGen and other partners has undertaken detailed surface studies of some of the most promising geothermal prospects in the country. Evaluation of these data sets suggest that 5,000MWe to 10,000MWe can be generated from the high temperature resource areas in Kenya in over fourteen sites (Government of Kenya, 2012; Simiyu, 2010). There are 14 large Quaternary volcanoes in Kenya and together with other prospective sites provides an estimate of possible generation of 10,000 MW according to Omenda & Simiyu (2015). These prospects are clustered into three regions namely the Central Rift, South Rift, and North Rift, see figure 2 for locations of geothermal prospects within the Kenyan Rift Valley.

Geothermal electricity generation has good potential for a base-load coverage in Kenya. The social and environmental aspects of electricity generation from geothermal sources in Kenya are proven to be minimal and can be mitigated and optimized (Mwangi, 2010).

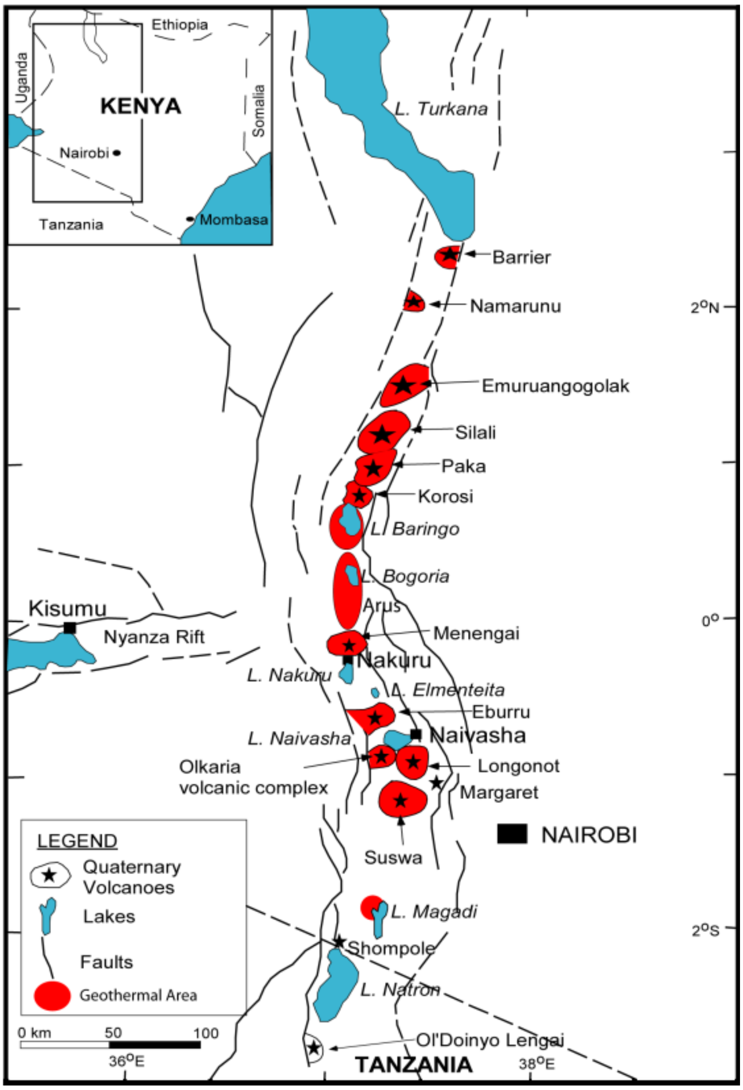


Figure 3, potential geothermal fields (Omenda & Simiyu, 2015)

Municipal Solid Waste

Municipal Solid Waste (MSW) is currently dumped at landfill sites. At the dumpsite, anaerobic digestion processes will take place due to the degradation of the organic components. This process creates Methane, a strong greenhouse gas that contributes to climate change. However, when captured, this gas can be used for electricity generation and therewith to low carbon base-load electricity production. Using this underutilised source could contribute to an improved waste management situation and therefore pose benefits to health and the environment. A study in 2010 showed that the potential for electricity generation using landfill gas recovery from MSW is 64MW in Nairobi (Fisher et al., 2010). A 2015 study by Scarlat et al. also included the possibility of incineration of MSW and estimated that the potential in Kenya for electricity generation from all collected waste was 214 GWh through incineration and 76 GWh through landfill gas recovery. These numbers will rise to subsequently 1150 GWh and 410 GWh in 2025 (Scarlat et al., 2015). A large potential considering the total electricity consumption in Nairobi was 3691 GWh in 2015 (KPLC, 2016).

Solar power

The penetration of solar power is currently very low in Kenya, only 0,569 MW is installed (KPLC, 2016). However, various authors state that is has serious potential for the future. Oloo et al. show that about 70% of Kenya has the potential of receiving approximately 5 kWh/m2/day throughout the year (2016). Kiplagat et al. argue that it is especially opportune because the places with the highest solar irradiation are located in arid areas with low agricultural potential and sparse population, hence large solar systems such as PV and concentrated solar thermal can easily be accommodated (Kiplagat et al., 2011). Kiplagat et al. also recognise the high price, although they are expecting it to decrease.

However, a recent case study in Kenya suggests the levelized costs of solar PV are already comparable and even lower than the most expensive conventional electricity generation technologies such as medium speed diesel and gas turbines (Ondraczek, 2014). Moreover, Rose et al. (2016) also indicate solar PV as an economic alternative to the current use of fuel oil plants.

Bio-energy,

Currently, biomass in the form of fire-wood and charcoal is Kenya’s largest energy resource, and mostly used in households (IEA, 2017). However, most of this use of biomass is inefficient and a great hazard to health, deforestation and the environment. More efficient power production from bio-energy could contribute to the low carbon development of Kenya. Dasappa estimates that the power potential of biomass at an availability of 30% of agricultural waste is 102 MW (Dasappa, 2011). Kiplagat et al identify 830 GWH/year of potential extra electricity production using co-generation from bagasse, apart from internal use of sugar mills (2011). However, the only sugar mill that did provide power to the grid, has lowered its output and even ceased to do so in 2015/2016 (KPLC, 2016). However, BioTrade 2020 indicates potential sustainable agricultural production surplus for export, which could be used locally for power generation (Mai-Moulin et al., 2016).

Wind energy

Wind energy is recently adopted as a new form of power generation in Kenya. The first wind farm was built in 2009, and is now producing 56.7 GWh annually (KPLC, 2016). Private wind farms are initiated and building was started, but they are however not operational yet (Kiplagat et al, 2011). Wind is indicated as having great potential in Kenya. Various case studies show a good potential at different sites in Kenya (Kamau et al., 2009; Choge et al., 2015) and a promising overall potential (Kandoi et al., 2007).

2. Methods

This chapter will elaborate on the methodological approach and demonstrate how the research question will be answered. Firstly some often used concepts and goal and scope of the study will be defined, after which sub-questions will be presented with the methodological considerations for each of them. It should be noted that a lot of assumptions will need to be made within this study. This chapter will give an overview of the method and these assumptions, however, detailed data sources, methods and their limitations will however be discussed in the individual chapters concerning the sub questions. This is to favour the readability of this and other chapters.

2.1 Goal and scope definition

The intended application of this research is to provide an analysis for the demand and potential of renewable electricity production for each county in Kenya. Furthermore, this data will be combined with the costs of different renewable electricity generation technologies and the CO_2 abatement potential and will result in a national optimal electricity mix for both for environmental impact and economics for the whole of Kenya. The CO_2e emission abatement costs of the low carbon scenario as compared to the business and usual scenario (BAU) will be presented. The results could be used by actors in the electricity sector in Kenya as well as contribute to policy making for future development plans.

2.2 Common used definitions

Electricity Demand

In this study, electricity demand is defined as the total demand for electricity in GWh. It includes losses and net imports.

Electricity Consumption

Electricity consumption is defined as the actual electricity used by end-users in GWh. It thus excludes losses but includes net-imports.

Electricity Generation

Electricity generation is defined as the total electricity generated in Kenya. Its thus includes losses but excludes net imports.

Peak demand

Peak demand stands for the maximum power demand at a given time and is therefore given in MW.

Supressed demand

When supply does not completely meet the peak demand, this results in less electricity consumption than would have been consumed if the supply would have been satisfactory. This difference in electricity demand and supply is called suppressed demand.

2.3 Research question and sub-questions

Research question

To what extent can regional renewable electricity production in Kenya contribute to a lower GHG emissions scenario towards 2030 as compared to a business-as-usual scenario based on central electricity production?

To answer this question, a good overview of the current situation and future consumption scenarios should be made first, after which the a business as usual scenario and a regional low carbon low carbon scenario can be created. These should be compared to each other in order to formulate a clear answer to the research question. In order to do so, the following sub-questions should be addressed;

Sub-questions

1. *How will the electricity consumption develop towards 2030 in the different counties based on historical and current trends?*
2. *What is the business as usual scenario for electricity generation towards 2030 in Kenya?*
3. *What is the potential for the different renewable electricity production technologies in the different counties?*
4. *What are the costs of installing and operating the renewable electricity production technologies?*
5. *What would be the optimal electricity mix for a low carbon scenario for Kenya, considering the constraints and potential for renewables in different counties?*
6. *What are the consequences for transmission and distribution losses when implementing the low carbon electricity generation scenario?*
7. *How does this low carbon scenario compare to the business as usual scenario for costs and GHG emissions in Kenya?*

2.4 Current situation and consumption forecasts

In order to define electricity generation scenarios, the first step needs to be examining the needs of the system. Starting from historical and current electricity consumption patterns, future consumption scenarios can be created. This section will subsequently answer the question; *How will the electricity consumption develop towards 2030 in the different counties based on historical and current trends?*

The KPLC encloses electricity consumption data for 9 regions, being Nairobi North, South, West, North eastern, Mt Kenya, North Rift, Central Rift, West region and the Coast region (KPLC, 2016). This data is separated in categories of consumption which are simplified to residential consumption and industrial and commercial consumption.

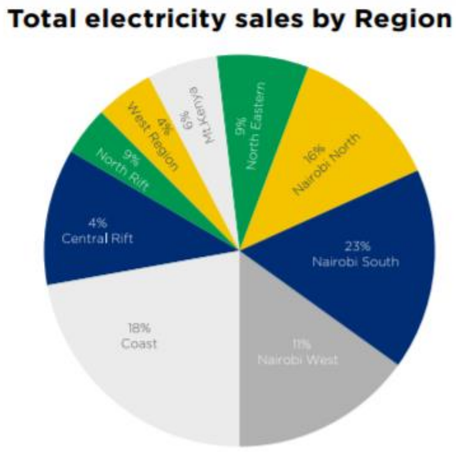


Figure 4, electricity Production by region (KPLC, 2016).

With these data, in combination with household and electricity access data provided per county within these regions (derived from o.a. world bank and the humanitarian data exchange) weighed consumption estimates per county are made for the past 5 years for residential consumption. Based on these estimates, combined with various assumptions for change towards 2030 listed below, the residential electricity consumption patterns can be extrapolated. To do so, assumptions are needed for the following indicators;

- population growth and urbanization
- change in household size
- GDP growth and resulting demand growth per household (kWh/household/year)
- Energy efficiency developments
- Electrification rate

For industrial and commercial consumption, the forecasts are based on GDP growth estimates as provided by secondary sources such as the World Bank.

2.5 BAU scenario

After the consumption scenarios have been created, these scenarios should be combined with data and forecasts of losses. This will give the overall demand scenario. Based on this, and existing plans of public and private bodies in the electricity sector a business as usual scenario can be created. This will answer the sub-question; *What is the business as usual scenario for electricity generation towards 2030?* This question will be answered using desk research and secondary data.

The Business as Usual (BAU) scenario is mostly based on the data of the Updated Least Cost Power Development Plan (UDLCPDP) 2011 – 2031, which is the official long-term electricity planning document of the Kenyan Electric Power Sector (2011) and the Ministry of Energy and Petroleum (MOEP) Strategic Plan 2013-2017. These reports are used for the baseline projection for the composition of the different electricity generating technologies in Kenya’s electricity mix in 2030 and corresponding transmission and distribution needs. However, the electricity mix is re-evaluated based on increase in output since the UDLCPDP and included technologies e.g. nuclear energy is assumed to be feasible before 2030 because it is not yet implemented in Kenya (Cameron et al., 2012) and generation plants have been built since these reports released. The amount of emissions of electricity generation from fossil fuels are calculated as follows (Andrews and Jelley, 2013):

Equation 1

$$Emissions_{GHG,fuel} = \sum_{tech} Fuel\ consumption_{fuel} * \ Emission\ factor_{GHG,fuel,tech}$$

Emissions =	emissions of a given GHG by type of fuel (kg GHG)
Fuel Consumption =	amount of fuel combusted (TJ). Fuel consumption per technology is calculated through multiplying the total generation (GWh) by the average conversion efficiency of the technology (%) by the conversion factor 3.6 GWh / TJ.
Emission Factor =	default emission factor of a given GHG by type of fuel (kg gas/TJ) (IPCC)

The total generation per technology type is calculated by multiplying the installed capacity (MW) of each technology by an average capacity factor (hours per year).

The emissions that are a result of the losses of transmission and distribution are estimated based on extrapolation of trends towards 2030 of the current losses as indicated by the KPLC.

2.6 Potential

To determine whether the forecasted electricity needs could also be satisfied with renewable sources close to the end user, the resources and potential for each renewable electricity technology included in this study should be studied per county. Which will answer the sub-question: *What is the potential for the different renewable electricity production technologies in the different counties?*

Solar and wind

In the Geographic Information System (ArcGIS or GIS), solar and wind potential maps are created based on irradiance maps, wind speed maps and elevation maps. The irradiance and wind speeds at suitable heights for electricity generation will then be analysed per county. After which the total amount of area with a good potential for electricity generation from wind or solar is determined. Agriculture land, nature reserve's, built environment, culturally important area's etc., derived from global land cover data (GLC 2000) are excluded. Land cover changes are extrapolated according to prospects on population growth. Future solar and wind prospects are based on extrapolation of trends.

Solar potential are defined using satellite images of irradiance on the surface of Kenya (National Renewable Energy Laboratory: NREL). The potential energy (alternating current) of a panel is calculated in the following manner (Andrews and Jelley, 2013):

Equation 2

$$E = A * h * \eta * \text{tilt and orientation effects (in \% of max)}$$

A = amount of land(M^2)
h = annual irradiation (kWh/m-2y-1)

Wind potential is derived from the Solar and Wind Energy Resource Assessment (SWERA) by NREL and global data on wind speed combined with elevation maps. Potential output is calculated using the following formula's (Andrews and Jelley, 2013);

Equation 3

$$P_w = ½ * \rho * A * u^3$$

&

$$P_{area} = 3.75 * 10^{-3} u^3$$

Where:

P_w = potential wind power output at a site (MW)
P_{area} = average power output per area (MW/km^2)
ρ = density of air (kg/m^3)
A = area (km^2)
u = wind speed (m/s)

Biomass and waste

The available local resources for electricity generation from biomass and waste is determined on the basis of available databases (for biomass, the BioTrade 2020 database) and various articles on biomass and waste potential. Assumptions are made on conversion efficiency and rates (e.g. IEA, IPCC). On basis of which the electricity potential in the case of CHP plants is calculated.

Geothermal & Hydro

Estimates for geothermal potential is based on extrapolation of trends found during desk research using secondary data. The hydro potential will also be based on climate change expectations.

2.8 Economics

After the potential of each renewable electricity technology is determined, the costs play a major role. After all, if the costs of a low carbon scenario based on renewable and local electricity production are too high, this will not be a viable option. This paragraph discusses the costs for each renewable electricity technology included in this study, thus answering the research question: *What are the costs of installing and operating the sustainable electricity production technologies?*

The costs of the technologies are determined by using the levelized costs of electricity generation (LCOE, \$/kWh). However due to a lack of information, numbers from previous studies derived from desk research have been used in most cases. LCOE are calculated by the following formula (o.a. Andrews & Jelley, 2013);

Equation 4

$$LCOE = \frac{\sum_{t=1}^{n} \frac{I_t + M_t + F_t}{(1+r)^t}}{\sum_{t=1}^{n} \frac{E_t}{(1+r)^t}} = \frac{sum\ of\ costs\ over\ lifetime}{sum\ of\ electricity\ produced\ over\ lifetime}$$

I_t = investment expenditures in the year t

M_t = operations and maintenance expenditures in the year t

F_t = fuel expenditures in the year t

E_t = electrical energy generated in the year t

r = discount rate

n = expected lifetime of system or power station

2.9 Optimal electricity mix

Based on the potential and costs of the various renewable electricity technologies, the optimal electricity mix for Kenya could be determined. To answer the question; *What would be the optimal electricity mix for a low carbon scenario for Kenya, considering the constraints and potential for renewables in different counties?* least cost supply curves need to be made for each county. These curve's show the potential per technology and the costs of these technologies. Starting with the least cost generation technology working towards the saturation of the demand. It should be noted that technologies which do have potential in the counties, could not be included in the electricity mix because the costs are higher than the other technologies if the demand is already saturated with their potential. Moreover, for the least costs supply curves, constraints for the optimal mix should be considered. One of those constraints is that the share of variable sources needs to be balanced with flexible sources to ensure a stable electricity grid, e.g. a maximum share of variable renewable electricity and minimum flexible capacity. Huber et al. indicate that a share of above 30% variable sources in the electricity mix increases the need for flexible sources significantly (Huber et al., 2014). The minimum flexible generation sources are determined based on the current load pattern. Further constraints will be discussed in chapter 6.

The optimal electricity mix for the low carbon scenario, subsequent transmission losses, avoided emissions and costs as will be discussed in the following sections, is based on the high demand growth scenario. This scenario is taken as a reference because in the high growth scenario, the largest pressure will be put on the renewable energy resources of the counties. This means that if a regional renewable electricity generation mix would be feasible in this scenario, chances are high it would also be feasible in the other two scenarios. However, this would not be the case if the low growth scenario would have been taken as a reference, since the high growth demand scenario would put more pressure on the resources. This choice thus secures the relevance of the results for all three consumption growth scenarios. The implications of the results for other scenarios will however be discussed in chapter 9.

2.7 Transmission and Distribution

Derived from electricity mix per county and the resulting deficits or surpluses in different counties a transmission and distribution system can be outlined which focusses on optimizing the distance between the electricity generation and demand. This will answer the question; *What are the consequences for transmission and distribution losses when implementing the low carbon electricity generation scenario?* This is done following 3 steps.

1. The locations of future generation plants should be determined. Starting from the demand and potential per county, considering the constraints that will be discussed later.
2. The regional power balances and estimating future potential flows (if applicable) between counties should be identified.
3. The needs for transmission between and distribution within counties should be determined.

Losses

The losses are calculated based on the distance between the generation and use sites. According to the following formula (Andrews and Jelley, 2013):\

Equation 5

$$\Delta P = RI^2 = \rho * \frac{I}{A} * L * I$$

ΔP= Power losses (W)
L= length (m)
A= Area (m^2)
ρ= Resistivity (Ωm, $1.7*10^{-8}$ for Cu)
I= Electric current (Ampere)

2.10 Comparison

In this section the answer for the final sub-question *How does this low carbon scenario compare to the business as usual scenario for costs and GHG emissions in Kenya?* will be given. This comparison is based on the electricity generation costs to meet the demand, and the CO2 emission abatements of the low carbon scenario compared to the BAU scenario. Both the lower transmission and distribution losses and the renewable electricity technologies will contribute to the CO2 emission abatements of the fossil fuel based technologies and high losses in the BAU scenario.

Often, such a comparison is done using a Marginal Abatement Costs Curve (MACC). MAC curves are used to illustrate the economic and technological feasibility of climate change mitigation options. A MAC curve is a graph that indicates the marginal cost of emission abatement for varying amounts of emission reduction (Kesicki & Ekins, 2012). However, since in this case both the baseline and the proposed technologies are a mix of technologies with different amounts of electricity output, such a curve does not represent the reality in a proper way. E.g. the new technologies could be evaluated against the weighted average price of the BAU technology mix, however since the real price range of technologies is wide, this would result in a MACC that only shows the statistical potential of the cheapest technologies, but does not reflect preferred choice technologies. Furthermore, a shortcoming of a MACC is that it treats different generation plants independently, just like with the LCOE, however this then ignores the interaction with the system in which they operate as Rose at al. point out rightly so (2016). The maximum share of variable technologies is important in the mix, this would be completely overlooked when using a MACC.

This study therefore compares the systems total and weighed costs of electricity generation. Furthermore, the total emissions savings are determined and compared to the BAU scenarios. This results in the marginal abatement costs of the full system.

3.Regional Overview

The KPLC considers 4 regions with 9 sub-regions being; Nairobi, including Nairobi North, South and West; Mt Kenya, including North eastern and Mt Kenya; West region, including North Rift, Central Rift, West Kenya and South Nyanza; and the Coast region (KPLC, 2016). The counties per region are presented in below.

Table 1, Regions and counties (KPLC, 2016)

Region	**County**
Central Rift	Baringo
	Bomet
	Nakuru
	Narok
	Nyandarua
Coast Region	Kilifi
	Kwale
	Lamu
	Mombasa
	Taita Taveta
	Tana River
Mt Kenya	Embu
	Isiolo
	Kirinyaga
	Laikipia
	Meru
	Murang'a
	Nyeri
	Tharaka nithi
Nairobi North	Nairobi (share)
Nairobi South	Machakos
	Nairobi (share)
Nairobi West	Kajiado
	Nairobi (share)
North Eastern	Garissa
	Kiambu
	Kitui
	Makueni
	Mandera
	Wajir
North Rift	Elgeyo Marakwet
	Marsabit
	Nandi County
	Samburu
	Trans Nzoia
	Turkana
	Uasin Gishu County
	West Pokot
South Nyanza	Homa Bay
	Kisii
	Migori
	Nyamira
West Region	Bungoma
	Busia
	Kakamega
	Kericho
	Kisumu
	Siaya
	Vihiga

Nairobi is the county with the largest city in Kenya. The county therefore has the highest share of urban population, but also the highest rate of access to electricity and the highest GDP as can be seen from figure 5 t/m 7 below. Kiambu, which is a neighbouring county to Nairobi and can be counted as the greater Nairobi region follows closely on all 3 levels. Interesting to see is that while Mombasa, the largest harbour city, does have a high share of urban population and the second highest access to electricity in Kenya, its GDP lags behind (see figure 6). This is mostly due to the fact that Mombasa has no GDP from the agricultural sector since it has no available land (Bundervoet et al., 2015). A trend can be identified between the access to electricity and urban population and GDP. However some counties with a higher GDP have instead very low access to electricity and a low share of urban population.

All counties with the higher rates of urbanisation, access to electricity and GDP are located in the south-west of Kenya. Total population numbers are also very low in these areas (KNBS, 2009).

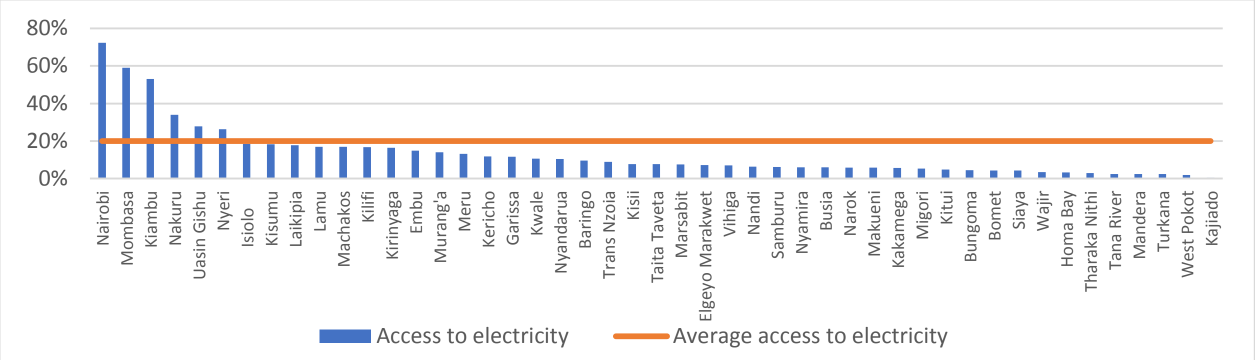


Figure 5, Access to electricity per county in 2009 (KNBS, 2009)

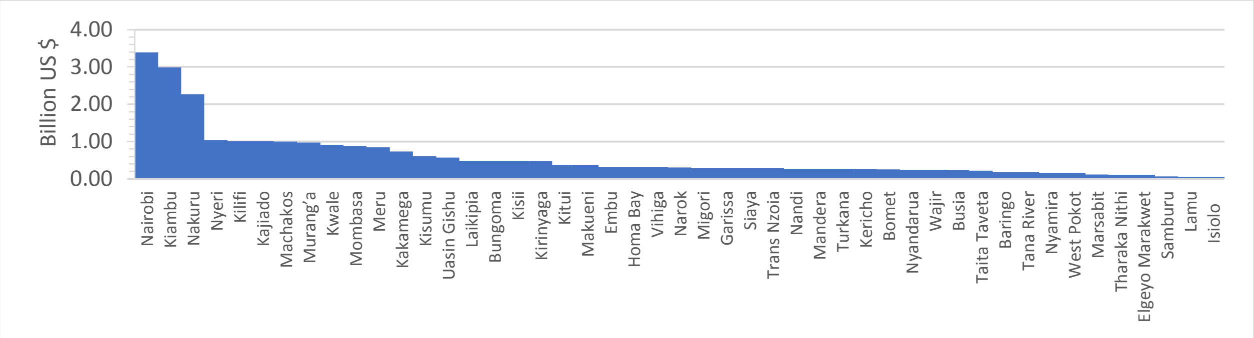


Figure 6, GDP per county (Bundervoet et al., 2015)

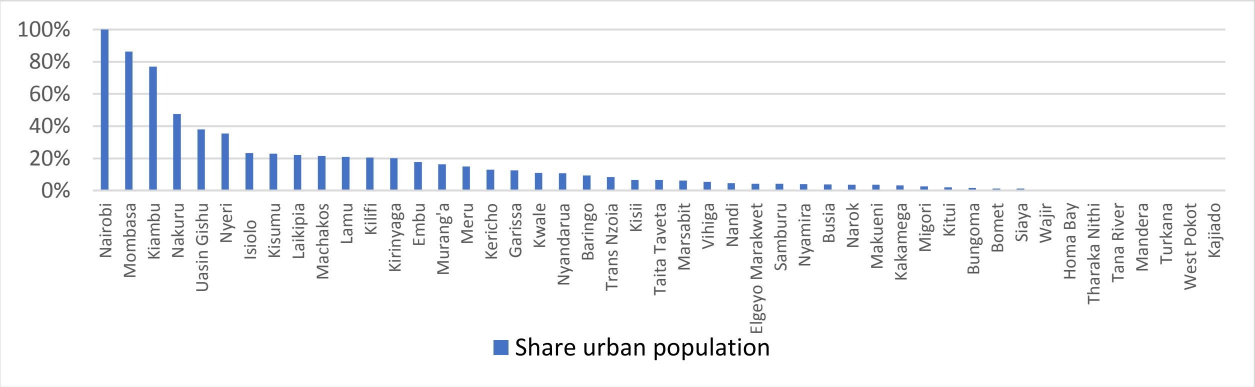


Figure 7, share of urban population per county in 2009 (KNBS, 2009)

4. Consumption forecasts

This section will assess the historical demand developments and the current situation of the different regions in Kenya. These historical demand trends per region will be interpolated to determine the demand per county within those regions and subsequently extrapolated to forecast the consumption trends towards 2030. Eventually answering the question; *How will the electricity consumption develop towards 2030 in the different counties based on historical and current trends?*

Period 2009-2015

The electricity consumption in Kenya is offered per region, as listed in the former chapter. Electricity consumption trends are used as a basis for the future consumption scenarios. These scenarios will be adjusted by including the current suppressed demand, discussed later in this section. To be able to determine the consumption per county, the data needs to be interpolated. In order to make an accurate estimate of the consumption per county the electricity consumption data provided by the KPLC were first separated in two categories: residential consumption, including rural electrification and street lighting and commercial and industrial consumption.

Table 2, data and sources

Input data and Assumptions:	Source:
Electricity consumption per region	KPLC, Annual report 2009 and 2016 (KPLC, 2009; KPLC, 2016)
Population and electricity access rates per county	KNBS county census, 2009 (KNBS, 2009)
GDP per county 2013	World bank Policy research working paper (Bundervoet et al., 2015)
Distribution and transmission losses data	KPLC annual reports (KPLC, 2009; KPLC, 2016)
Electricity access growth rates, (urban and rural) population growth rates, GDP growth rates	World Bank indicators (World bank, 2016)

Figure 10 shows that the electricity consumption is persistently rising over the past years. While the Nairobi region still consumes the largest amount of electricity in 2015, the Mt. Kenya region is rapildy enlarging its share. From figure 11 can be derived that the largest part of the consumption is due to commercial and industrial electricity use (Category 2). Furthermore, distribution and losses consist of a relatively large share of the total demand. The access rate has been rising in Kenya and this is especially seen in Urban areas where it has risen from 72% in 2009 to 100% in 2015 (figure 9). The demand per capita also shows an increase over the years, however, the rapid rise in demand per capita in the year 2013 is most likely not due to a rise in residential electricity use but it is thus industrial and commercial electricity use which shows a rapid increase in that specific year. This corresponds with the start of GDP growth after a decrease in the years prior (figure 8).

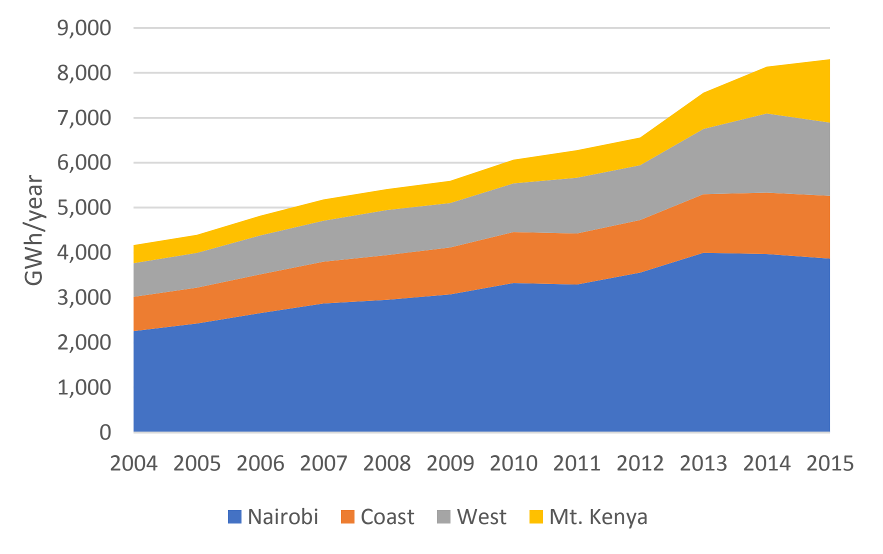


Figure 10, electricity consumption per region (KPLC, 2016; KPLC, 2011)

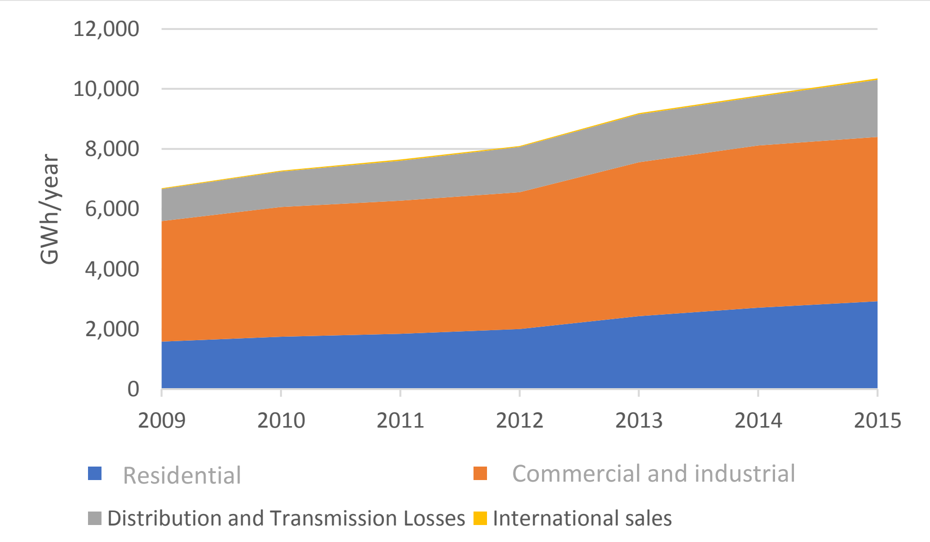


Figure 11, electricity demand broken up in categories and losses (KPLC, 2016)

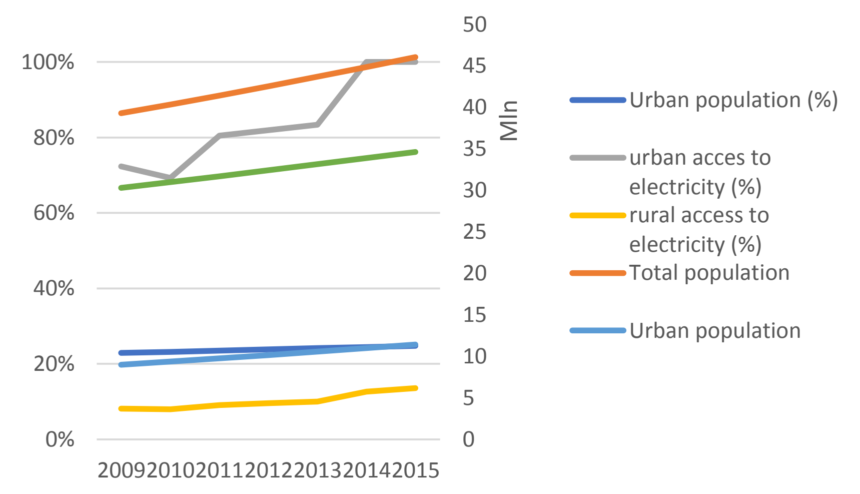


Figure 9, population and electricity access growth (World Bank, 2016)

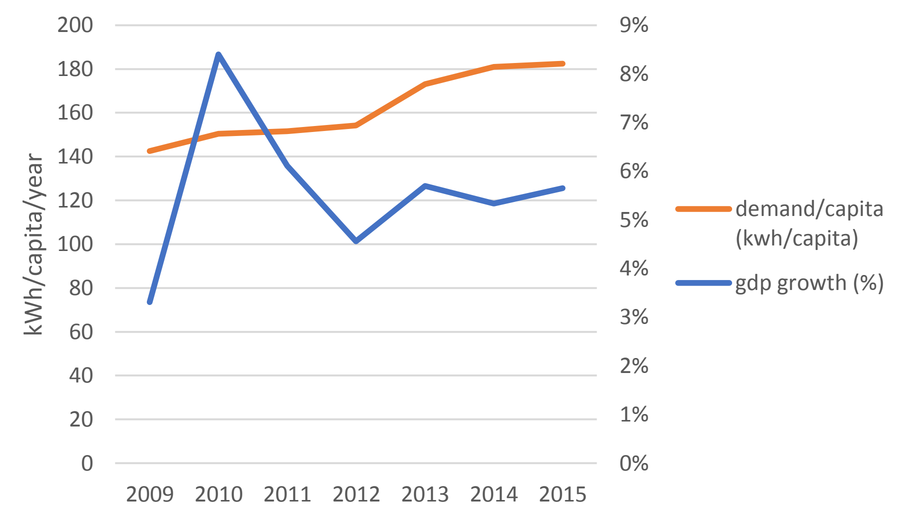


Figure 8, Demand per capita and GDP growth (own results; World Bank, 2016)

Residential Consumption

The amount of people with access to electricity per county is based on data covering electricity access rate and total population per county in 2009, given in the county census done by the Kenya National Bureau of Statistics (KNBS, 2009). The total population and average electricity access rate for Kenya derived from this census are slightly lower from the estimates provided by the World Bank, but are assumed to be accurate due to the high amount of detail and thoroughness of the study. To be able to analyse these numbers in combination with electrification growth rate estimates of the world bank, the numbers from the KNBS have been upscaled to the same level. Based on the electricity access rates, population per county and electricity access rates in rural and urban Kenya, estimations could be made about the share of urban and rural population per county. The percentage urban population per county in 2009 could be derived from the following formula:

Equation 6

$$\begin{aligned}&\%\,electricity\ access/county\ (known) = 0.7237\ (\%\,urban\ electricity\ access\ in\ 2009) * \\ &\%\,urban\ population + 0{,}0810\ (\%\,rural\ electricity\ access\ in\ 2009) * \\ &\%\,rural\ population\ [Where;\ \%\,urban\ population + \%\,rural\ population = 100]\end{aligned}$$

Interestingly, in year 2010 the World Bank estimates on the share of population with electricity access have dropped, this could be possible if the population would have grown very fast and the growth in amount of connections would have lacked. However, the access to electricity rate dropped faster in the estimates then the effect of population growth could level out. This would have meant an enormous decrease of people with access to electricity, which is not likely. The amount of people with access is therefore kept at the same level in 2010 as in 2009.

Working with the urban and rural electricity access and population growth rates provided by the World Bank, the total electricity access rate per county and thus the population per county with access to electricity could be calculated for the following years. On the basis of which the electricity consumption per county could be derived.

Here the assumption is made that the residential and industrial consumption is based on the amount of people with access to electricity.

Equation 7

$$\begin{aligned}&Electricity\ consumption\ in\ county\ x = \\ &electricity\ consumption\ per\ region * \frac{people\ with\ access\ to\ electricity\ in\ county\ x}{total\ amount\ of\ people\ with\ access\ to\ electricity\ in\ region}.\end{aligned}$$

The residential electricity consumption of people with access to electricity on which the weighing per county is based differs greatly per region. Figure 12 below shows that the regions with the highest shares of urban population and the highest GDP also have the highest residential electricity use per capita. However, the differences are decreasing.

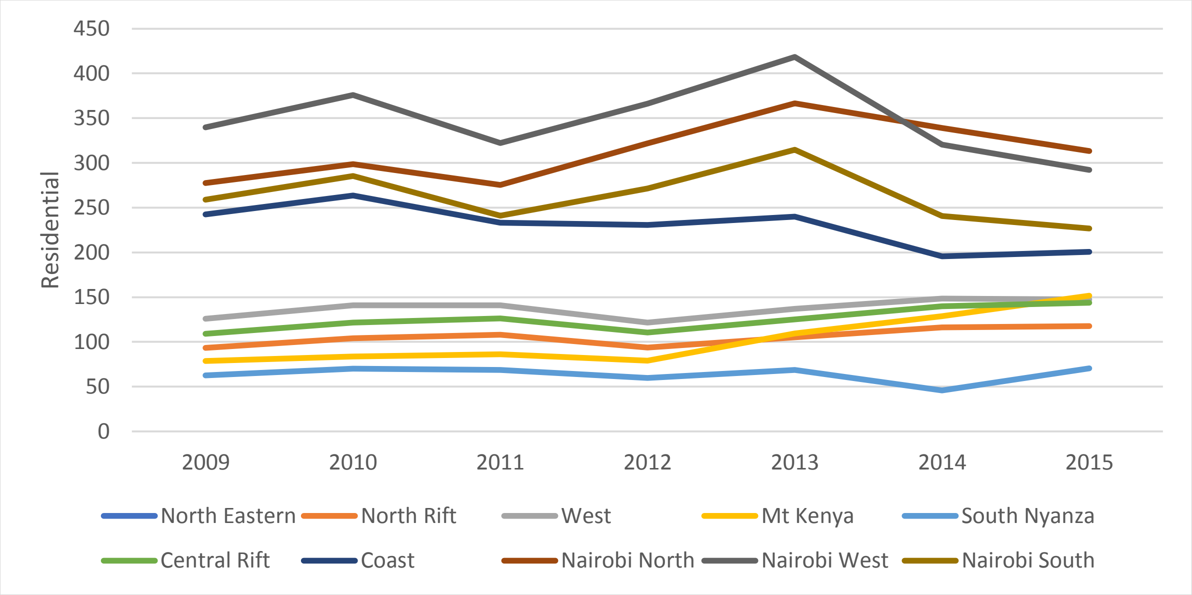


Figure 12, regional residential electricity consumption per capita of people with access to electricity

Interesting to see is that while the average total electricity consumption per capita is rising and the residential use per capita is rising, the residential consumption per person who has actual access to electricity is fluctuating around the average, while the total consumption per person who has access is even decreasing. This is because the share of Kenyans with access to electricity is rapidly increasing while the total electricity consumption growth is not rising as fast.

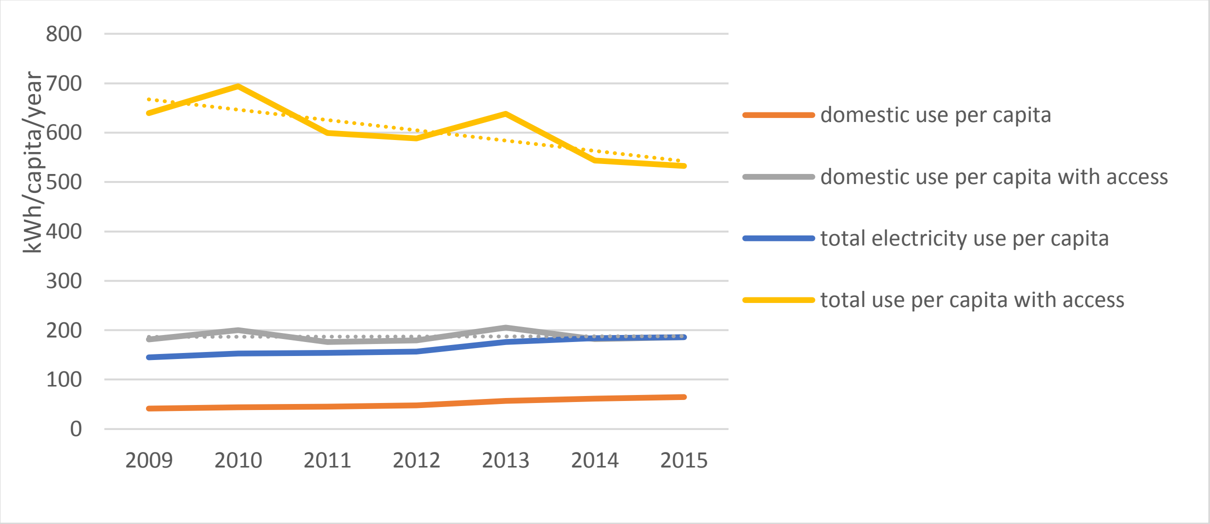


Figure 13, electricity consumption per capita (domestic = residential)

Industrial and commercial consumption

The weighing for commercial and industrial consumption is based in the differences in GDP per county (World Bank, 2015). GDP per county is determined by the World Bank in 2013. The annual GDP growth rates as presented by the World bank have been used to extrapolate the GDP per county over the years. Furthermore, GDP and electricity use is highly correlated as shown by various studies (o.a. C. Lee, 2005) and it can therefore be used as an indicator to estimate the county share of the regional electricity consumption. The amount of industrial and commercial electricity consumption per county is calculated by weighing the regional consumption per county based on the share of GDP per county of the total GDP per region.

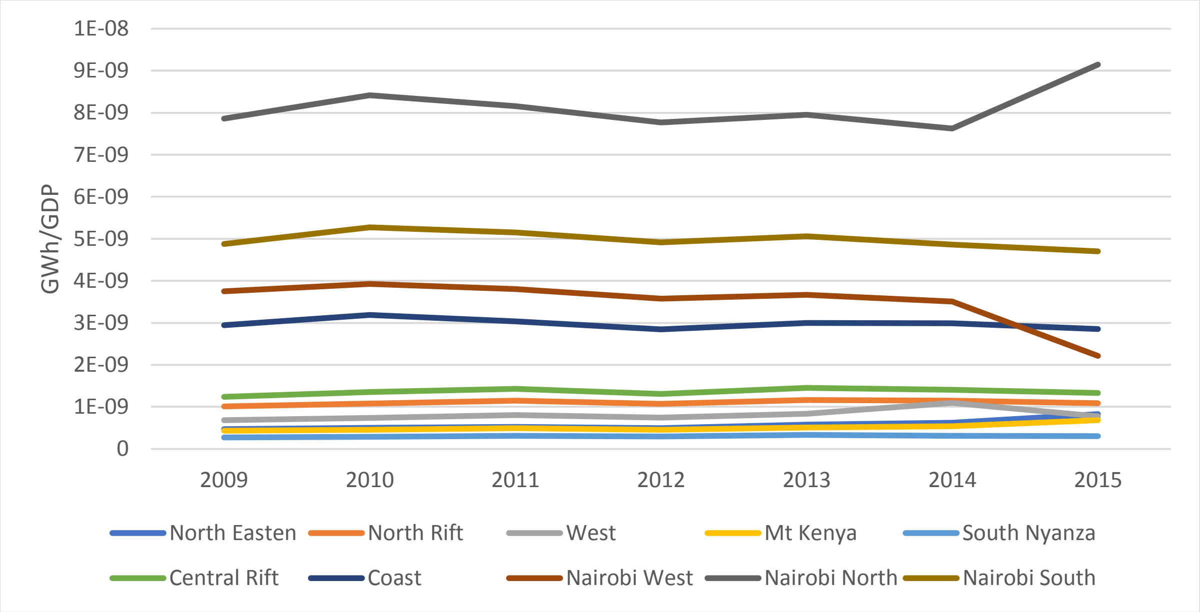


Figure 14, electricity consumption per unit of GDP per county

The highest industrial and commercial electricity use per GDP can again be found in the regions in which the GDP from agriculture is lowest and urban areas are largest. Furthermore, in all regions, the electricity use per GDP is somewhat stable. Only 2015 is a deviant year for Nairobi North and West; this is due to a steep increase in industrial electricity consumption in the former and a steep decrease in the latter region. This could be a real trend, however, it might also be possible that this difference could be caused by changing the calculative jurisdiction of the Nairobi regions.

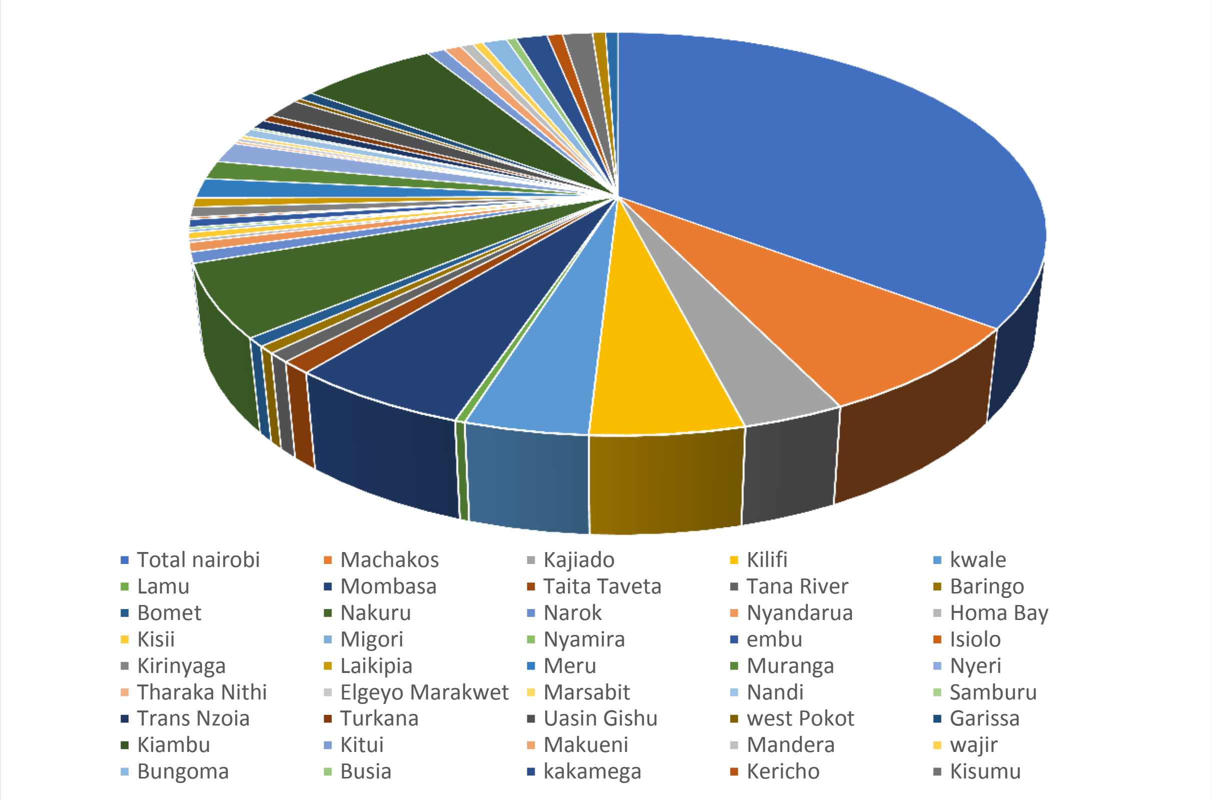


Figure 15, share of electricity consumption per county in 2015

From the figure 15 can be derived that Nairobi county is the largest electricity consuming county of Kenya.

Period 2015-2030

The consumption forecast will be based on extrapolated trends of GDP growth, urban and rural population growth and subsequent change in electrification rates as estimated by the World Bank. Again the consumption is separated in the two categories.

For each of the above mentioned indicators 3 growth scenarios have been developed; ‘low growth’, ‘medium growth’ and ‘high growth’. The basis of the medium scenario for population and urban population growth lies in the numbers provided by the Frederick S. Pardee centre for International Futures, University of Denver, who created a forecasting model based on historical numbers of the World Bank (Pardee, 2017). The low and high growth scenarios are alternative growth scenarios. The graphs in which the variation in scenarios for the variables used are shown on page 29.

The population growth scenarios as seen in figure 16, are based variation in yearly population growth rates. In the high growth scenario it is assumed that the yearly population growth rates remain 2.65%, while in the medium and low scenario, these numbers drop to 2.085% and 1.595% in 2030. While the diferrence between the growth rates of the different scenarios is equal in 2030, the total population for the three scenarios seems to run a very different course. The population for the low and medium scenario do not seem to differ much, while the high growth scenrio has a much higher population. This is due to the medium growth scenario as provided by Pardee, which shows a little dip in growth rate in the years 2015 and 2016. The low growth scenario is based on a linear decline of the growth rate of 0.07% per year. This results in the medium and low scenario to only firrenentiate after 2016, which goes at a slower speed due to the lower growth rates than in the high growth scenario.

Figure 17 shows the yearly urban population growth rates per scenario. The medium growth scenario as provided by Pardee eqyuals a yearly decline of around 0.03%. Based on this, the high growth scenario declines by 0.02% per year and the low growth scenario by 0.04%. The three scenarios decline to a 3.82%, 3.95% and 4.10% urban growth rate by 2030.

The GDP growth rate has been fluctuating over the past years, an extrapolation of trends was therefore difficult. In the medium demand growth scenario the GDP growth is assumed to remain stable at 6%. In the low growth scenario it is assumed to drop towards 4.05% and rise towards 7.34% in the high scenario in 2030 (see figure 18).

To estimate a scenario for the rural access to electricity the historical trends have been extrapolated for the medium growth scenario. The trends are adjusted up and down for the low and high growth scenarios as shown in figure 19.

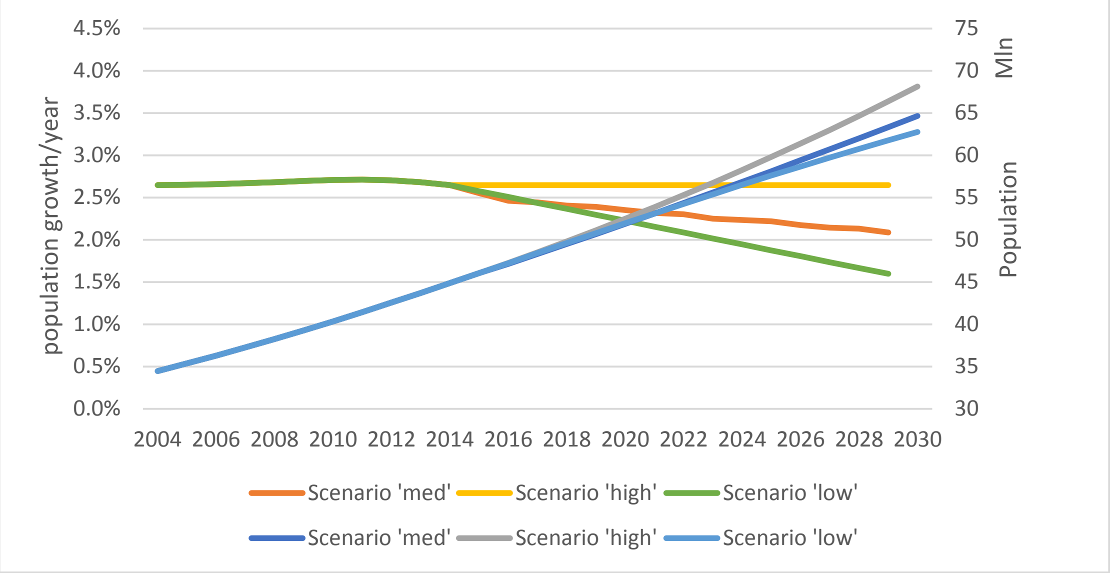


Figure 16, population growth scenarios

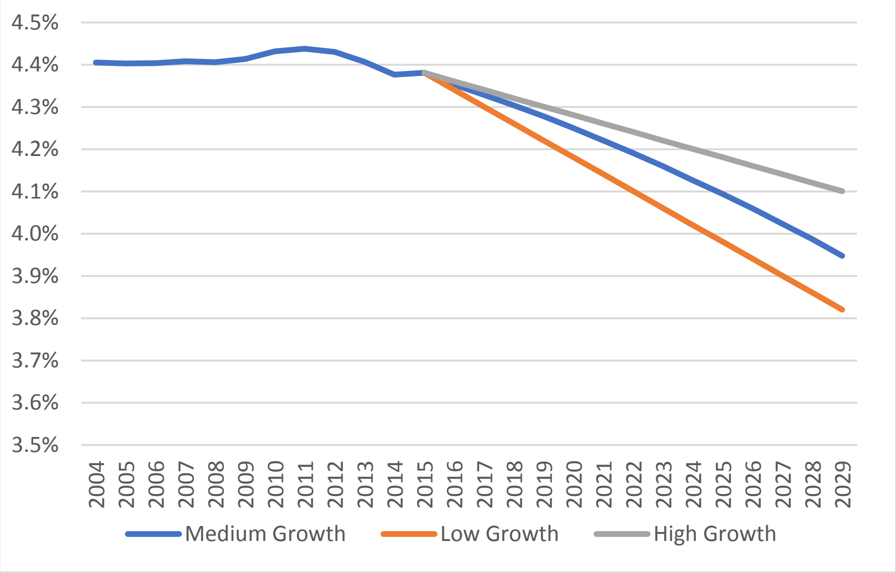


Figure 17, urban population growth scenarios

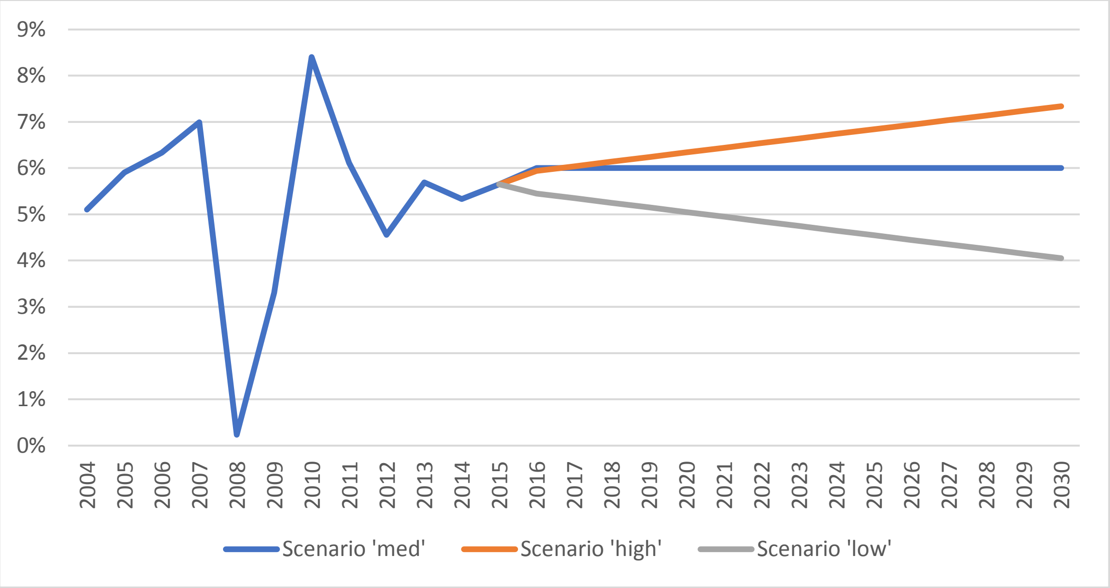


Figure 18, GDP growth scenarios

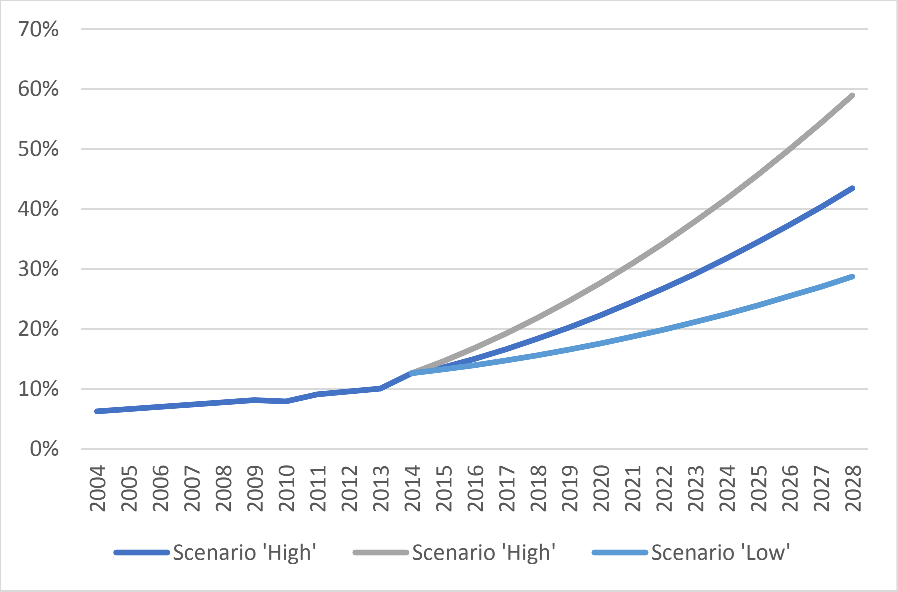


Figure 19, Rural electricity access scenarios

Additional Assumptions

Residential electricity use per capita & Industrial and commercial electricity use per GDP

Low growth

Since the residential power consumption per capita of people with access to electricity is stable over the past 7 years as shown above, this indicator is kept stable in the low growth scenario forecast up till the moment that a county reaches 90% electricity access. After this point, the residential power consumption per capita with access is assumed to be very close or equal to the residential power consumption per capita of the whole population and will thus follow the same growth rate as this indicator.

Industrial electricity use per GDP was also found to be relatively stable over the past 7 years. The trends per region have been extrapolated with exemption of the regions in which the trend was negative, these are kept stable. The cases of Nairobi North and West in 2015 have been identified as outliers; they are not included in the trend analysis.

Medium and high growth

In the Medium and high growth scenario the electricity consumption per capita with access and the industrial and commercial electricity use per GDP have been connected with the GDP growth. Final electricity consumption follows the yearly GDP growth per country. However, often at a slightly lower rate. This decoupling was 2% on average in Africa (Graus et al, 2011). This has been taken as a reference for the medium growth scenario. For the high growth scenario a decoupling of 1% has been taken as a reference, comparable to the decoupling rate of transition economies (Graus et al., 2011). The growth of power consumption per capita in the medium and high growth scenarios will follow the growth of GDP according to the following formulas:

Medium Growth

Equation 8

$$Growth\ in\ \%\frac{\Delta kWh}{GDP} = \%\Delta GDP * (1 - 0.02)^{\wedge year}$$

High Growth

Equation 9

$$Growth\ in\ \%\frac{\Delta kWh}{GDP} = \%\Delta GDP * (1 - 0.01)^{\wedge \mathrm{year}}$$

Suppressed demand

Owing to the low electricity penetration levels and power cuts mostly originating from medium and low voltage network failures, supply does not completely meet the demand at peak load hours.

The UDLCPDP assumed the amount of suppressed demand be approximately 100MW in 2010. It was assumed that this amount would progressively decrease with the increased penetration levels and the refurbishment and upgrading of the network. However, since the penetration has not increased as expected in the UDLCPDP, the supressed demand is still expected to be at the 2010 value. The resulting suppressed demand would therefore be as follows;

2016: 80MW
2017: 60MW
2018: 40MW
2019: 20MW
2020 and beyond: no more suppressed peak load.

To determine the peak demand the system load factor is used for calculation. The historical Kenyan system load factor is shown in figure 20. This is an indication of the variability in the demand.

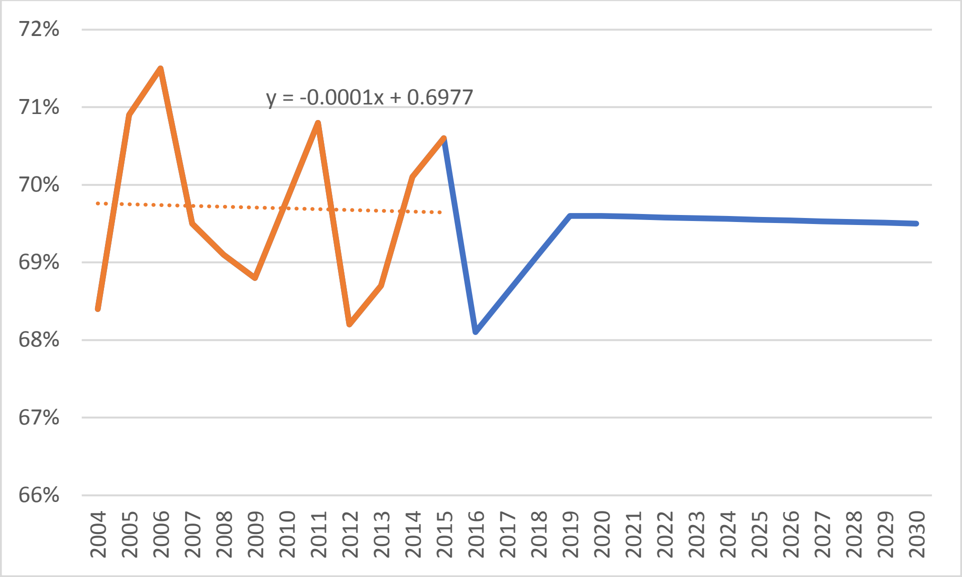


Figure 20, Historical annual system peak load and forecast towards 2030 (KPLC, 2016; KPLC 2011)

As can be seen, the Kenya System load factor is relatively high and stable. The graph therefore indicates a low variability between peak demand and base demand. This corresponds with a suppressed peak demand. The load factor is therefore expected to decrease along with the higher peak demand in the first 5 years, after which it will continue with the slight historic decrease (presented in the graph above) due to increased amount of households connected to the grid which also enlarges the variability. When keeping the total generated power stable; increasing the peak demand with 100MW, 80MW, 60MW, 40MW and 20MW, gives subsequently 5%, 4%, 3%, 2%, 1% decrease in load factor. However, since the power generated is expected to rise due to the higher demand peak, this effect has been halved.

The total consumption, including the 'extra' consumption due to the inclusion of supressed demand is weighed per county on the basis of the share of total electricity consumption in each county. This is given by scenario in figures 21-26.

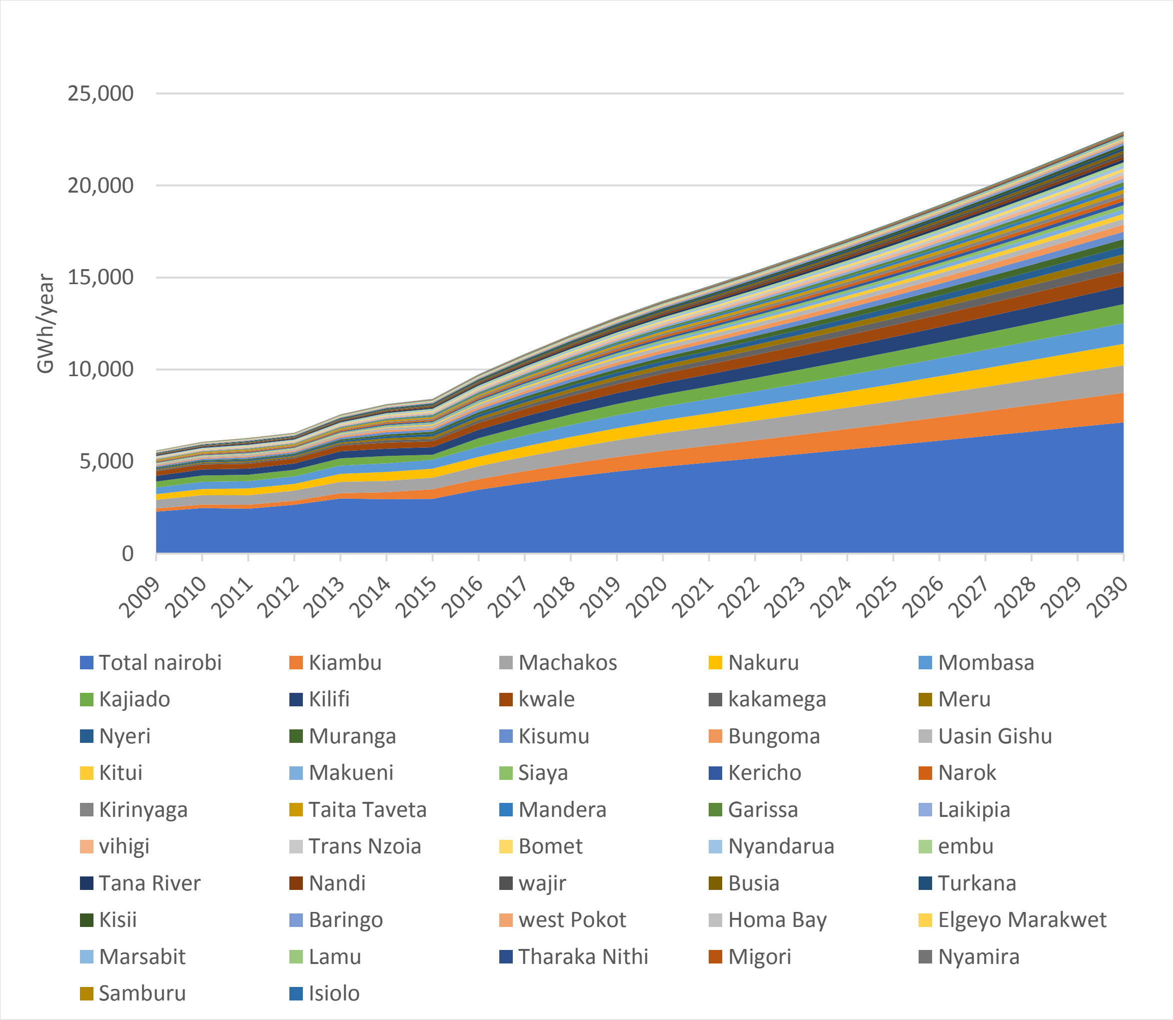


Figure 21, consumption forecast per county 'low growth' scenario

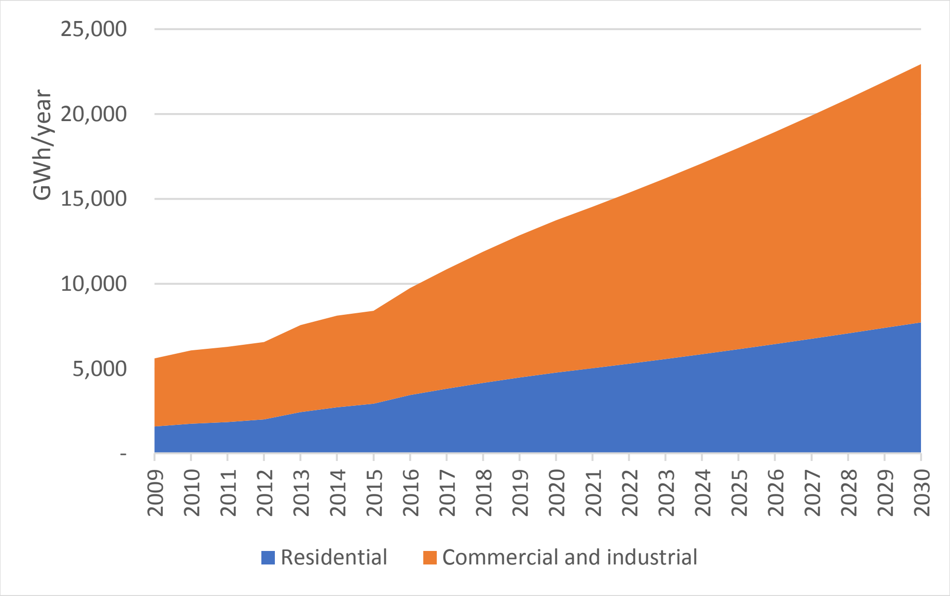


Figure 22, consumption forecast per category 'low growth' scenario

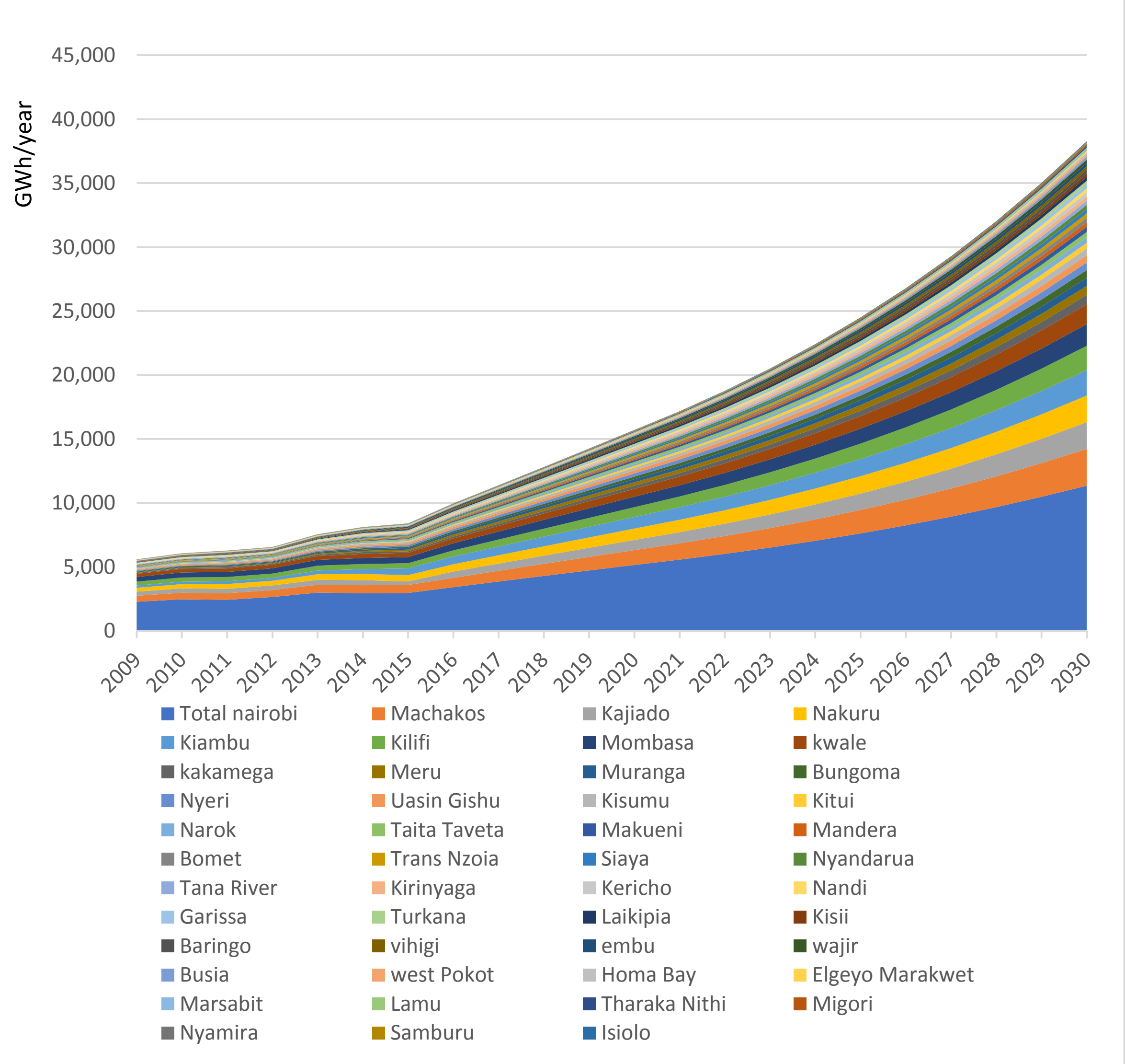


Figure 23, consumption forecast per county 'medium growth' scenario

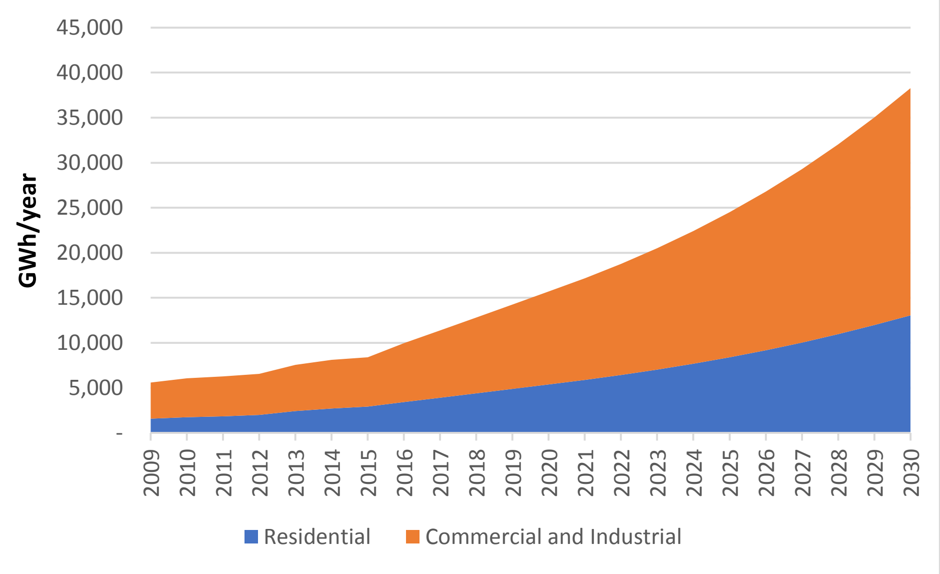


Figure 24, consumption forecast per category 'medium growth' scenario

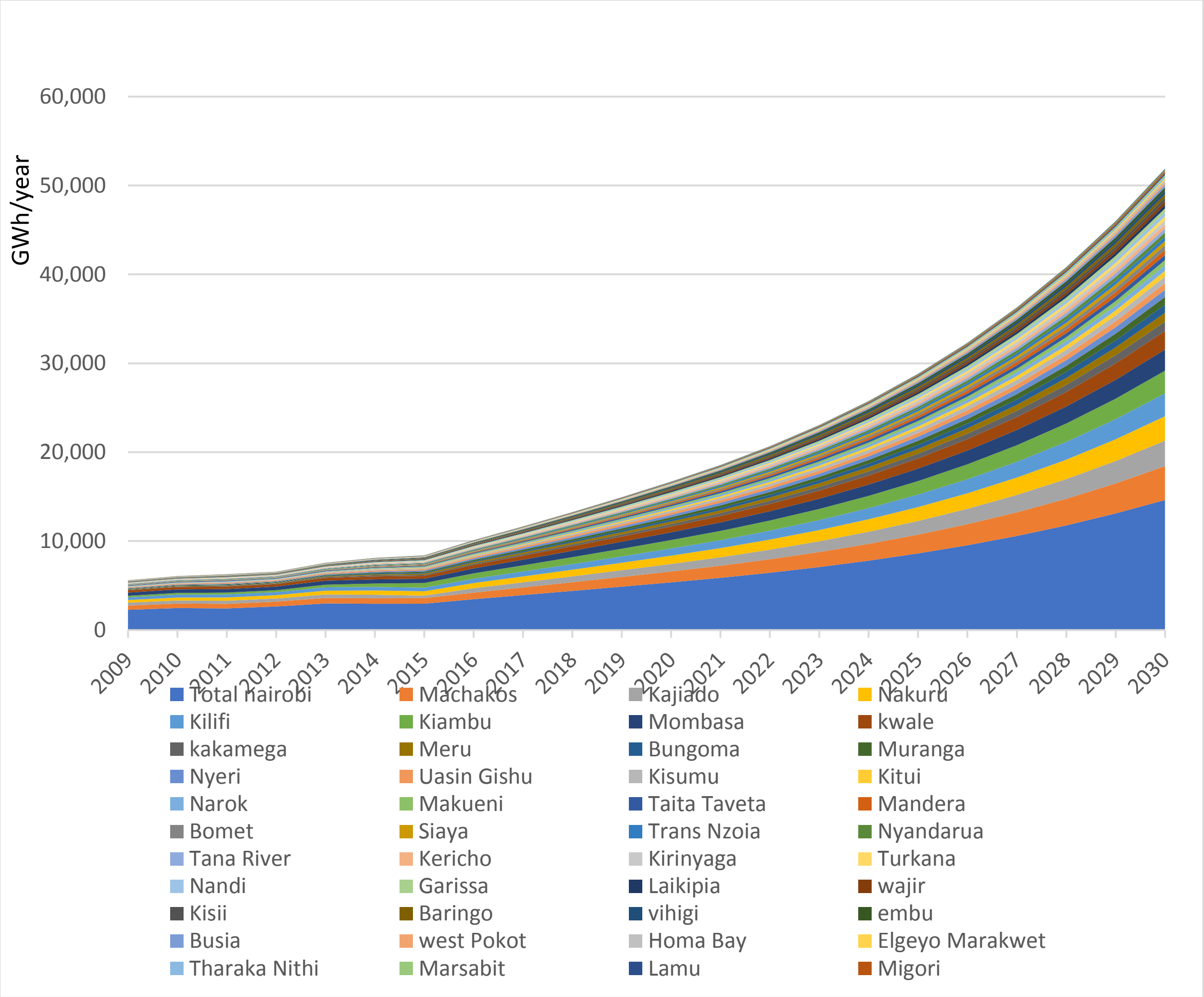


Figure 25, consumption forecast per county 'high growth' scenario

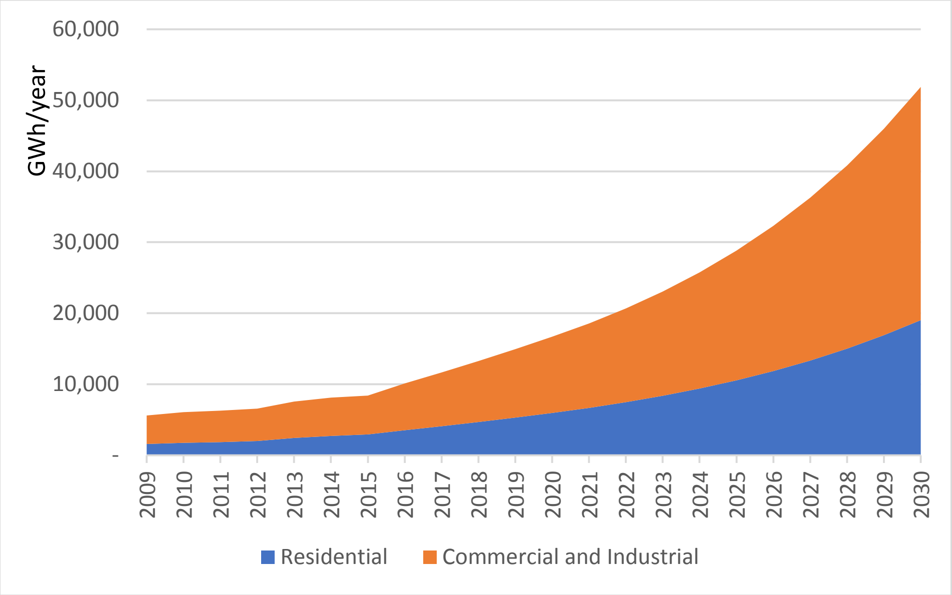


Figure 26, consumption forecast per category 'high growth' scenario

5. BAU scenarios

Now that the consumption forecasts have been made, the business as usual scenario needs to be defined as a reference case to compare the low carbon scenario nwith. The sub-question *What is the business as usual scenario for electricity production towards 2030?* Will be answered in this chapter, starting from the developed consumption forecast in chapter 4.

The current installed capacity[1] is 2270 MW of which 35.06% is Hydro, 27% is Geothermal, 35.6% is Thermal of which 99% is Medium Speed Diesel, 0.02% is Solar, 1.2% is co-generated biomass and 1.11% is Wind Power (KPLC, 2016)[2]. The current electricity generated in 2015 was 9816 GWh (+5% accounting differences).

Demand scenarios

The historic transmission and distribution losses are shown below in figure 27. An Increasing percentage of losses can be found. This trend seems unlikely to continue in the light of ongoing improvements of the electricity system. The increasing losses could be due to more pilferage. However, unfortunately no historical figures of the shares technical and non-technical losses could be found. The losses are therefore kept stable at 18.39% for the BAU scenario.

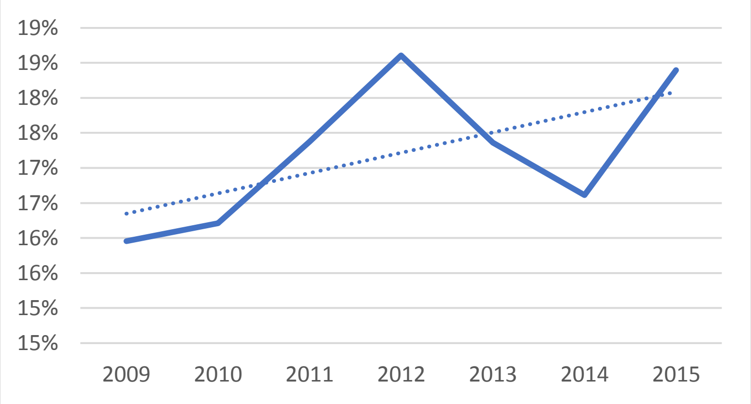


Figure 27, historical losses (KPLC, 2016)

Figure 28 shows that the total demand projection scenario's used in this study including the losses and international sales are much lower than the projections used in de UDLCPDP and the ECN study. The first interesting note is that both these reports have not included a scenario in which the current growth is reflected, which has been done in this study; being the 'low growth' scenario. Moreover, the electricity demand in 2015 is much lower than expected both by the ECN study and the UDLCPDP. The actual growth between 2010 and 2015 reflected the historical growth, which was, as said before, not a scenario that was included. Although the high growth scenario used in this study is much lower than the high UDLCPDP scenario in 2030, the same trendline can be observed. Only the starting point of the growth trendline lies 5 years later.

The consumption and demand scenarios made in this study will be used as a basis for the BAU scenarios and low carbon scenarios.

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[1] June 2016

[2] Total list can be found in Appendix 1

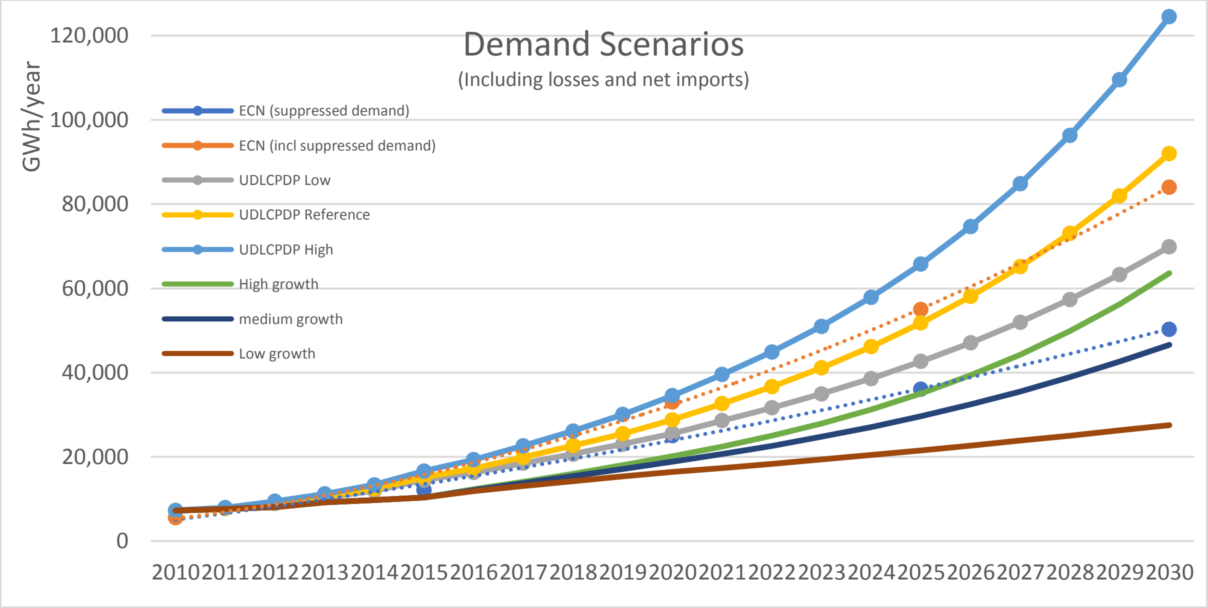

Figure 28, Demand scenarios compared with ULCPDP and ECN

5.1 BAU electricity mix

Between 2015 and 2020 the generation mix is based on the capacity installed and the installed capacity planned multiplied by the capacity factors weighed based on the demand scenarios. The projects in table 3 will be added to the installed capacity. All projects in the development phase or further have been included. Most projects are owned by KenGen, unless they are specified as Independent Power Producers (IPP) or the Kenya Rural Electrification Authority (REA). The projects below are referred to as planned (installed) capacity.

Table 3, planned generation projects towards 2030 (KenGen, 2016; Electric Power Sector Kenya, 2011; Wikipedia, 2017)

Project	Installed Capacity (MW)	Status	Capex (MUSD)	Commissioning Year
Ngong I wind Phase 3 wind	10	Project completed	25	2016
Olkaria Wellheads geothermal	25	Project under implementation	27	2016
Olkaria I AU Uprating geothermal	30	Project development	20	2017
Olkaria IV Uprating geothermal	30	Project development	20	2017
Garissa Solar power Station (REA)	55	Approval of design	136	2018 (end)[3]
Olkaria I Rehab geothermal	6	Project development	106	2018
Olkaria V geothermal	140	Procurement Of Contractors on-going	555	2018
Akiira One Geothermal Power Station (IPP)	70	Project under construction	300	2018
Olkaria I Unit 6 geothermal	70	Project financing	314	2018
Lake Turkana Wind	300	Final construction	853	2018

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[3] (Mwakio, 2017)

Power station (IPP)				
Meru Wind Phase 1	80	Project financing	143	2019
Olkaria VI geothermal	140	Project development	571	2019
Menengai I, II and III Geothermal Power Station (IPP)	3x 35	Project under construction	3X 40	2019
Lamu Wind Farm (IPP)	90	Under development	235	2020
Lamu coal power station	960	Under development (delayed)	2000	2020[4]

Moreover, some generation plants are assumed to be taken out of service because of the end of lifetime. These plants and their installed capacity are listed in table 4 Below. The first decommissioning listed however has not been taken out of service and is even scheduled to be uprated and rehabilitated as listed in table 3 above. This is therefore assumed to be cancelled. The kerosene gas turbines which were also scheduled to be taken out of service have been replaced and refurbished for future use instead of decommissioned (KenGen, 2016).

Table 4, projects to be decommissioned towards 2030 (kenGen, 2016)

Year	Type	Installed capacity
2015 (cancelled)	Geothermal (Olkaria I)	45 MW
2019	Co-generation (Mumias)	26 MW
	MSD (Iberafrica I)	56 MW
2021	MSD (Tsavo)	74 MW
2023	MSD (Kipevu I)	60 MW
2028	Geothermal (OrPower I)	48 MW
2029	Geothermal (Olkaria II)	70 MW

The capacity factors of technologies that are already in the mix are assumed by the UDLCPDP (pg 114) however, verified and adjusted compared to historical capacity factors derived from KPLC data. For the capacity factors that are not assumed in the UDLCPDP and/or without historical data through the KPLC, data of external sources has been used (see footnotes).

Table 5, capacity factors (IRENA, 2017; IRENA, 2017b; EIA, 2015; Electric Power Sector Kenya, 2011)

Capacity factors	
Hydro	0.50
Solar[5]	0.16
MSD	0.28
Co-gen	0.35
GT-kero	0.20
Biomass[6]	0.60
GT-NT[7]	0.55
Geothermal	0.90
Coal	0.73
Wind	0.35

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[4] There is a lot of controversy and debate around this power plant; see o.a. www.savelamu.org

[5] Historical data Kenya via IRENA (2017)

[6] Historical data Africa via IRENA (2017b)

[7] (EIA, 2015)

After 2020 the BAU scenario is based on the shares of generated electricity per technology in the UDLCPDP. However, the baseline is re-evaluated based on included technologies. Nuclear energy is not assumed to be feasible before 2030 because it is not yet implemented in Kenya (Cameron et al., 2012). Moreover, since the planned capacity of coal power generation in 2020 will be much higher relative to the UDLCPDP scenario, the share of coal in power output will be adjusted to this after 2020, phasing out the adjustment towards 2030.

Furthermore, it is interesting to see that the actual power generated from MSD and Natural Gas is very low in the UDLCPDP, ranging from 51 GWh to 279 with an installed capacity of 1315 MW for MSD and 966 GWh with an installed capacity of 1620 MW for Natural Gas. This is much lower than the capacity factor of 28% (MSD) and 20% (NG) suggest. While this same plan does grow their capacity further towards 2030. This does not seem realistic since it would make the LCOE of MSD very high and incompatible. This study therefore assumes that the capacity factors of MSD and NG will remain 28% and 20%, thus keeping a higher share of MSD and NG in the electricity mix.

The imports are adapted to match the electricity demand as determined in this study and generation from the installed capacity that is derived from the UPLCPDP plans and planned projects. In the BAU scenario’s this means that the shares of import will decrease compared to the UDLCPDP because the installed capacity in 2020 will be more sufficient to meet the demand than expected in their scenario. This is also due to the lower expected demand in the demand scenario’s as used in this study.

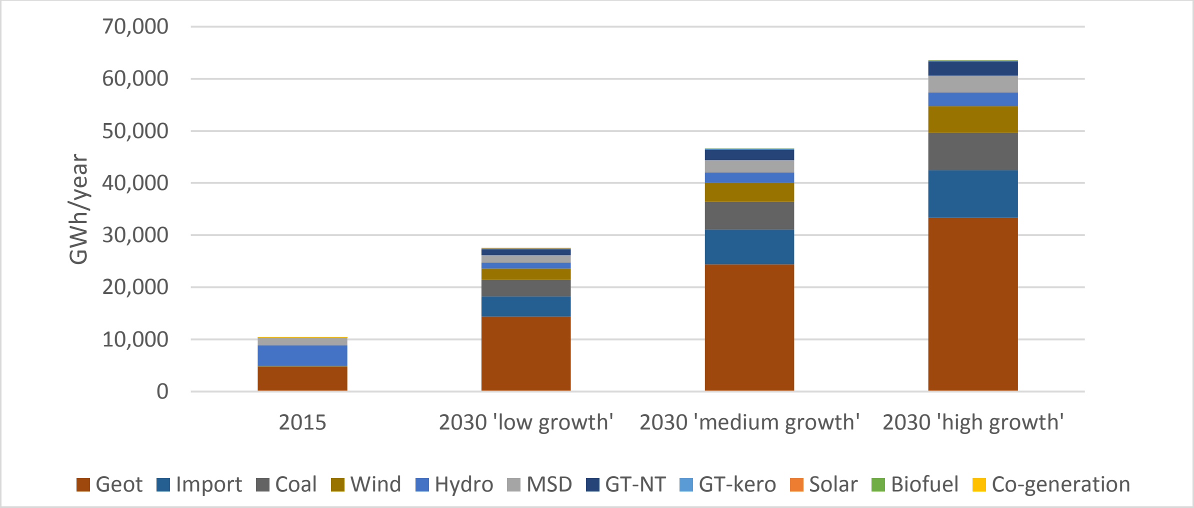

Figure 29, fuel mix scenarios

What can be concluded in that the BAU scenario is heavily dependent on Ethiopia. While the country itself only had 27.2% electricity access in 2014 (IEA, 2014). Furthermore Ethiopia only has an electricity consumption of 69.7 kWh per capita and 9615 GWh total production annually. This electricity is originates for almost 100% from hydro power (World Bank, 2017c). Future development of their electricity system is therefore uncertain causing a potential risk for the supply to Kenya. It may seem an easy way to access renewable electricity since their generation is currently almost 100% renewable, however, this might change in the future.

5.2 BAU emission scenario's

The data used to convert total future generation of fossil fuel technologies into GHG emissions is provided in Table 6. Emission factors are from IPCC 2006 guidelines[8]. Average conversion efficiencies reflect those that are reported in the LCPDP; MSD 35%, Gas Turbine natural Gas 45%, Coal plant 40%, Gas turbine kerosene 35%.[9] The emissions from the imported electricity is assumed to be nihil since almost 100% in from hydro power (World Bank, 2017c).

Table 6, emission factors (IPCC, 2006)

Fuel type	Kg CO_2e/TJ
Kerosene	71,900
Diesel	74,100
Coal	94,600
Natural Gas	56,100

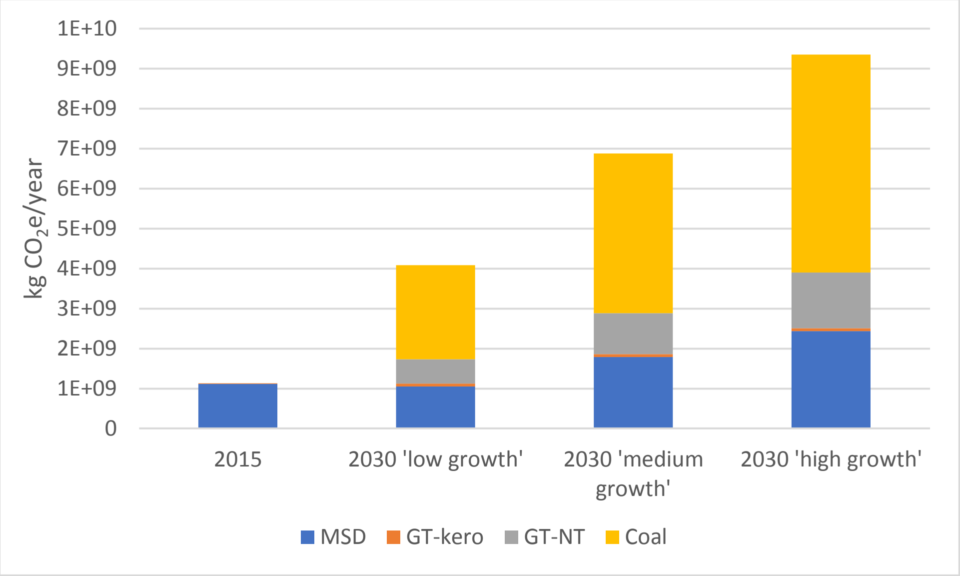

Figure 30, BAU emissions scenarios

The reason the emission scenarios are all the same in the first years is because the generation capacity is based on actual plans. The difference between the demand scenarios and the maximum power generated with this installed capacity is bridged with imports. Furthermore, the largest share of emissions originates from coal generation, see figure 30. Since the BAU scenario is based on the ULCDP scenario, and in their scenario, the expected output of coal generation decreases in 2026 due to the expected expansion in geothermal capacity and the preference for this technology in this study, the resulting emissions from the electricity mix fluctuate accordingly.

The emissions that are a result of the losses of transmission and distribution are estimated based on extrapolation of trends towards 2030 of the current losses as indicated by the KPLC.

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[8] IPCC, 2006 IPCC guidelines

[9] And comparable with US average (IEA, 2015b)

6. Potential electricity resources per county

Before being able to present a low carbon scenario, the potential of renewable electricity sources in Kenya needs to be determined. This chapter discusses the resources and potential for each renewable electricity technology included in this study. The aim is to answer the sub-question: *What is the potential for the different renewable electricity production technologies in the different counties by 2030?*

Electricity generation technologies can have major impact on the area they are situated in and its ecology. However, these impacts are not part of the scope of this study but should at least be considered when calculating the wind and solar energy potential per area. Surface areas that are in use for agriculture, which are forests, woodlands, swamps, protected areas built environment etc. where taken into account and excluded from the potential area for electricity generation. Land cover data for 1992-2015 was derived from the European Space Agency (ESA). The changes in agricultural land and expansion of built environment were assumed to follow the same trendline towards 2030 as between 1992 and 2015. Data maps have been created using ArcGIS Pro. Furthermore, to limit the impact of technologies, this study has taken 1% of the county surface as a maximum coverage with solar farms of wind farms.

6.1 Solar

The solar potential in Kenya has been assessed using the data in the Kenyan Geospatial Toolkit provided by the National Renewable Energy Laboratory (NREL), last updated December 2015. The solar irradiance data in this toolkit is however from 2004, provided by the Deutsches Zentrum für Luft- und Raumfahrt (DLR). More recent solar maps with high resolution where however not available.

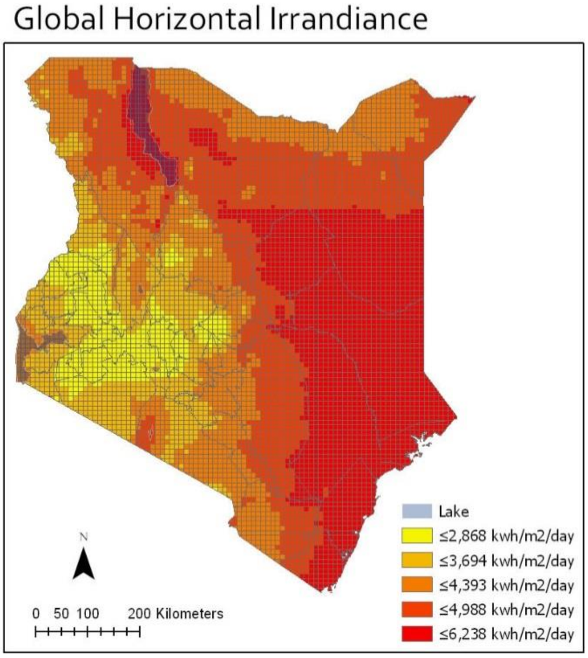


Figure 31, Map of GHI in Kenya

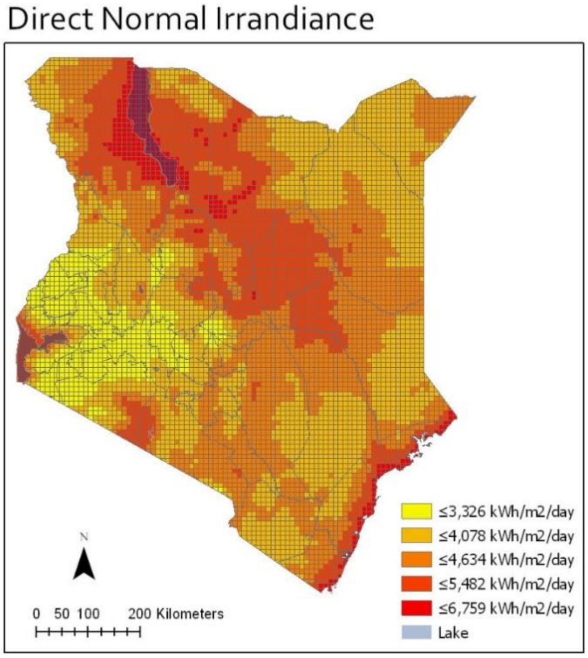


Figure 32, Map of DNI in Kenya

6.1.1 CSP

Concentrated Solar Power (CSP) plants are viable at Direct Normal Irradiance (DNI) levels higher than 2100 kWh/m2/year (Andrews and Jelley, 2013), this corresponds to above 5.75 kWh/m2/day. Kenya has an area of 15279 km2 in which the DNI level is higher than 5.75kWh/m2/day. However, when only the barren land, lands with less than 15% vegetation and grasslands are selected, 5547 km2 remains.

To determine the potential power generation using CSP per county assumptions will need to be made regarding the type of CSP plants and its characteristics. For this study a CSP plant with molten salt storage capacity >12 hours is chosen. Storage gives the potential to use this plant not as a variable source, but as base load. This is possible both for Parabolic Trough and Solar Tower technologies. The solar tower technology is still in the commercial pilot phase, however the first results are positive and promising (IRENA, 2012). For this study the Gemasolar power plant in Spain is taken as reference, it is also located in an area with an annual DNI of 2100 kWh/m2. It has a capacity of 19,9 MW, 15 hours of storage, its land use is 195 hectares and the capacity factor is around 70% (Irena, 2012; Zhang et al., 2013). When the amount of contiguous land area larger than 195 hectares is considered potential for a CSP plant. A total of 2832 plants could be built in Kenya. The total power generation potential using CSP technology would therefore be 310530 GWh/year. The actual number might even be higher since some areas have a slightly higher level of irradiance then the reference technology. Most of the potential area for CSP is located in the North-West, and central Kenya. The coast area does not offer enough contiguous space for a CSP plant according to this data. The exact potential per county will be discussed on the end of this chapter.

6.1.2 Solar PV

Kenya has an area of 510,405 km2 with Global horizontal irradiance of 3kWh/m2/day or higher. When agricultural land, bushland, woodland, forests, waterbodies and protected areas are excluded, 103,315.9 km2 is left. 361 km2 of which is built environment.

The solar potential per county for PV is calculated using a standard efficiency of 15% (Andrews and Jelley, 2013). Moreover, the panels (in a solar farm) on the ground are assumed to minimize the tilt and orientation effects. These effects are assumed to be 80% of the maximum in the built environment. Moreover, the amount of land that can be covered with PV panels is assumed to be 40% on the ground, corresponding with a power density of around 11 MW/km2. In built environments this amount is assumed to be 5% based on an analysis in Slovakia, where 8.1% of the urban zones (built environment) is suitable for PV systems. This is 59% of all roof area, since the tilt, orientation and shape of the remaining 41% of the roofs made them unfit for PV power generation (Hofierka &Kanuk, 2009). Considering less area of suitable roofs due to a lower building standard in Kenya, only 5% of the urban areas is assumed fit for PV generation. The amount of urban areas has been expanded towards 2030 based on the historic land use changes and ongoing urbanisation trends as mentioned.

Solar PV has potential in almost all counties, at least for rooftop generation. Only 6 counties have insulation levels below 3 kWh/m2/day and are therefore not included in the analysis. If all available land and all suitable rooftops in Kenya would be covered in solar panels, to total annual generation would be 20932 TWh. However, when a maximum 1% of the land is can be used, the total potential is 574 TWh.

6.2 Wind

Wind potential is derived from the SWERA dataset, made available by Risoe DTU, National Laboratory for Sustainable Energy Denmark.

Kenya has a total area of 30.086 km^2 with wind speeds higher than 6.5 m/s, viable for power generation (Andrews and Jelley, 2013). This leaves 22154 km^2 after deduction of dense agricultural land, dense bushland, forests, woodlands, built environments and protected areas.

The power densities of potential wind areas range from 1.29 MW/km2 to 3.75 MW/km2. The total electricity potential from wind generation is 305930 GWh/year.

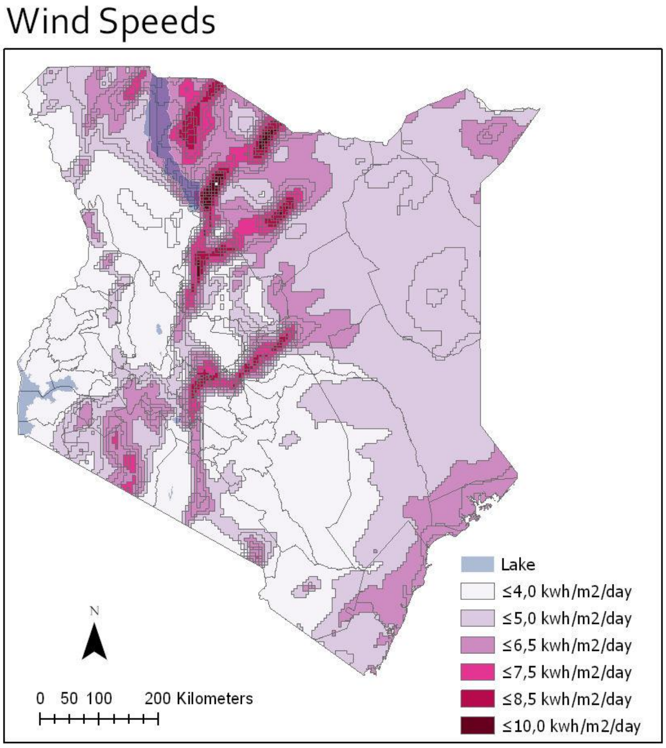


Figure 33, Map of windspeeds in Kenya

6.3 Biomass

In this study only agricultural residues are taken into account as feedstock for renewable electricity generation from biomass. Energy crops could be competition for food production and should therefore be studied individually. A recent study by Mai-Moulin et al. indicate that there is no potential for dedicated energy crops due to that reason and the deficit of arable land (Mai-Moulin et al., 2016).

The available local resources for electricity generation from biomass and waste will be determined on the basis of the available database of Biotrade 2020. Various different authors have studied the potential of biomass power in Kenya, however, this database provides the largest overview. It includes the exportable potential of various agricultural waste products and residues. 'Exportable' is defined as surplus left with sustainable farming after deduction of domestic use for animal feed, firewood, fertilization and other needs. However, instead of exporting this surplus these amounts of biomass are also a potential for power generation in Kenya. Surpluses were found for sugarcane waste(straws etc.), bagasse, rice husk, rice straw, coconut husk, sawdust, sisal ball, and coffee silverskin.

Table 7, potential biomass in TJ (Biotrade2020.nl)

TJ	rice straw	sugar cane waste	sawdust	coconut husk	rice husk	sisa ball	bagasse	coffee silverskin	Total
Kenya	4174,8	16145	6681	13140	1470	10750	10514	10	62885

The exact characteristics and potential contamination of the biomass are however unknown, while these factors are of importance for the conversion technology. This study has therefore assumed electricity generation through combustion in a stoker grate boiler of the biomass because this technology is less sensitive to fluctuations (IRENA, 2012). A CHP plant with a conversion efficiency of 30% as given as an average by IRENA (Taylor at al.,2015). This brings the total potential of biomass for power generation to 5240 GWh/year.

6.4 Municipal Solid Waste (MSW)

Currently all waste in Kenya is landfilled. Not only is this a major concern for the environment and a threat to human health. Vulnerability of pollution of surface and groundwater is high because local authorities rarely considered environmental impact in siting MSW disposal sites. Illegal dumping of MSW on the river banks or on the roadside poses environmental and economic threats on nearby properties (Henry et al., 2005). This is also a major potential energy source for municipalities. Incineration and landfill gas are the most common techniques to capture the energy.

For MSW incineration is the preferred choice of technology since various studies show that it yields higher energy potential than landfill gas, which is anaerobic digestion (AD) (De Souza et al., 2014; Kaplan at al., 2009; Funk et al., 2013). Moreover, space for landfill sites is decreasing since cities become larger and more dense.

Estimates of Scarlat et al (2015) show that the total waste generation was 110 kg/capita in 2012, corresponding to 1071 ktonne per year, of which 40% was collected. They assume that this number grows to 219 kg/capita in 2025, when 60% will be collected; being 2301 kton. These collection numbers are in line with the share of MSW Henry et al. have found to be collected in Kenya in 1999, ranging from 28% to 58%. In 2014 the Kenyan National Environmental Management Authority (NEMA) published a report which estimates that the average share of waste collected in the big cities of Kenya is 55% (NEMA, 2014). Moreover, only the total estimated waste of these 6 cities together would be 2168 ktonne MSW annually. More than twice the amount Scarlat et al. estimated 2 years earlier. However, the World Bank shows that the higher the income level and urbanization, the more waste is created (Hoornweg & Bhada-Tata, 2012). This study therefore assumes an average middle ground being that the MSW in urban areas will grow to 400 kg/capita/year and 200kg/capita/year in rural areas. Moreover, the goal of NEMA is to recover, recycle and re-use 80% of all waste by 230. This study assumes a collection rate of 95% and a recycling rate of 35%. These numbers are ambitious however, should possible to achieve in 13 years. As a comparison; in the EU, 36% of the waste is recycled (Eurostat, 2017).

The composition of the waste is assumed to change derived from historical changes as described by Khamala & Alex (2013). Who thoroughly studied the content of Nairobi’s MSW. The assumptions regarding calorific values of the composition will be used in this study combined with the average heating value of Plastic solid waste as provided by Al-Salem et al. (2009) since that data was lacking. The moisture content measured by Khamala is high, 0.689 kg/kg of MSW. This reduces the energy potential of the waste. However, they also note that the measured waste did not have any chance of natural drying. Moreover, because of the later and the fact that this study assumes the fraction of organic waste to decrease towards 2030 (see table 8), this study assumes to moisture content to decrease to 0.55 kg/kg. The total power output will be 436 kWh/tonne MSW.

Table 8, composition of MSW (Khamala & Alex, 2013)

Waste class	**1985**	**1998**	**2013**	**2030** (extrapolation)
Plastics	4.1%	11.8%	13.8%	16.1%
Papers	10.2%	7.3%	11.3%	11.3%
Organic	78.0%	61.5%	58.8%	56.2%
Leather and textile	2.1%	11.8%	7.8%	7.3%
Glass, metal, other	5.8%	7.6%	8.3%	9.1%
Total	100%	100%	100%	100%

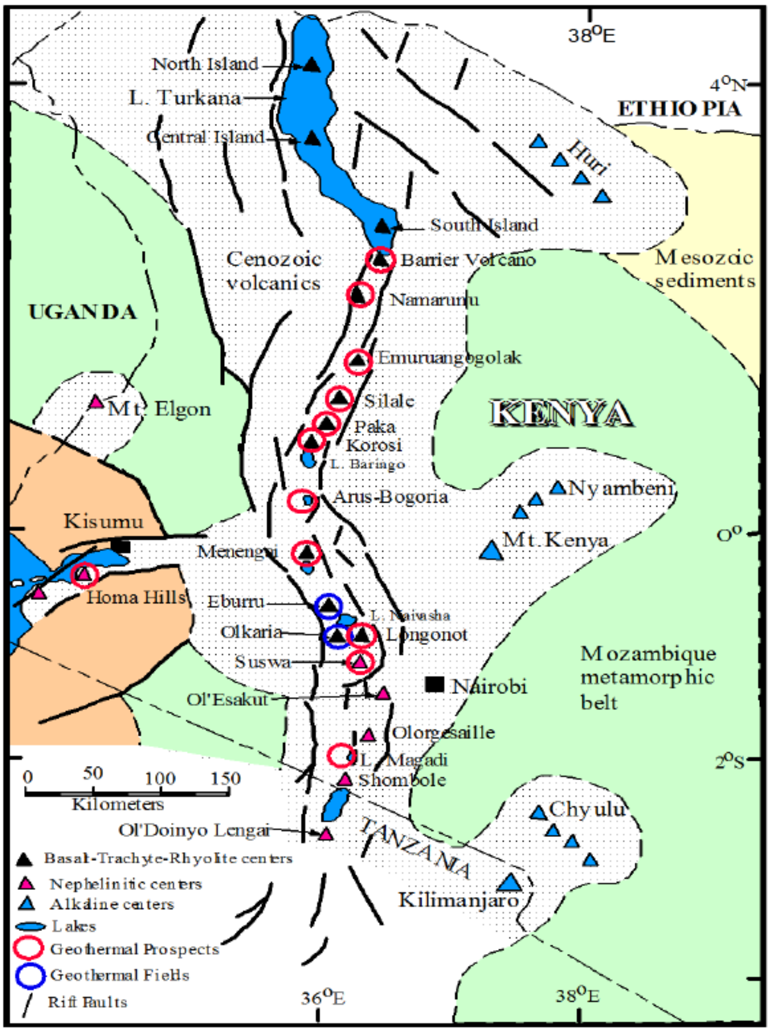
Depending on the population growth scenario's, the potential electricity generation for Kenya as a whole will be 3600 – 3813 GWh/year. For the combustion of MSW a CHP plant with a 25% conversion efficiency to electricity was assumed (ISWA, 2013). The produced heat is not included in this study.

6.5 Hydro

Few studies have featured Kenya's hydropower potential. Kiplagat et al. (2011) indicate that Kenya exploits only about 30% of its hydropower potential. However. The data underlying that indication where estimates made for the power development plan in 1987. The latest power development plan, the UDLCPDP, states that the country has marginal commercially viable large hydro power resources as most of the promising hydro sites have already been exploited. They only indicate 2 more candidate hydropower sites; Mutonga (60MW) and Low Grand Falls (140MW) (Electric Power Sector Kenya, 2010). Since no further accurate data could be found on hydropower potential in Kenya, the baseline of the UDLCPDP will be followed.

6.6 Geothermal

The geothermal potential is derived from the studies done by the Ministry of Energy, the Geothermal Development Company and KenGen and summarized in the UDLCPDP. Figure 34 below summarizes the total potential. Since the rift Valley is situated on the border of multiple counties, these sites could provide 6 counties with geothermal energy.



Rift Region	Potential (MW)
Central Rift	
- Menengai	1,600MW
- Eburru	250MW
- Arus Bogoria	400MW
	2,250MW
South Rift	
- Olkaria	2,000MW
- Longonot	750MW
- Suswa	600MW
- Lake Magadi	100MW
	3,450MW
North Rift	
- Lake Baringo	200MW
- Korosi	450MW
- Paka	500MW
- Silali	1,200MW
- Emuruangogolak	650MW
- Namarunu	400MW
- Barrier	450MW
	3,850MW
Nyanza	
Homa hills	100MV
Akira	350MW
	450MW
Total Potential	**10,000MW**

Figure 34, Map and potential of Geothermal energy (Electric Power Sector Kenya, 2011)

6.7 Potential per county

The paragraphs above have summarized the potential per renewable electricity source. The total potential per county in 2030 is listed in table 9 on the next page. It can be seen that the total technical potential from renewable sources for electricity production is 782.9 TWh per year. Which equals 12.3 times the demand in 2030. Moreover, all counties have multiple electricity sources. The technology with the highest potential is Solar PV. However, the areas indicated per county are still very large, meaning that it would impact the area's appearance, wildlife etc. This should be further examined site specific. The amount of land that would potentially be viable for solar power generation will depend on its costs and the electricity mix per county, both later discussed.

Table 9, potential energy per county (own results)

GWh	**wind**	**solar PV**		**Solar CSP**	**Biomass**	**Geothermal**	**MSW**			**hydro**	
County		**roof**	**ground**				**low**	**med**	**high**		**total**
Baringo	0	2	10915	0	6	12220	48	49	50	0	23192
Bomet	0	0	0	0	207		58	59	61	0	219
Bungoma	0	27	0	0	293		130	134	138	0	389
Busia	0	13	85	0	20		40	41	42	0	156
Embu	107	2	210	0	3		47	48	50	829	1201
Garissa	0	155	55111	110	0		55	56	58	0	55434
Homa Bay	0	58	35	0	9	788	68	70	73	0	961
Isiolo	111	3	30517	0	0		14	14	14	0	30645
Kajiado	4	111	20984	0	7	5519	49	51	54	0	26677
Kakamega	0	8	0	0	1062		135	138	142	0	964
Keiyo-Marakwet	0	1	2338	0	30		30	31	32	0	2393
Kericho	0	4	0	0	43		67	69	71	0	107
Kiambu	0	147	1877	0	11		217	223	230	0	2263
Kilifi	0	161	14887	770	632		104	107	110	0	16412
Kirinyaga	160	20	0	0	312		49	51	52	0	471
Kisii	0	0	0	0	3		126	130	134	0	136
Kisumu	0	179	50	0	434		92	95	98	206	865
Kitui	0	14	29372	0	5		81	83	86	211	29686
Kwale	0	390	347	0	555		56	58	60	0	1222
Laikipia	0	0	7192	0	9	5125	38	39	40	0	12363
Lamu	0	11	6387	0	68		10	10	10	0	6459
Machakos	0	29	4656	0	5		103	106	109	445	5244
Makueni	0	4	2269	0	210		72	74	76	0	2511
Mandera	0	57	26856	0	0		73	75	78	0	26990
Marsabit	18167	52	80609	37730	0		24	25	26	0	136583
Meru	0	12	6830	0	7		121	125	128	156	7131
Migori	0	18	0	0	315		45	47	48	5	313
Mombasa	0	381	21	0	28		132	135	140	0	564
Murang'a	0	6	0	0	1		85	88	90	72	168
Nairobi	0	1191	533	0	3		441	455	473	0	2198
Nakuru	0	4	5756	0	231	39026	181	186	191	0	45155
Nandi	0	0	0	0	15		62	63	65	0	77
Narok	2019	6	16735	0	222		69	71	73	0	19004
Nyamira	0	0	0	0	18		49	50	52	0	66
Nyandarua	523	0	0	0	18		52	53	55	0	591
Nyeri	397	1	0	0	21		72	74	76	4	495
Samburu	4544	0	21436	5390	0		18	19	19	0	31389
Siaya	0	1	167	0	37		67	69	71	0	267
Taita Taveta	0	6	20578	0	309		24	24	25	0	20845
Tana River	0	139	42662	220	39		17	18	18	0	43069
Tharaka	64	0	73	0	6		26	27	28	360	529
Trans Nzoia	0	0	0	0	1		69	71	73	0	74
Turkana	8067	1	86240	40370	0	16556	61	63	65	0	151299
Uasin Gishu	0	0	0	0	18		95	97	100	1	115
Vihiga	0	3	0	0	8		46	47	48	0	57
Wajir	0	31	67260	0	0		46	47	49	0	67340
West Pokot	0	1	8296	0	19		36	38	31	270	8613
Total	**34164**	**3247**	**571281**	**84590**	**5240**	**79234**	**3600**	**3702**	**3813**	**2558**	**782904**

7 Optimal electricity mix per county

To answer the question; *What would be the optimal electricity mix for a low carbon scenario for Kenya, considering the constraints and potential for renewables in different counties?* least cost supply mix need to be determined for each county. The optimal mix per county is based the demand in the high growth scenario as determined in chapter 5. The optimal mix will be chosen starting with the least cost generation technology working towards the saturation of the demand. It should be noted that technologies which do have potential in the counties, could not be included in the electricity mix because the costs are higher than the other technologies if the demand is already saturated with their potential. However, before determining the optimal mix, several constraints need to be taken into account.

7.1 Constraints

There are some constraints that need to be taken into account before determining the optimal electricity mix per county. The first one is that the low carbon scenario does not include electricity imports. As can be seen from the former chapter, Kenya has enough natural resources to fulfil their own needs, and the dependence on imports imposes high risk on the availability and price of electricity.

Furthermore, the share of variable sources needs to be balanced with flexible sources to ensure a stable electricity grid, e.g. a maximum share of variable renewable electricity and minimum flexible capacity. Geothermal electricity generation is considered a flexible technology (GEA, 2015). The current (2015) system load factor of 0.706 indicates that the load profile is quite flat (KPLC, 2016). Meaning that the differences between peaks and dips is relative small. This load factor has been very stable over the past 6 years. The latest load profile of Kenya and the different regions is shown below:

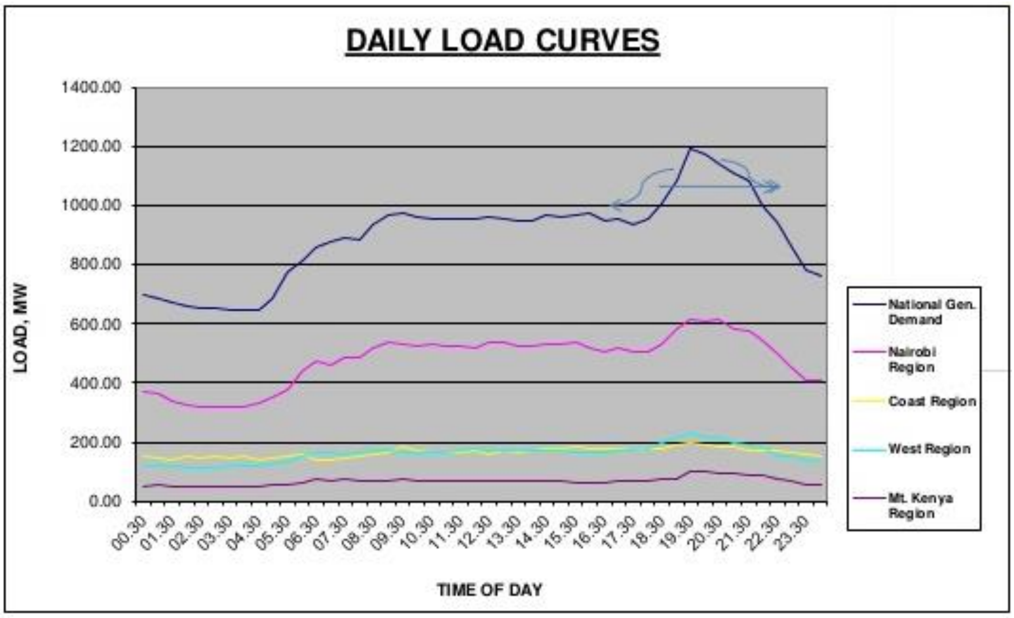


Figure 35, Load curve, 2011 (KPLC)

The peak loads have risen to +- 1550 in 2015 (KPLC, 2016). However, since the system load factor has not changed, the profile is assumed to be similar. The minimum baseload should therefore be 900

MW in Kenya in total. Is it assumed that the peak load will rise towards 10,065 MW in 2030 based on the electricity demand in 2030 derived from this study and the peak load forecasts of the Kenya Electric Power Sector (2011). Huber et al. indicate that a share of above 30% variable sources in the electricity mix increases the need for flexible sources significantly (Huber et al., 2014). This percentage is therefore taken as a maximum of flexible electricity generation per county. However, exceptions were made for some counties, where the existing or planned installed capacity exceeded 30%.

Moreover, the low carbon scenario does include the existing powerplants, including fossil fuelled power plants and planned fossil fuelled power plants in construction. The Lamu Coal fired power plant which is planned for 2020 will however not be included in the low carbon scenario since there is a lot of controversy around the plans causing delays and might even cancelation (Daily Nation, 2016). In addition, the kerosene fired gas turbine is assumed to be decommissioned since it has already reached its original lifetime. It is however recommissioned in another location (KenGen, 2016) and therefore included in the BAU scenario. But, since it would not convey significant cost implications because it has already reached its original lifetime, the kerosene plant is not included in the low carbon scenario. This means, only existing MSD plants are included in the low carbon scenario.

Lastly, minimum sizes of powerplants have been determined for each type of technology because smaller scales could have different cost implications (Taylor et al., 2015). Biomass and waste plants have been constrained to a minimum of 10 MW, assuming capacity factor of 60%, this means a minimum output of +- 50 GWh. For CSP plants a minimum of 20 MW is adopted, corresponding with 110 GWh. For wind generation a minimum of 3GWh is assumed, corresponding with 1 turbine of 1MW. Since PV could be installed per panel, no minimum is adopted for this technology. Furthermore, geothermal and Hydro did not require a minimum output since the potential per county was significant in all cases.

7.2 LCOE of Technologies

Due to unavailability of detailed data, the specific costs per technology were hard to determine. The optimal mix of technologies per county are chosen on the basis of secondary data on costs and are therefore only an indication. Costs should be determined per technology per location specifically. The costs below are however chosen carefully and reflect plausible levelized costs of electricity generation in Kenya. Some more uncertain values will be subjected to a sensitivity analysis later discussed.

Table 10, LCOE per technology

Technology	LCOE (USc/kWh)	Source
Imports	0.065	(Electric Power Sector Kenya, 2011)
Geot	0.073	(Pueyo et al., 2016)
Biomass (incineration)	0.080	(Taylor et al., 2015)
Biomass (existing: landfill gas)	0.090	(Fischer et al., 2010)
Wind	0.103	(Pueyo et al., 2016)
Hydro	0.107	(Pueyo et al., 2016)
MSW	0.120	(Taylor et al., 2015)
Coal	0.127	(Electric Power Sector Kenya, 2011)
Solar PV	0.148	(Pueyo et al., 2016)
Gas (NT)	0.151	(Electric Power Sector Kenya, 2011)
MSD	0.217	(Electric Power Sector Kenya, 2011)

CSP	0.280	(Taylor et al., 2015)
Gas (kero)	0.302	(Electric Power Sector Kenya, 2011)

All LCOEs are calculated with a societal discount rate. The social discount rate is a reflection of a society's relative valuation on today's well-being versus well-being in the future. It is argued that with long term issues such as climate change, discount rates should be very low or nihil when considered in mitigation investments. The social discount rate taken by the UDLCPDP is 8% (Electric Power Sector Kenya, 2011) and 10% by Pueyo et al.

The Levelized costs of Electricity for Solar, wind, hydro and geothermal technologies in Kenya are provided by Pueyo et al. (2016). Who did an in-depth study of the costs of these technologies in Kenya. They have used a 10% discount rate. The cost of fossil fuel generation in Kenya were estimated at 15.1 US cents per kWh for Natural Gas turbines, 12.7 US cents per kWh for coal plants, 21.7 cents per kWh for MSD and 30.2 cents /kWh for Kerosene gas turbines, at 8 per cent discount rates in 2011 by the Electric Power Sector Kenya (Electric Power Sector Kenya, 2011). The LCOEs of Biomass incineration, MSW incineration and CSP are global and where possible area averages derived from IRENAs report on renewable electricity technology costs due to a lack of data for Kenya specific since these technologies are not implemented (on a large scale) yet.

Costs are heavily subjected to change. Technologies which need resources endeavour feedstock price fluctuations, e.g. the oil price. Other technologies undergo significant cost reduction due to 'learning' and benefits of scale. This is especially evident for CSP and Solar PV. Other technologies such as Geothermal and coal e.g. have matured, meaning that their costs will probably not decline much further in the future. See figure 36 below for an overview of the renewable technologies.

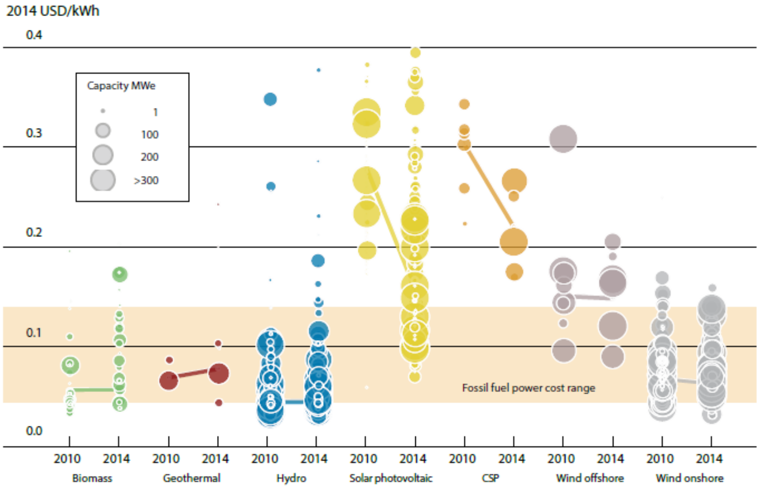


Figure 36, Levelized costs of electricity from utility scale renewable technologies 2010 - 2014 (Taylor et al., 2015)

Solar PV module prices in 2014 were around 75% lower than their levels at the end of 2009, Moreover, the most competitive utility-scale solar PV projects are now regularly delivering electricity for just USD 0.08 per kilowatt-hour (kWh) without financial support. Even lower costs are being realised, down to USD 0.06/kWh, for utility-scale solar PV where excellent resources and low-cost finance is available (Taylor et al., 2015). Furthermore, they see that for CSP as costs are falling, recent projects are being built with LCOEs of USD 0.17/kWh, and power purchase agreements are being signed at even lower values where low-cost financing is available (Taylor et al., 2015). Figure 37 indicates their cost reduction forecasts towards 2025.

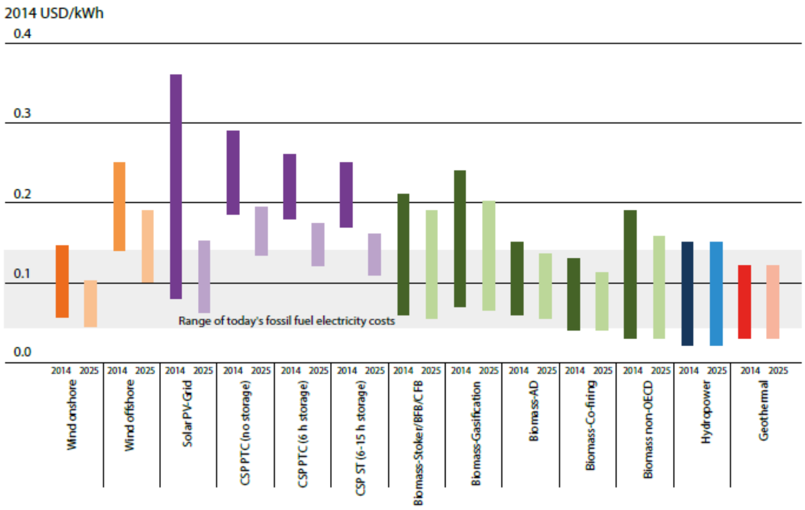


Figure 37, LCOE ranges by renewable power generation technology, 2014 and 2025 (Taylor et al., 2015)

When comparing the scenarios, these future expected price changes will be taken into account in a sensitivity analysis.

7.3 Electricity generation mix by county

In the low carbon scenario almost all counties supply at least a part of their electricity demand within the county as shown in table 11. However, the amount generated per county vary heavily. Counties generate as little as Vihiga; 3 GWh to as much as Nakuru; 31755 GWh. This makes the later county the biggest electricity generator with around 50% of the counties total generation. This is mostly due to the central location of the county and the cheap energy source, geothermal, that is abundantly available. In this scenario Nakuru fulfils the electricity demand of the countries two biggest cities, Nairobi and Mombasa since their ability to generate electricity from renewable sources is restricted to waste and solar and this is by far not enough to meet the demand (see Appendix 3 for the power balance with electricity flows between the counties).

The total installed capacity of the mix is 10443 MW[10]. As expected the largest share of installed capacity and therewith the most generated electricity comes from geothermal sources since this is widely available in Kenya, it has a high capacity factor and it is the lowest cost generation technology. The variable sources, solar PV and Wind combined compose of 18% of the total installed capacity. Due to the low capacity factor of both technologies this comprises in 3% of the total electricity generation for both technologies. The remainder of the electricity is supplied by Geothermal sources. This is a large share of the electricity generation, however due to the low costs, availability central location and close proximity of the geothermal fields to Nairobi, the largest consumer of electricity in Kenya, this option was preferred in most cases where not enough electricity could be generated within the county. This was the case in many counties due to the constraints in variable electricity sources .

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[10] It should be noted that for this low carbon scenario and the BAU scenario no extra margin for installed capacity has been included as compared to the estimated peak load demand in 2030.

Table 11, generation per county under low carbon 'high growth' scenario (own results)

Generated GWh in 2030 (high growth scenario)

	Geothermal	Biomass[11]	Wind	Hydro	Waste	Solar PV	MSD	CSP	Total
Baringo	5092	9							**5100**
Bomet		207			61				**267**
Bungoma		293			138	27			**458**
Busia		0			0	60			**60**
Embu		0	107	829	0	42			**978**
Garissa					58	83	174	163	**478**
Homa Bay	788				73	93			**954**
Isiolo			17						**17**
Kajiado	5519		65		54	55			**5693**
Kakamega		1062			142	8			**1212**
Keiyo-Marakwet						37			**37**
Kericho					71	4			**74**
Kiambu					230	42			**272**
Kilifi		632			110	306	180	770	**1997**
Kirinyaga		312	118						**430**
Kisii					134				**134**
Kisumu		434		206	98	133			**871**
Kitui				211	86	54			**351**
Kwale		555			60	111			**725**
Laikipia	3449								**3449**
Lamu		68	150			39			**257**
Machakos				445	109	218	651		**1423**
Makueni		210			76	52			**338**
Mandera					78	14			**92**
Marsabit			751					593	**1343**
Meru			200	156		16			**372**
Migori		315		5		18			**338**
Mombasa					140	67	230		**437**
Murang'a				72	90	6			**168**
Nairobi					473	85			**558**
Nakuru	31747	9							**31755**
Nandi					65				**65**
Narok		222	127						**349**
Nyamira					52				**52**
Nyandarua			64						**64**
Nyeri			91	4					**95**
Samburu			39					110	**149**
Siaya					71	13			**84**
Taita Taveta		309				56			**364**
Tana River						86		173	**260**
Tharaka			64	360		1			**425**
Trans Nzoia					73				**73**
Turkana	557								**557**
Uasin Gishu				1	100				**101**
Vihiga						3			**3**
Wajir						74			**74**
West Pokot				270		49			**319**
Import									**0**
GWh	**47152**	**4636**	**1794**	**2558**	**2641**	**1850**	**1235**	**1809**	**63674**
	74%	7%	3%	4%	4%	3%	2%	3%	**100%**
MW Inst. Cap.	**5788**	**882**	**585**	**584**	**502**	**1320**	**504**	**295**	**10460**
	55%	8%	6%	6%	5%	12%	5%	3%	**100%**

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[11] 17.5GWh is produced by existing biogas plants located in Baringo and Nakuru

8 Transmission and Distribution

Regional generation on the county level has consequences for transmission and therewith transmission losses. Even though a large part of the electricity is still produced in central locations as seen in the former chapter, more dispersed generation in also shown. To examine the saved losses from regional electricity production in the low carbon scenario, the potential losses as would occur in the BAU scenario should be forecasted, after which the difference with the low carbon scenario with regional production can be determined. This will answer the question; *What are the consequences for transmission and distribution losses when implementing the low carbon electricity generation scenario?*

8.1 BAU scenario losses

The baseline scenario transmission losses are calculated with the consumption of the high BAU scenario as proposed in chapter 5 and based on the installed capacity, projects under development and the modelled future locations of generation plants as listed in the UDLCPDP (Electric Power Sector Kenya, 2011; 153). Some minor changes needed to be made to secure the consistency with the electricity source mix as proposed earlier in the report due to differences in the expected installed capacity and the actual installed capacity. Furthermore, the modelled installed capacity needed to be adjusted it to the lower demand from the BAU scenario as used in this study and no extra margin of installed capacity as opposed to the estimated peak demand in 2030 has been taken into account. This was done by eliminating surplus plants proposed to be built the latest and plants that are not in the BAU scenario electricity mix (all nuclear, all coal and 3 MSD).[12]

In the BAU scenario 84% of all electricity generation in Kenya originates from 5 counties, being Baringo(26%), Nakuru(22%), Lamu(10%), Kaijiado(6%) and Marsabit(4%) and import from Ethiopia (16%). The sources of electricity being subsequently; geothermal (x2), coal, geothermal, wind and Hydropower. Having to fulfil the demand in all counties, this will account for long distance transmission. The total transmission distance in this case is 9094 km.

The losses will be calculated based on the distance between the generation and use sites. The distances are analysed building upon the electricity flow between counties. For every county the site for both generation and consumption is assumed to be the middle point. These power balance between counties can be found in appendix 3. In reality the location of generation and use will be spread out over the counties, this is thus a simplification. However, since this will both shorten some and lengthen other distances, it is assumed to be adequate. Derived from the proposed transmission plan by KETRACO, KPLC and in the UDLCPDP, the network is assumed to consist of 50% 400kV transmission lines, 25% 220kV transmission lines and 25% 132 kV transmission lines. The line between Ethiopia and the Suswa, Kenya is assumed to be a HVDC 500kV line which is currently planned for construction (KETRARCO, 2015).

The material and area of the cables used for the transmission lines per voltage level are derived from specifications in tenders for such transmission lines by KETRACO and KPLC, the average has been taken if different kind of power lines were used on different locations (KETRACO, 2015; Midal Cable, 2017; KETRACO, 2009). The conductor was in all cases aluminium, which has a resistivity of 2.8 *10^-8 Ωm.

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[12] The current installed capacity and the projects under development can be found in chapter 5 The list of modelled installed capacity can be found in Appendix 2.

The total losses arising from the BAU generation scenario are 176 MW in 2030, being 2.4% of the total electricity demand. This is in line with the expectations since the transmission losses were 3.4% 2010, almost a quarter of the total losses that year; 16.2% (Kenya Electrical Power Sector, 2011; KPLC, 2016) and a lot of improvements of the transmission system with higher voltage cables were taken into account. The total losses also include further distribution losses and non-technical losses. More than 30 MW of the losses were resulting from the transmission of imports, which is more that 17% of the losses.

8.2 Low carbon Scenario Losses

The transmission losses in the low carbon scenario are based on the generation as described in chapter 7, optimal electricity mix per county. In this scenario it is still 5 counties in which a considerably larger share of electricity is generated than the other counties, however, in this scenario this is not more than 75%. The total distance is reduced to 6050 km.

Similar assumptions have been made to the BAU scenario, the only change is that the 500 kV cable is not included in this scenario since no imports from Ethiopia will be needed. Moreover, the main power producer for Nairobi and Mombasa, will be Nakuru in this scenario. The distance between generation and consumption is assumed to be crossed with a 400kV cable. The power balance between counties can also be found in Appendix 3.

The total transmission losses are estimated to be 114 MW in 2030, corresponding with 1.57% of the total power demand. This is 0.83% lower than in the BAU scenario. This may seem a small number, however, this equals 546.73 GWh avoided generation yearly. This would thus save significant amounts of electricity and therewith emissions and costs.

9 Comparison

In this section the answer for the final sub-question *How does this low carbon scenario compare to the business as usual scenario for costs and GHG emissions in Kenya?* will be given. This comparison will be based on the electricity generation costs to meet the demand, and the CO2 emission abatements of the low carbon scenario. Both the lower transmission and distribution losses from the low carbon scenario as determined in chapter 8, and the avoided emissions of the renewable electricity technologies themselves will contribute to the CO2 emission abatements of the fossil fuel based technologies and high losses in the BAU scenario. Lastly the implications of the results for the medium and low growth scenarios will be discussed.

9.1 Emissions

All renewable electricity generation technologies discussed are assumed to have zero Green House Gas (GHG) emissions, since this study focusses on avoided emissions in the use phase. The emissions of the fraction of MSD in the electricity mix of the low carbon scenario has been calculated in the same way as described for the BAU scenario. The waste incineration method includes both organic and non-organic components originating from fossil fuel sources. Only the share of the waste that originates from organic matter will be counted as renewable power. Plastics composite 16.1% of the total waste, however weighed with its energetic value, it forms 29.9% of the electricity output. Combined with Leather and Textiles which also contain non-organic carbon this amount is 37.1% of the waste.

To determine the climate relevant emissions from the incineration of MSW the Tier 2a method as proposed by the IPCC has been used. This method can be used if the total amount of MSW is known and the fraction of each component are known, for the dry matter content of the different components and their fraction of carbon and carbon from fossil origin IPCC 2006 default values have been adopted (IPCC, 2006). Derived from the these calculations; the climate relevant emissions from 1 tonne of waste incinerated are 266.40 kg CO_2e. This equals 0.61 kg/kWh of electricity generated. This is lower electricity generation from fossil sources in this study MSD, Coal and kerosene; subsequently 0.77, 0.76 and 0.74 kg/kWh, but higher than Natural Gas, 0.51 kg/kWh. However, MSW incineration is not only a partly renewable source of electricity generation, it also manages waste streams and therewith avoids the need for landfilling. Landfilling results into the emissions of the strong greenhouse gas Methane. Incinerating MSW is therefore a way to reduce the emissions. The GHG emissions from landfilling the Kenyan MSW are determined using the Tier 2 method as proposed by the IPCC (2006). Landfilling 1 tonne of MSW results in 614.71 kg CO_2e .This results in net avoided indirect emissions from MSW incineration of 348.31 kg CO_2e /tonne.

The avoided emissions compared to the BAU scenario are therefore significant. 7.91 ktonne CO_2e /year compared to the high growth BAU scenario, 6.87 ktonne CO_2e /year compared to the medium growth BAU scenario and 4.08 ktonne CO_2e /year compared to the low growth BAU scenario. This means that the more electricity is produced the more emissions are avoided. This is counterintuitive, but because if more waste is transferred to electricity, more waste is avoided in landfills, and thus more methane emissions are saved.

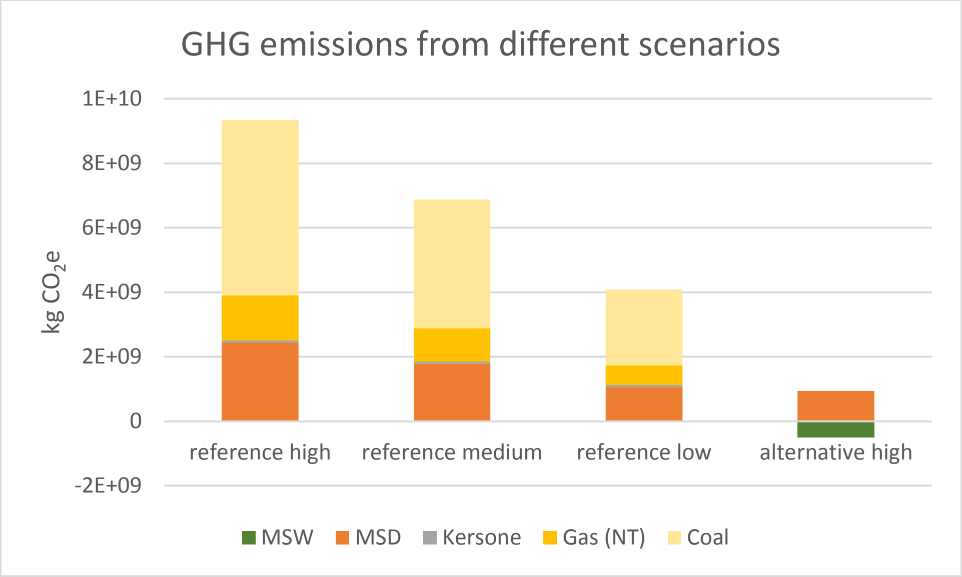

Figure 38, emissions from low carbon and BAU scenarios

The avoided emissions derived from the lower transmission losses depend on the reference taken. The average emissions per kWh in Kenya are low due to the high share of renewables in the electricity mix. This is already true for the BAU scenario; 0.15 kg CO_2e/kWh, and this is even lower for the low carbon scenario; 0.007 kg CO_2e/kWh. When taking the BAU scenario as the BAU for the avoided emissions from lower transmissions losses, the 546.73 GWh avoided generation gives 80 tonne avoided emissions. However these lower transmissions losses are a result of the regional generation mix as proposed in the low carbon scenario, this scenario should be taken as a reference, resulting in only 3.8 tonne emissions savings yearly. It should however be noted that regional generation whether this is a result of a renewable electricity mix or not has the potential to save emissions arising from the avoided transmission losses.

Combined the avoided emissions from the low carbon electricity mix and the avoided emissions from the lower transmission losses bring the total avoided emissions to 8907 tonne CO_2e annually.

9.2 Costs

The total yearly costs of electricity generation in Kenya is based on the LCOEs of each technology and the weighed total. This is a simplification and should be interpreted with care, but this analysis could serve as an indication for the economic viability of a regional renewable electricity generation system in Kenya. The LCOE of technologies have been used as listed in table 10, combined with the electricity mix from the BAU scenario as shown in chapter 5 and from the low carbon scenario as presented in chapter 7.

Table 12, costs comparison

Costs in 2030 (2017US$)	Costs (mln US$/Year)	Weighted average specific costs (US$/kWh)
BAU (high growth)	5902,6	0,093
Low carbon (high growth)	5634,7	0,088

As can be seen from the table above, the low carbon regional renewable electricity generation scenario has a lower weighted average costs price then the BAU scenario. This is mostly due to the even larger amount of low costs geothermal capacity in the low carbon scenario. The weighed share of each technology in the total price is shown in figure 39 below.

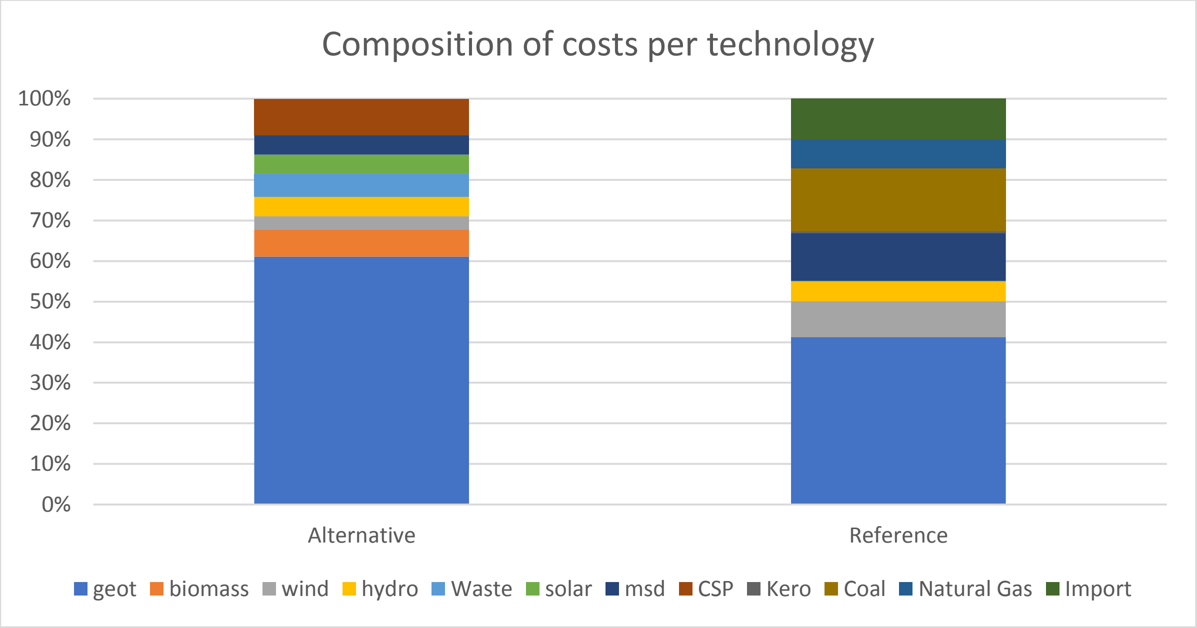

Figure 39, Composition of costs per technology

Costs reduction from reduced transmission losses

The cost reduction from the reduced transmission losses will only be apparent when less capacity is installed due the resulting lower need or when generation plants have high operation costs, e.g. plants with feedstock costs. Since the latter is not the case in the low carbon scenario due to the low fraction of fossil fuel, the former is assumed to calculate the average yearly cost reduction. It should however be noted that this is a simplification and only gives an indication of the possible cost reduction due to lower transmission losses. Furthermore, It is important to take in account that the cost of the transmission network itself or any related costs are not included in the costs analysis. Assuming the 546.73 GWh avoided losses as presented in chapter 8, the avoided costs would be 50,8 mln US$ compared to the BAU scenario and 48.1 mln US$ compared to the low carbon scenario.

sensitivity

As discussed before, chances are high that the costs of Solar PV and CSP will reduce in the future and since the proposed mix is for 2030 is already at a lower costs than the BAU scenario, this will mean that the low carbon scenario will get even more competitive.

The LCOE of solar PV is assumed to drop towards 0,105 US$/kWh on average in 2025 and the LCOE of CSP towards 0.135US$/kWh on average in 2025 (Taylor et al., 2015). Significant reductions considering the current LCOEs of 0.15 US$/kWh and 0.28 US$/kWh subsequently. Onshore wind technologies are also expected to become more costs competitive and their average LCOE is expected to drop to 0.075 US$/kWh. The costs of biomass, hydro and geothermal generation are not expected to significantly decrease (Taylor et al., 2015).

These reduction will bring the average LCOE of the low carbon high growth scenario generation system to 0.08 US$/kWh. These changes in LCOE will however not change the order of the preferred technologies based on pricing, thus the optimal electricity mix per county will remain as it is. These changes also affect the average LCOE of BAU high growth scenario, where wind even has a higher share than in the low carbon scenario. The average LCOE of the BAU scenario is expected to decrease towards 0.09 US$/kWh. Remaining 10% higher than the low carbon scenario.

9.3 Emissions abatement costs

Derived from the results as shown in the two paragraphs prior, the costs per GHG abatements can be calculated by subtracting the costs of the BAU scenario electricity system from the low carbon scenario and dividing this by the total avoided emissions. This results in negative emissions abatement costs of -0,03 US$/avoided tCO_2e. When taking into account the lower system costs as discussed in the sensitivity analysis, these negative abatement costs will further reduce to -0,06 US$/avoided tCO_2e. The low carbon scenario could therefore be interpreted as a cost effective mix of technologies to reduce the GHG emissions of the electricity generation system of Kenya.

9.4 Medium and Low growth scenario

The analysis of the electricity mix, its avoided emissions and costs as discussed in chapter 7 t/m 9.3 as based on the high demand growth scenario. The results would differ if the medium or low growth demand scenario would have been analysed. The effects of both scenarios on the analysis will be discussed below.

In the medium growth and low growth scenario the percentage of losses would be even lower for the low carbon scenario since the counties are more eligible to fulfil their own electricity demand with their available renewable resources. Moreover, costs of the generation are also expected to be lower due to the ability to fulfil the need with cheaper technologies. The BAU scenario does not have those advantages since the costs of the electricity mix is not based on availability. Furthermore, the share of transmission losses in the BAU scenario will not decrease as much in the medium and low growth scenario. The amount of power transmitted will be lower, however due to the central generation, the distance will get longer. It therefore seems that the advantages of a more distributed electricity generation system has more benefits for lower demand profiles.

The avoided emissions from the medium and low growth scenario will not differ much from the high growth scenario. This is because these emissions are based on the avoided emissions of MSW incineration and the emissions of the MSD plants. The latter will remain the same in all three scenarios since these are existing plants and are therefore part of every scenario. The avoided emissions of MSW are expected to be slightly lower in the low and medium growth scenarios since less generation will be needed per county, which could mean less waste incineration would be needed. The benefits of the avoided emissions from the low carbon scenario are therefore expected to be lower in the lower growth demand scenarios.

Discussion & Limitations

Most discussion points have been addressed throughout this thesis, however, there are some additional points that deserve extra attention. First the more general issues will be discussed after which some considerations about specific topics will be expressed.

The first and foremost limitation of this study is the lack of availability of consistent and reliable data. Gathering data proved challenging and while analysing the data many inconsistencies were incorporated. Every research encounters these dilemmas, but it was especially challenging because of the physical distance between the sources and the researcher. The inconsistencies were rectified with other sources as much as possible, however it remains an issue that should be taken in mind while interpreting this thesis.

This study has shown an overview of the renewable energy sources per county on the level of the whole of Kenya. The results are therefore based on large scale assumptions and studies. E.g. the wind and solar potentials are measured using a satellite imagery of 50 by 50 km2. The results given in this study therefore serve as an indication. Additional research is needed to determine the potential and costs of various technologies location specific.

Moreover, a lot of assumptions have been made throughout the thesis. These have been backed up with trustworthy sources, however this remains a point of consideration. The more assumptions made, the more the 'real value' decreases. This study tried to be as inclusive as possible while being transparent on assumptions and uncertainties. Furthermore, assumptions differ depending on the source. For example, different studies show different solar potential. However, not all could be used in this study because they did not provide high resolution data or did not have data for analysis. Different sources such as NASA, NREL and DLR show different irradiance patterns. This causes the potential to differ among studies, e.g. Oloo et al. find a much higher potential for the different counties. The data used in this study however corresponds to the UDLCPDP used the BAU scenario.

Furthermore, not only emissions in the use phase are important in the assessment of technologies; a large share of the environmental impacts are found in the extraction of raw materials, construction and end-of-life this is the idea of life cycle impact (Guinée, 2010). It is therefore needed to have tool that can assess the environmental impact of products throughout an entire life cycle, to identify opportunities for improvement. This tool is a life cycle assessment (LCA); LCA addresses "the environmental aspects and potential environmental impacts (e.g. use of resources and the environmental consequences of releases) throughout a product's life cycle from raw material acquisition through production, use, end-of-life treatment, recycling and final disposal" (ISO 14040, 2006). Because the only avoided emissions are considered in this study, the emissions in the use phase are taken into account. Life-cycle emission data are not available for all renewable electricity sources in Kenya, analysed in this study. The comparison of fossil fuel sources with renewable sources could therefore not include life-cycle emissions. Further studies should focus on LCA of renewable sources in Kenya.

The last important limitation of this study is in the economic analysis. This study uses a simplified costs analysis, based on LCOEs from different external sources. Furthermore, by calculating the costs based on the current prices these could differ significantly from the future 'real' prices. Technologies could become cheaper, prices of resources can vary etc. However, since the future is always unknown it is hard to project these changes. Where possible, future price forecast are taken into account, however this is subjected to a high level of uncertainty. The costs analysis performed in this study gives an indication of the system costs, however, further more in depth analysis is needed to determine the full system costs.

Conclusion

Kenya’s current electricity system has a large share of renewable generation, originating from hydro and geothermal sources. The current electricity consumption is for the largest share from commercial and industrial parties, and coming from the greater Nairobi area. The rural electricity access rate is low compared to other developing countries, however rapidly rising in the past few years. The Transmission and distribution losses arising from Kenya’s current distribution system are considerable and have not decreased in the last years. A least cost power development plan has been created by the Kenyan electricity sector partners to develop the electricity system, increase the access to electricity and amount of available electricity. This plan however includes large shares of fossil fuelled electricity generation which increases the emissions from electricity generation and therefore contributing to human endorsed climate change. Moreover, the UDLCPDP also includes large shares of imports from Ethiopia, making Kenya dependent on the already vulnerable electricity system of Ethiopia. There is another development scenario made by ECN in which only renewable energy was taken into account, however this study looked at Kenya as a whole, not taking into account the potential transmission benefits of more regional generation. This study aimed to explore the potential of a low carbon electricity future for Kenya as compared to the business as usual scenario, and research the feasibility to generate this renewable energy as close to the end-user as possible, therewith reducing transmission and distribution losses.

Three scenarios have been created to forecast the demand growth towards 2030. The low growth scenario is based on an extrapolation of trends. The medium and high growth scenarios are based on slightly higher assumptions on population growth, electricity access growth, GDP growth and urbanisation. The consumption is expected to grow towards 22,937 GWh, 38,269 GWh and 51,876 GWh subsequently. The demand scenarios as assumed in this study are considerably lower than expected in both the UDLCPDP and ECN study, however these scenarios were both starting in 2010, already expected a significantly larger demand by 2015 then the actual demand in 2015. The growth rates of each scenario are however comparable with the other studies.

The electricity mix in the BAU scenarios still consist of a substantial amount of renewables in the form of geothermal power, since this a low cost technology in Kenya. The shares of coal and imports are however increasing towards 2030, added with wind and natural gas. The amount of hydro and MSD are relatively stable in the BAU scenario. The resulting emissions are mostly due to the increased amounts of coal in the generation mix since coal has the highest share and highest emission factor.

The low carbon scenario is based on the current installed capacity combined with the total of the optimal electricity mixes by county. These optimal electricity mixes by county were derived from the potential electricity from hydro, solar PV, solar CSP, MSW Biomass, wind and geothermal generation by county, while considering a maximum amount of variable generation, and minimum size. The amount of renewable resources for electricity generation in total is significant, enough to meet Kenya’s current demand 12 times. Moreover, each county also has a considerable potential for generation within the county. While some counties have much more potential than others due to o.a. geothermal sources, higher irradiation levels, higher wind speeds or simply more available land for electricity generation. However, not all electricity demand can be satisfied within the counties. This causes the optimal electricity mix to have a 74% share of geothermal electricity since this is a low-cost technology that can be used for both base-load and flexible load and has a very central location within Kenya, enabling the supply to counties around while keeping the transmissions distances low.

Although still are large share of the electricity is produced on central locations, a larger share of the electricity will be produced within the counties as opposed to the BAU scenario. This causes the transmission losses to be 0.83% lower than in the BAU scenario, resulting in GHG and costs savings. The emissions of the electricity mix in the low carbon scenario are assumed to be very low do to the large share of zero carbon generation technologies. Only the existing MSD plants will cause emissions from electricity generation. The MSW plants are assumed to avoid emissions, because the emissions from incineration are determined to be lower than that of the otherwise landfilled waste. This results in net emissions savings of 7.91 ktonne CO_2e/year as compared to the BAU scenario. The average costs of the low carbon generation mix are 0.088 US$/kWh, well below that of the average costs of 0.093 US$/kWh in the BAU scenario, while its emissions are mostly avoided. Combined with the avoided benefits of the lower transmissions and distribution losses, this results in negative abatement costs of -0,03 US$/avoided tCO_2e.

To answer the research question; *To what extent can regional renewable electricity production in Kenya contribute to a lower GHG emissions scenario towards 2030 as compared to a business-as-usual scenario based on central electricity production?* This study indicates that the low carbon renewable electricity generation system would save both costs and emissions compared to the BAU scenario if implemented. Furthermore, no imports are needed in the low carbon scenario making Kenya independent from its neighbour. Generating electricity closer to the end-user in Kenya will save losses and thus costs and emissions. However, a fully regional electricity system in which all electricity is generated within the county it is consumed is not feasible at this moment.

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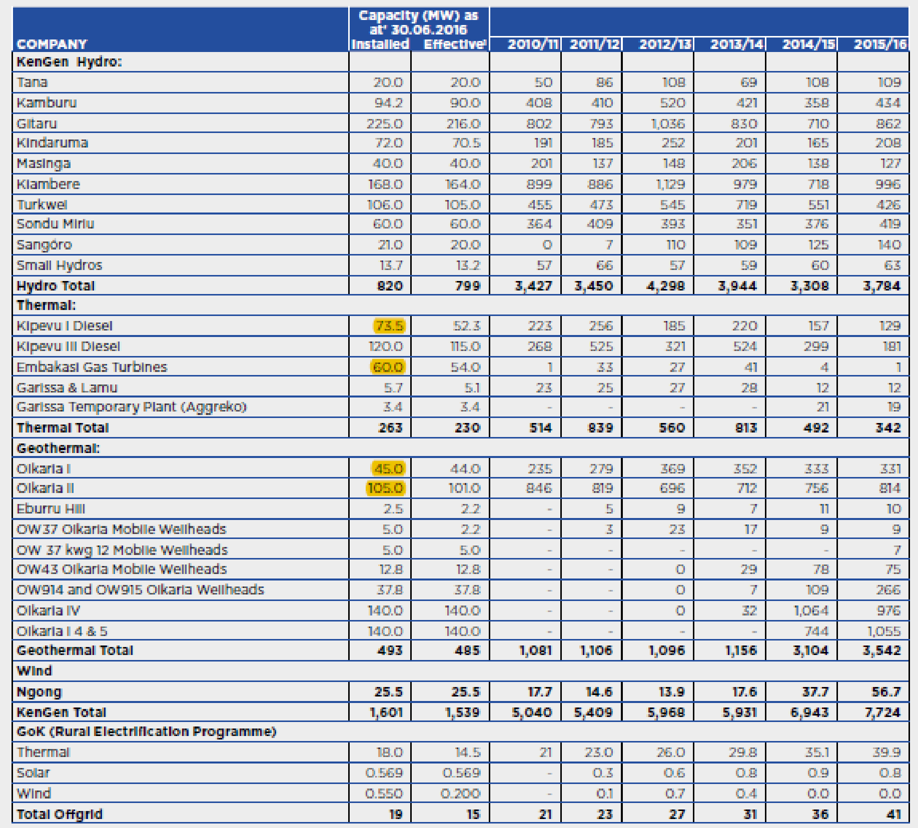
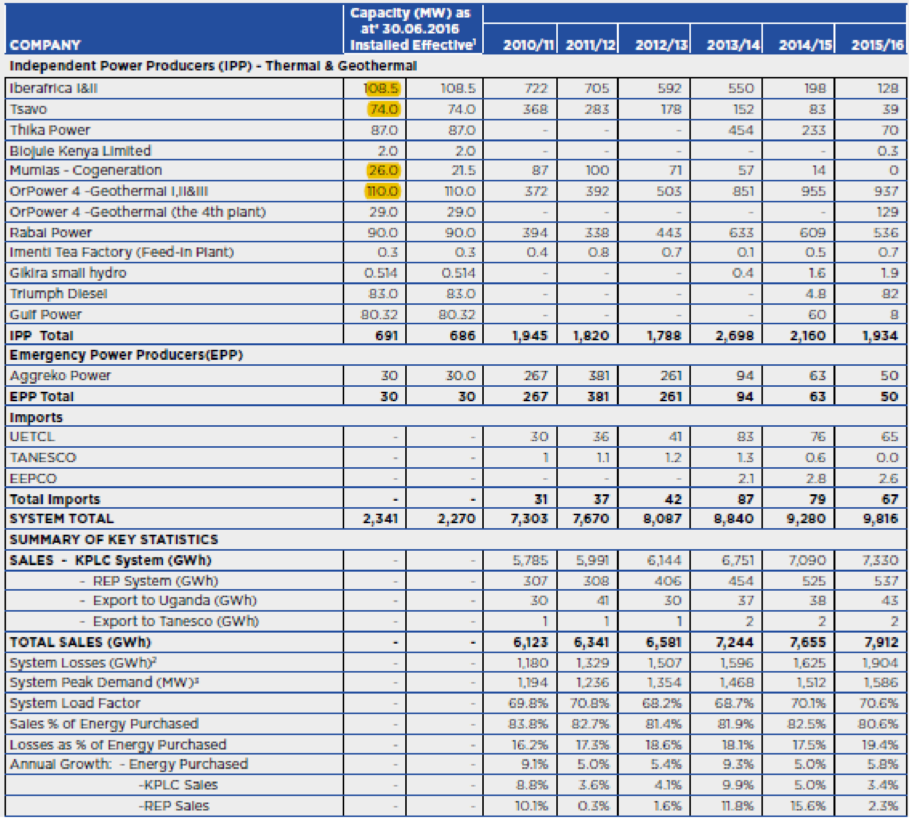
Appendix 1, current installed capacity

Table 13, current installed capacity (KPLC, 2016)



COMPANY	Capacity (MW) as at' 30.06.2016							
	Installed	Effective[1]	2010/11	2011/12	2012/13	2013/14	2014/15	2015/16
KenGen Hydro:								
Tana	20.0	20.0	50	86	108	69	108	109
Kamburu	94.2	90.0	408	410	520	421	358	434
Gitaru	225.0	216.0	802	793	1,036	830	710	862
Kindaruma	72.0	70.5	191	185	252	201	165	208
Masinga	40.0	40.0	201	137	148	206	138	127
Kiambere	168.0	164.0	899	886	1,129	979	718	996
Turkwel	106.0	105.0	455	473	545	719	551	426
Sondu Miriu	60.0	60.0	364	409	393	351	376	419
Sangóro	21.0	20.0	0	7	110	109	125	140
Small Hydros	13.7	13.2	57	66	57	59	60	63
Hydro Total	**820**	**799**	**3,427**	**3,450**	**4,298**	**3,944**	**3,308**	**3,784**
Thermal:								
Kipevu I Diesel	73.5	52.3	223	256	185	220	157	129
Kipevu III Diesel	120.0	115.0	268	525	321	524	299	181
Embakasi Gas Turbines	60.0	54.0	1	33	27	41	4	1
Garissa & Lamu	5.7	5.1	23	25	27	28	12	12
Garissa Temporary Plant (Aggreko)	3.4	3.4	-	-	-	-	21	19
Thermal Total	**263**	**230**	**514**	**839**	**560**	**813**	**492**	**342**
Geothermal:								
Olkaria I	45.0	44.0	235	279	369	352	333	331
Olkaria II	105.0	101.0	846	819	696	712	756	814
Eburru Hill	2.5	2.2	-	5	9	7	11	10
OW37 Olkaria Mobile Wellheads	5.0	2.2	-	3	23	17	9	9
OW 37 kwg 12 Mobile Wellheads	5.0	5.0	-	-	-	-	-	7
OW43 Olkaria Mobile Wellheads	12.8	12.8	-	-	0	29	78	75
OW914 and OW915 Olkaria Wellheads	37.8	37.8	-	-	0	7	109	266
Olkaria IV	140.0	140.0	-	-	0	32	1,064	976
Olkaria I 4 & 5	140.0	140.0	-	-	-	-	744	1,055
Geothermal Total	**493**	**485**	**1,081**	**1,106**	**1,096**	**1,156**	**3,104**	**3,542**
Wind								
Ngong	**25.5**	**25.5**	**17.7**	**14.6**	**13.9**	**17.6**	**37.7**	**56.7**
KenGen Total	**1,601**	**1,539**	**5,040**	**5,409**	**5,968**	**5,931**	**6,943**	**7,724**
GoK (Rural Electrification Programme)								
Thermal	18.0	14.5	21	23.0	26.0	29.8	35.1	39.9
Solar	0.569	0.569	-	0.3	0.6	0.8	0.9	0.8
Wind	0.550	0.200	-	0.1	0.7	0.4	0.0	0.0
Total Offgrid	**19**	**15**	**21**	**23**	**27**	**31**	**36**	**41**



COMPANY	Capacity (MW) as at' 30.06.2016							
	Installed	Effective[1]	2010/11	2011/12	2012/13	2013/14	2014/15	2015/16
Independent Power Producers (IPP) - Thermal & Geothermal								
Iberafrica I&II	108.5	108.5	722	705	592	550	198	128
Tsavo	74.0	74.0	368	283	178	152	83	39
Thika Power	87.0	87.0	-	-	-	454	233	70
Biojule Kenya Limited	2.0	2.0	-	-	-	-	-	0.3
Mumias - Cogeneration	26.0	21.5	87	100	71	57	14	0
OrPower 4 -Geothermal I,II&III	110.0	110.0	372	392	503	851	955	937
OrPower 4 -Geothermal (the 4th plant)	29.0	29.0	-	-	-	-	-	129
Rabai Power	90.0	90.0	394	338	443	633	609	536
Imenti Tea Factory (Feed-in Plant)	0.3	0.3	0.4	0.8	0.7	0.1	0.5	0.7
Gikira small hydro	0.514	0.514	-	-	-	0.4	1.6	1.9
Triumph Diesel	83.0	83.0	-	-	-	-	4.8	82
Gulf Power	80.32	80.32	-	-	-	-	60	8
IPP Total	**691**	**686**	**1,945**	**1,820**	**1,788**	**2,698**	**2,160**	**1,934**
Emergency Power Producers(EPP)								
Aggreko Power	30	30.0	267	381	261	94	63	50
EPP Total	**30**	**30**	**267**	**381**	**261**	**94**	**63**	**50**
Imports								
UETCL	-	-	30	36	41	83	76	65
TANESCO	-	-	1	1.1	1.2	1.3	0.6	0.0
EEPCO	-	-	-	-	-	2.1	2.8	2.6
Total Imports	**-**	**-**	**31**	**37**	**42**	**87**	**79**	**67**
SYSTEM TOTAL	**2,341**	**2,270**	**7,303**	**7,670**	**8,087**	**8,840**	**9,280**	**9,816**
SUMMARY OF KEY STATISTICS								
SALES - KPLC System (GWh)	-	-	5,785	5,991	6,144	6,751	7,090	7,330
- REP System (GWh)	-	-	307	308	406	454	525	537
- Export to Uganda (GWh)	-	-	30	41	30	37	38	43
- Export to Tanesco (GWh)	-	-	1	1	1	2	2	2
TOTAL SALES (GWh)	**-**	**-**	**6,123**	**6,341**	**6,581**	**7,244**	**7,655**	**7,912**
System Losses (GWh)[2]	-	-	1,180	1,329	1,507	1,596	1,625	1,904
System Peak Demand (MW)[3]	-	-	1,194	1,236	1,354	1,468	1,512	1,586
System Load Factor	-	-	69.8%	70.8%	68.2%	68.7%	70.1%	70.6%
Sales % of Energy Purchased	-	-	83.8%	82.7%	81.4%	81.9%	82.5%	80.6%
Losses as % of Energy Purchased	-	-	16.2%	17.3%	18.6%	18.1%	17.5%	19.4%
Annual Growth: - Energy Purchased	-	-	9.1%	5.0%	5.4%	9.3%	5.0%	5.8%
-KPLC Sales	-	-	8.8%	3.6%	4.1%	9.9%	5.0%	3.4%
-REP Sales	-	-	10.1%	0.3%	1.6%	11.8%	15.6%	2.3%

Appendix 2, planned installed capacity BAU scenario

Table 14, planned installed capacity (Electric Power Sector Kenya, 2011)

Year	Plant location	Capacity (mw)	Region	Plant type
2015	Menengai 1,2	280	6	GEOTH
2020	Athi River	160	2	MSD
	Lamu	300	4	COAL
	Mariakani	180	4	GT
	Mariakani	180	4	GT
	Grand Falls	140	5	HYDRO
	Menengai 3,4	280	6	GEOTH
	Menengai 5,6	280	6	GEOTH
	Longonot 1,2	280	6	GEOTH
	Lessos	160	8	MSD
	L. Turkana	100	9	WIND
	Marsabit	100	9	WIND
	Marsabit	100	9	WIND
2025	Isinya	180	2	GT
	Isinya	180	2	GT
	Lamu	300	4	COAL
	Malindi	100	4	WIND
	Malindi	100	4	WIND
	Kilifi	1,000	4	NUCL
	Mutonga	60	5	HYD
	Kitui	300	5	COAL
	Kitui	300	5	COAL
	Longonot 3	140	6	GEOTH
	Longonot 4	140	6	GEOTH
	Silali 1,2	280	6	GEOTH
	Paka 1,2	280	6	GEOTH
	Paka 3, Barrieri 1	280	6	GEOTH
	Kisii	160	7	MSD
	Eldoret	160	8	MSD
2030	Lamu	600	4	COAL
	Galu	160	4	MSD
	Kilifi	1,000	4	NUCL
	Malindi	160	4	MSD
	Machakos	160	5	MSD
	Kitui	900	5	COAL
	Isiolo	180	5	GT
	Thika	180	5	GT
	Silali 3,4,5	420	6	GEOTH
	Korosi 1,2,3	420	6	GEOTH
	Emuruango 1,2	280	6	GEOTH
	Suswa 1,2,3	420	6	GEOTH
	Arusbogoria 1,2,3	420	6	GEOTH
	Kinangop	200	6	WIND
	Kisumu	180	7	GT
	Kakamega	160	7	MSD
	Marsabit	100	9	WIND
	Marsabit	300	9	WIND

Appendix 3, Losses

Table 15, BAU scenario power balance 2030 (own results)

Losses (MW)		nairobi	Machakos	Kajiado	Kilifi	kwale	Lamu	Mombasa	Taita Tave	Tana River	Baringo	Bomet	Nakuru	Narok	Nyandaru	Homa Bay	Kisii	Migori	Nyamira	embu	Isiolo	Kirinyaga	Laikipia	Meru	Muranga	Nyeri	Tharaka N	Elgeyo Ma	Marsabit	Nandi	Samburu	Trans Nzo	Turkana	Uasin Gish	west Poko	Garissa	Kiambu	Kitui	Makueni	Mandera	wajir	Bungoma	Busia	kakamega	Kericho	Kisumu	Siaya	vihigi	import	
nairobi	-2048.9									915.0		591.9		4.5																																	537.5	0.0
Machakos	-380.2											380.2																																				0.0
Kajiado	57.8												-57.8																																			0.0
Kilifi	-228.4					105.5					122.9																																				0.0
kwale	-211.8					211.8																																										0.0
Lamu	697.6			-105.5	-211.8		-299.9	-80.4																																								0.0
Mombasa	-299.9					299.9																																										0.0
Taita Taveta	-80.4					80.4																																										0.0
Tana River	-64.5																		56.8						7.7																						0.0
Baringo	1836.7	-915.0									-71.8		-28.4		-33.3	-10.7	-22.7	-21.0								-28.0		-17.7		-67.2	-25.5	-59.8							-127.8	-45.0	-147.9	-64.5	-27.8	-68.4	-54.3		0.0
Bomet	-71.8									71.8																																						0.0
Nakuru	1239.7	-591.9	-380.2		-122.9																																-61.7	-83.0										0.0
Narok	-86.3		57.8						28.4																																						0.0
Nyandarua	4.5	-4.5																																															0.0
Homa Bay	-33.3									33.3																																						0.0
Kisii	-10.7									10.7																																						0.0
Migori	-22.7									22.7																																						0.0
Nyamira	-21.0									21.0																																						0.0
embu	62.8								-56.8																																						-6.1	0.0
Isiolo	23.0																																		-13.6				-9.5								0.0
Kirinyaga	-64.0																																															64.0	0.0
Laikipia	-56.7																											56.7																			0.0	0.0
Meru	-89.4																											89.4																				0.0
Muranga	-111.1																																															111.1	0.0
Nyeri	-112.5																																															112.5	0.0
Tharaka Nithi	22.9								-7.7																									-15.2													0.0
Elgeyo Marakwe	-28.0									28.0																																						0.0
Marsabit	289.8																					-56.7	-89.4						-17.0								-79.9	-46.6								0.0
Nandi	-17.7									17.7																																						0.0
Samburu	-17.0																											17.0																				0.0
Trans Nzoia	-67.2									67.2																																						0.0
Turkana	-28.6									25.5																							3.1														0.0
Uasin Gishu	-59.8									59.8																																						0.0
west Pokot	3.1																															-3.1																0.0
Garissa	-28.8																			13.6					15.2																						0.0
Kiambu	-322.5																																															322.5	0.0
Kitui	-61.7											61.7																																				0.0
Makueni	-83.0											83.0																																				0.0
Mandera	-79.9																											79.9																				0.0
wajir	-56.1																			9.5							46.6																				0.0
Bungoma	-127.8									127.8																																						0.0
Busia	-45.0									45.0																																						0.0
kakamega	-147.9									147.9																																						0.0
Kericho	-64.5									64.5																																						0.0
Kisumu	-27.8									27.8																																						0.0
Siaya	-68.4									68.4																																						0.0
vihigi	-54.3									54.3																																						0.0
import	1141.6	-537.5																	6.1		-64.0			-111.1	-112.5										-322.5												0.0
total	0.0	-2048.9	-380.2	57.8	-228.4	-211.8	697.6	-299.9	-80.4	-64.5	1836.7	-71.8	1239.7	-86.3	4.5	-33.3	-10.7	-22.7	-21.0	62.8	23.0	-64.0	-56.7	-89.4	-111.1	-112.5	22.9	-28.0	289.8	-17.7	-17.0	-67.2	-28.6	-59.8	3.1	-28.8	-322.5	-61.7	-83.0	-79.9	-56.1	-127.8	-45.0	-147.9	-64.5	-27.8	-68.4	-54.3	1141.6	0.0

Table 16, low carbon scenario power balance 2030 (own results)

high		nairobi	Machakos	Kajiado	Kilifi	kwale	Lamu	Mombasa	Taita Tave	Tana River	Baringo	Bomet	Nakuru	Narok	Nyandaru	Homa Bay	Kisii	Migori	Nyamira	embu	Isiolo	Kirinyaga	Laikipia	Meru	Muranga	Nyeri	Tharaka N	Elgeyo Ma	Marsabit	Nandi	Samburu	Trans Nzoia	Turkana	Uasin Gish	west Poko	Garissa	Kiambu	Kitui	Makueni	Mandera	wajir	Bungoma	Busia	kakamega	Kericho	Kisumu	Siaya	vihigi	import	
nairobi	-1985,21												1985,213																																					0
Machakos	-371,06												363,6452							7,416602																														0
Kajiado	248,65					-209,798			-38,8482																																									0
Kilifi	-131,59												131,5937																																					0
kwale	-209,80			209,798																																														0
Lamu	5,16							-5,16309																																										0
Mombasa	-282,22						5,163092						277,0551																																					0
Taita Taveta	-38,85			38,84824																																														0
Tana River	-34,82																										42,23601									-7,411868														0
Baringo	527,69																											-23,7441		-55,06095		-59,86353107		-93,145								-75,5459	-110,389		-56,0022			-53,9427		0
Bomet	-41,25												21,05461			20,19732																																		0
Nakuru	3239,79	-1985,213	-363,645		-131,594			-277,055				-21,0546		-31,1995	-58,1394																						-327,483		-44,4103											0
Narok	-46,44												31,19949					15,23965																																0
Nyandarua	-58,14												58,13937																																					0
Homa Bay	75,61											-20,1973					-40,2653		-15,1435																															0
Kisii	-40,27															40,26531																																		0
Migori	15,24													-15,2396																																				0
Nyamira	-15,14															15,14346																																		0
embu	58,62		-7,4166																																			-51,2042												0
Isiolo	-11,03																												11,03108																					0
Kirinyaga	-14,88																						14,87666																											0
Laikipia	336,98																					-14,8767		-117,903	-101,968	-102,237																								0
Meru	-96,76																						117,9031				-21,1407																							0
Muranga	-101,97																						101,9677																											0
Nyeri	-102,24																						102,2372																											0
Tharaka Nithi	21,10									-42,236														21,14067																										0
Elgeyo Marakwe	-23,74										23,74411																																							0
Marsabit	128,10																				-11,0311																			-69,4259	-47,6475									0
Nandi	-55,06										55,06095																																							0
Samburu	0,00																																																	0
Trans Nzoia	-58,79										59,86353																								-1,07104															0
Turkana	0,00																																																	0
Uasin Gishu	-93,14										93,14497																																							0
west Pokot	-1,07																															1,071035767																		0
Garissa	-7,41									7,411868																																								0
Kiambu	-327,48												327,4834																																					0
Kitui	-51,20																			51,20422																														0
Makueni	-44,41												44,41029																																					0
Mandera	-69,43																												69,42593																					0
wajir	-47,65																												47,64755																					0
Bungoma	-75,55										75,54593																																							0
Busia	-38,11										110,3891																																	-72,2826						0
kakamega	-9,52																																										72,28264				-62,7662			0
Kericho	-56,00										56,00221																																							0
Kisumu	-3,92																																														3,920332			0
Siaya	-58,85																																											62,76619		-3,92033				0
vihigi	-53,94										53,94269																																							0
total	0																																																	0