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Grid Extension versus Photovoltaic Stand-Alone Solutions for Rural Electrification in Kenya- Development of a Spatial Explicit Energy System Model

A Master's Thesis submitted for the degree of
"Master of Science"

supervised by
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Vienna, 10th of June 2010

Affidavit

I, **Marianne Zeyringer**, hereby declare

1. that I am the sole author of the present Master's Thesis, "Grid Extension versus Photovoltaic Stand-Alone Solutions for Rural Electrification in Kenya- Development of a Spatial Explicit Energy System Model", 80 pages, bound, and that I have not used any source or tool other than those referenced or any other illicit aid or tool, and
2. that I have not prior to this date submitted this Master's Thesis as an examination paper in any form in Austria or abroad.

Vienna, 10.06.2010

Signature

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Abbreviations

AC... Alternating current

AFD... African Development Fund

Ah… Ampere-hour

DC... Direct current

EIB... European Investment Bank

EPIA... European Photovoltaic Industry Association

EUR... Euro

GWh... Giga Watt- hour

GoK... Government of Kenya

IEA... International Energy Agency

KenGen… Kenya Electricity Generating Company

KES... Kenyan Shilling

KIHBS... Kenyan Integrated Household and Budget Survey

KLPC... Kenyan Power and Lighting Company

kV… Kilovolt

kW... Kilowatt

kWh... Kilo Watt-hour

LPG... Liquefied petroleum gas

LV... Low voltage

MDGs... Millennium Development Goals

MW... Megawatt

O&M… Operation and Maintenance

PV... Photovoltaic

REM... Rural Electrification Master Plan

SSA... Sub-Saharan Africa

UA… Unit of account (IMF)

UN... United Nations

UNDP... United Nations Development Programme

USD... United States Dollar

V…Volt

WB... World Bank

Wh...Watt hour

Wp... Watt peak

WTP... Willingness-to pay

Abstract

The achievement of the United Nations Millennium Development goals is strongly connected with access to electricity. The rate of electrification in Kenya is beyond the average in Sub-Saharan Africa. Expressed as a percentage, 14% of Kenyan inhabitants are connected to the grid. About 42% of the population have access to electricity in urban areas compared to only 4% in rural areas. A large majority of the population still relies on firewood for cooking and paraffin for lighting.

Incentives to invest into rural areas are rather low due to high connection costs, low electricity consumption, and low income. In order to allow affordability it is imperative to choose the least cost option ensuring a basic supply. This thesis assesses two rural electrification options by applying a spatial explicit energy system model. The two options are electrification through grid extension and photovoltaic stand-alone systems.

Results show that for most locations the extension of the national grid is less costly. However, for districts with low population densities resulting in high connection costs, photovoltaic technologies are the better option.

1. Introduction

The introduction describes the motivation for this thesis. The motivation behind the research will help to understand the choice of research question. The last part of this chapter will explain the structure of the thesis, guiding the reader.

1.1. Motivation

In order to reach the United Nations Millennium Development Goals (MDGs), energy of satisfactory quality and quantity is necessary for economic development of a country. None of the MDGs can be met without an improvement in energy services (United Nations Development Programme, s.a.a). However, currently the available energy services fail to meet the needs of the poor. In Kenya, about 46% of the population lives below the poverty line. This deviates strongly from the MDG target which is set at 28% for Kenya (United Nations Development Programme, s.a.b). Globally, 1.6 billion people do not have access to electricity and 2.4 billion people use biomass for cooking. Four fifth of the people without access to electricity live in rural regions, mainly in South Asia and Sub-Saharan Africa (United Nations Development Programme, s.a.a.).

Both an increase in investment coming from the public as well as the private sector is needed to offer grid based electricity services to all people, irrespective if they are living in urban or rural areas. Yet, as the necessary resources may not be sufficiently available, new technologies and stand-alone systems can also contribute to a change either as a transitory-or long-time solution (United Nations Development Programme, s.a.a.). Access to electricity can significantly contribute to the attainment of each of the Millennium Development Goals: Goal number one is to eradicate extreme poverty and hunger. The proportion of people in sub-Saharan Africa living on less than USD 1 per day is unlikely to be reduced by the target of one-half (United Nations, 2008). Access to electricity may contribute to this goal because it increases production possibilities as well as living standards by providing light after sunset. Moreover, the change to modern electricity services from previously used forms of energy decreases costs. Furthermore, many activities which require machines are not possible without electricity (Modi et al., 2008; United Nations Energy, 2005).

MDG number two is to achieve universal primary education (United Nations, 2008). Lighting offers study opportunities for students after sunset. It also decreases the hours children have to spend on collecting firewood. As a result, they have more time and energy to focus on school. Moreover, electricity increases quality at school as teachers can rely on basic electricity services for their classes.

MDG number three aims to promote gender equality and empower women. Women are often responsible for keeping the household and collecting fire wood. Therefore, electricity saves them personal energy as well as time. Women will also benefit largely from increased health services. Lastly, electricity used in the forms of street lighting increases safety for women (Modi et al., 2008; United Nations Energy, 2005).

MDG number four is targeted on reducing child mortality (United Nations, 2008). Reliable electricity services are needed for improved health and birth centres as well as for the storage of medicine and vaccines which largely increases child health. Beyond this, the possibility of cleaner food and water decreases child mortality. In addition, children largely benefit from better indoor air quality due to reduced use of biomass as cooking/heating fuel (Modi et al., 2008; United Nations Energy, 2005).

MDG number five is to improve maternal health (United Nations, 2008). Electricity increases the services and spreading of health centres. Light allows medical attendance after darkness. Furthermore, the increase in indoor air quality decreases health problems especially for women and children. Women's health during pregnancy can be increased through switching from heavy labour caused by collecting of firewood to the use of electricity (Modi et al., 2008; United Nations Energy, 2005).

MDG number six aims to combat HIV, aids, malaria and other diseases (United Nations, 2008). Campaigns against HIV and aids reach a large share of the population through radio and television, for which electricity is necessary. As already mentioned, health services depend on reliable electricity for lighting, medical devices and the storage of medicine and vaccines.

MDG number seven is to ensure environmental sustainability (United Nations, 2008). The collecting of firewood increases deforestation and often leads to land degradation and erosion. Thus, overall CO_2 emissions can be reduced by decreasing

land use changes induced by bioenergy consumption. Furthermore, electric water pumps increase water quality (Modi et al., 2008; United Nations Energy, 2005).
The last goal, number eight emphasises on the development of a global partnership for development (United Nations, 2008). Developing countries rely on technologies and the knowledge of developed countries. Transfer of technology and the formation of people can largely facilitate the implementation of an electricity system.

1.2. Definition of the research problem

As previously discussed, access to electricity is essential for poverty reduction and the attainment of the Millennium Development Goals. However, the possibility of poor households to pay for electricity services is limited: In the first place, only basic electricity needs, such as cooking, lighting and the use of radio can be satisfied. Once households experience an increase in wealth, caused amongst others by access to electricity, those services can be extended. Least-cost options are paramount to satisfy basic needs and to foster sustainable development. Therefore, the research problem is to identify least-cost options for electrification in Kenya, which primarily satisfies basic needs of rural households and communities.

1.3. Outline of the research question

The electricity grid in Kenya is still undeveloped and only supplies 25 of 57 districts. Grid extension to yet non-electrified districts represents one option for electrification. Solar irradiation is an abundant resource in Kenya suggesting the use of photovoltaic technologies can be a viable option for electrification in Kenya. The problem is to find the cheaper option for the electrification of a district while at the same time guaranteeing a basic supply.
The goal of this study is to answer the following research question:
Is it preferable for a given location in Kenya to extend the existing electricity grid or to implement stand-alone photovoltaic systems with the objective of minimizing total system costs subject to guaranteeing a basic electricity supply?

1.4. Structure of the thesis

The thesis consists of six chapters. The first one describes the motivation for this research. Furthermore, it states and elaborates on the research problem and question.

The second chapter provides the reader with the background knowledge to the topic and the information to reconstruct the input data. It therefore gives an overview on Kenya in general and its electricity system. Moreover, the energy demand of non electrified households is discussed. Furthermore, the characteristics of stand-alone photovoltaic systems and grid extension with a focus on the costs are described. The third chapter is dedicated to the explanation of the methodical approach. It gives an overview on optimization and energy modelling and describes in more detail the theory behind the method used. This more theoretical section provides the understanding for the next chapter, which is the applied part. Firstly, all the input data are presented. Secondly, the model organization and the used scenarios are illustrated. In chapter five the results are in a first step presented and discussed. The influence of different input parameters on the results is also analysed. The last chapter will summarize and critically discuss the findings and an outlook will be presented.

2. State of the Art

In order to be able to develop an energy system model it is essential to first acquire background knowledge on off-grid and grid extension options and Kenya in general with a focus on its electricity system and electricity demand. In a second step the latest studies on the comparison of grid to off-grid technologies will be summarized.

2.1. Background knowledge

In a first step, an overview on grid connected and stand-alone systems will be provided. Secondly, off-grid photovoltaic and grid technologies will be analysed in detail with a separate chapter on costs of photovoltaic systems and grid extension. Subsequently, the electricity system of Kenya will be discussed. The last part will be dedicated to the elaboration of the electricity demand of non- electrified households.

2.1.1. Grid connected versus stand-alone energy systems

For various reasons, it is important to differ between grid connected and decentralised system. Firstly, the costs differ, secondly the electricity supply is dissimilar and thirdly the advantages and disadvantages of each system vary significantly. It is therefore central to examine each case carefully and decide according to the priorities one aims to achieve. For example, one cannot use the same input data for assessing the electrification of an industrial complex with high energy demand and a poor rural household.

The costs of energy in centralized systems are composed of generation, transmission and distribution costs, compared to a stand-alone system where the system energy costs consist only of generation cost. The economies of scale of a thermal power station are effective in generating power on a large scale and distributing it through high tension lines. However, it suffers a diseconomy of scale in distributing power through medium or low tension lines in rural areas and in places located far from the centre itself. This is due to high line losses caused by the distance and the low capacity utilization triggered by a lack of demand (Jebaraj and Iniyan, 2006). Centralised energy systems are exposed to disturbances in the supply chain. In order to circumvent the uncertainty of transportation infrastructure and the wish to minimise risks through the deployment of smaller-scale, modular generation and transmission system, small decentralised systems offer a viable option (Bouffard and Kirschen, 2008).

Stand-alone or off-grid systems produce power disconnected from the grid. The operational capacity is in line with the demand. Most of the photovoltaic systems in remote areas are stand-alone systems, where the system is needed to operate at low plant load factors. For isolated regions stand-alone technologies often represent the most economical option. Fewer resources are needed, as the systems are small scale. As a result no exploitation of biomass or other natural resources is taking place. Due to the fact that off-grid systems are not connected to the grid, batteries to store the electricity during off-peak demand periods are required. This implies higher costs due to battery and storage costs (Kaundinya et al., 2009).

2.1.1.1. Off-grid photovoltaic technologies

Photovoltaic technologies represent one option for an off-grid solution. In the following section their characteristic, parts and application possibilities in developing countries are described.

Photovoltaic systems offer various advantages. Firstly, they are composed of modules, which can be easily transported and installed. Furthermore, in case more power is required, the modules can be easily extended. Due to the fact that the parts of the generator cannot be moved, only minor efforts have to be invested into maintenance (International Energy Agency, 2010). Furthermore, differently to the possibility of grid extension, a single household can decide to install a PV (photovoltaic) system without requiring large community support (International Energy Agency and Renewable Energy and Efficiency Partnership, 2008).
The reliability of PV is higher compared to the supply and transport of diesel and propane and the supply security of grid lines in developing countries. This is especially important for medical operations such as vaccine refrigeration, hospital lighting and other medical applications. The WHO (World Health Organization) states that PV system ensure a more reliable energy supply for refrigerators resulting in an increase in efficiency of stored vaccine. Furthermore, people can save time as they do not have to travel long distances in order to buy fuel (International Energy Agency, 2003). In Kenya sunset takes place between 6:52 pm in February and 6:21 pm in October and sunrise between 6:42 am in February and 6:11 am in November. Many activities taking place before sunrise or after sunset depend on access to lighting. Compared to kerosene lamps, PV provides a better quality of light, which ensures that activities related to education and commercial activities can take place after nightfall (International Energy Agency, 2010). Lastly, a switch to PV technologies from small paraffin lamps improves indoor quality and as a result decreases respiratory illnesses (International Energy Agency, 2003).

However, off-grid PV systems also imply certain disadvantages. Firstly, they only generate electricity on sunny days and not during night. Therefore storage of electricity is required. In order to store the electricity, a battery is needed, which is made of chemicals which are a potential threat to the environment, especially if it is not disposed of properly. Secondly, solar PV systems are only economic in sunny regions. Finally, only direct current is directly available without a converter (International Energy Agency and Renewable Energy and Efficiency Partnership, 2008).

In developing countries PV systems offer a good alternative to conventional types of energy supply. They can be used in the following areas (International Energy Agency, 2010):

1. “Agriculture: For water pumping, irrigation and electronic fencing.
2. Community services: For water pumping, desalination, purification systems, lighting for schools and other community buildings.
3. Domestic uses: For lighting which allows study, reading and a general increase in living standards, for water pumping, for TV, radio, and other small appliances.
4. Healthcare: Lighting for wards, operating theatre and staff quarters, medical equipment, refrigeration for vaccines, communications (telephone, radio communications systems), water pumping and security lighting.
5. Small enterprises: Lighting systems, to extend business hours and increase productivity, power for small equipment such as sewing machines, freezers, grain grinders, battery charging, lighting and radio in restaurants, stores and other facilities.”

Off-grid concepts can be divided into photovoltaic systems with battery storage and hybrid systems. Hybrid systems are photovoltaic systems with battery storage and an additional power generator. Photovoltaic systems can only provide as much energy as supplied by the photovoltaic plant. Therefore, hybrid systems can provide a more constant supply. Most commonly, hybrid systems are equipped with a diesel generator. In case the battery charge is too low due to insufficient solar radiation or there is an excessive power demand, the supply can be generated through the diesel generator. The advantage is that diesel fuel can be easily stored. There are two possibilities on how diesel generators can be used, either they recharge the battery or provide current directly to the appliances (International Energy Agency, 2010).

In general, PV systems consist of a solar generator, a charge controller, a device for energy storage and directly connected DC appliances (International Energy Agency, 2010). Also support structures such as cables and sockets are needed (Goetzberger and Hoffmann, 2005). The parts are interconnected through a direct current bus-bar. PV modules produce electricity as direct current (DC) at 12 or 14 volts. Direct current appliances have the advantage of high energy efficiency. However, the installation of an inverter also allows supplying standard alternating current. This permits to use any kind of consumer devices (Kaltschmitt et al., 2007). Figure 1 shows the scheme of an off-grid photovoltaic system, consisting of a PV-generator, a charge controller, a battery, and the consumer appliances. For a system with conversion from DC (direct current) to AC (alternating current), voltage conversion takes place between the battery and the consumer devices (see Figure 1).

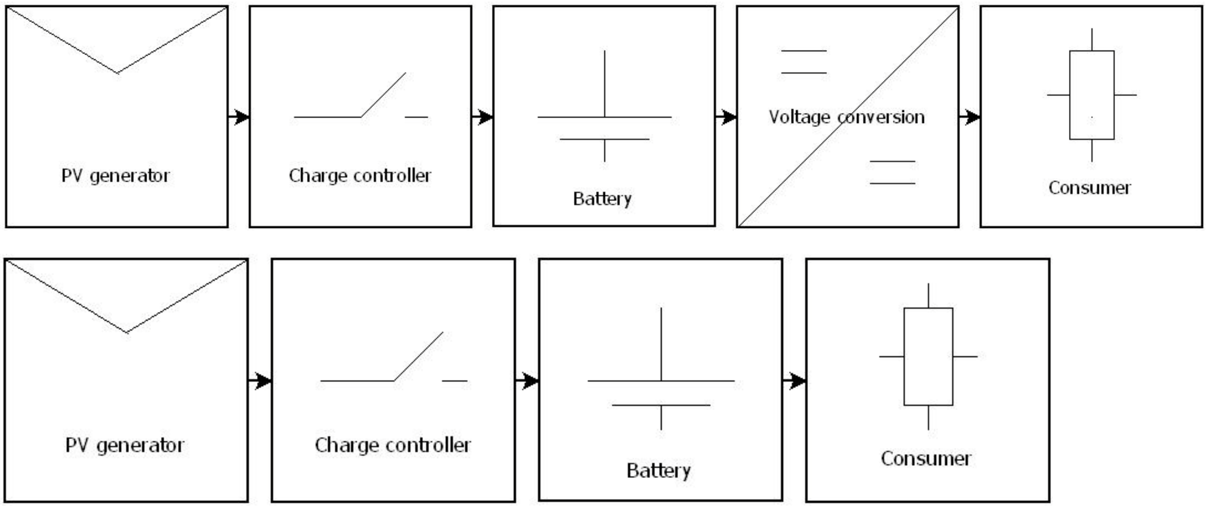

Figure 1: Schema of an off-grid PV system without and with voltage conversion

In most cases, stand-alone PV systems include the following basic modules (International Energy Agency, 2010):

- A Photovoltaic generator with its support structure (a single module or several modules),
- A Power conditioning equipment (Including inverters and control and protection equipment),
- Power storage (usually provided by batteries),
- Cables,
- A load (e.g. lights, pumps, refrigerators, radio, television), and
- Batteries: In order to ensure the supply of the stand-alone system with electric power also in the times without radiation (at night) or with very low radiation (in case of strong cloud cover), stand-alone systems mostly have an integrated storage system. Batteries are the weakest component of the whole

system, as they usually last between one and five years. A controller or charge regulator is needed for the battery (Goetzberger and Hoffmann, 2005).

In order to cover basic needs such as lighting and communication and information technologies a household needs to be equipped with the following modules (Kaltschmitt et al., 2007):

1. A 40 to 70 W solar module,
2. A 12 V lead-acid battery of an approximate capacity of 60 to 120 Ah, and
3. A charge controller.

The devices used need to fulfil the following characteristics: long lifetime, high efficiency, high reliability, correct operation even at extreme temperatures, sound operation for all possible input voltages offered by battery operation and low maintenance and service requirements (Goetzberger and Hoffmann, 2005).

The modules can be operated for about twenty years and they only require cleaning from dirt or dust deposits from time to time. Most of the other parts can be used for about ten years requiring only simple maintenance measures. However, batteries need to be replaced every five years. It is very important to ensure that all components, especially batteries are of good quality. Most problems with PV systems are not due to a malfunctioning of the PV module but due to bad system design or other parts which are not working (International Energy Agency, 2010).

In order to reach the best possible performance of the system the training of the user is very important. Otherwise serious problems can occur. For instance, the user of the system decides to purchase further devices. As a result, the system can not meet the increase in demand of all the appliances at the same time. In order to avoid the problem, the owner may interfere with the charge controller, so that batteries can be completely discharged. In the long run this action can fatally decrease the lifetime of the battery (Goetzberger and Hoffmann, 2005).

Stand-alone PV systems can have powers ranging from milliwatts to kilowatts. The output power is the product of operating current and voltage. In order to increase the overall output voltage, modules need to be wired together serially or when the aim is to increase the overall output current, they need to be put together in parallel to match the voltage and power required by the load application. The peak power rating (Wp) is measured under standard tests conditions which amounts to 1,000 W/m^2 and 25 degrees Celsius. The 1,000 W/m^2 corresponds to the solar irradiation in the tropics at noon. For lower irradiation levels and/or higher temperatures, PV modules generate less power than the peak power rating. The best conditions are cloudless, cold, long sunny days (Goetzberger and Hoffmann, 2005).

2.1.1.2. Grid extension

The following section describes in what way a national grid is constructed and what parts are needed for grid extension. Finally, the latest grid extension project in Kenya is portrayed.

An electricity supply system consists of two parts. Firstly, the mega-voltage (MV) distribution line from the supply point to the load centre and the distribution transformers at this load centre. Secondly, the low-voltage (LV) distribution system, which supplies consumers within a load centre (United Nations Development Programme and World Bank, 2000). At the substation, high voltage power is stepped down to medium voltage, which means less than 50 kV. Through medium voltage lines the electricity penetrates the distribution to commercial or other bulk users, and through medium-to-low voltage transformers (< 1 kV, often pole-mounted) it is transferred to households (Deichmann et al., 2010). Distribution voltages are between 100 V and 1,000 V for secondary distribution and between 10 kV to 35 kV for primary distribution. Every distribution system consists of poles, wires, and transformers (Energy Sector Management Assistance Program, 2007).

In order to extend the grid one needs the infrastructure. This enables the transmission of power at a medium voltage from the supply basis, which can either be the national grid or an isolated power plant to demand location centres where it is accessible at low voltage (United Nations Development Programme and World Bank, 2000). “The design of a transmission and distribution grid is essentially a network optimization problem in which the total length (and thus cost) of transmission links is minimized” (Parshall et al., 2009).

Grid equipment needs to be maintained on a regular basis. Apart from maintenance works, reparation becomes necessary in case of damages due to storms or accidents. On an annual basis, operation and maintenance account for approximately 1/8 to 1/30 of capital costs (Willis and Scott, 2000).

In order to calculate depreciation, one assumes a lifetime of the grid between 20 and 30 years. However, when maintenance and reparation is carried out on a regular basis and depending on the equipment-type, construction and operating conditions, including temperature, humidity and exposure to corrosives, the grid can function for more 50 years (Energy Sector Management Assistance Program, 2007). Electricity losses can be between 10% and 25%. Lower distribution voltages are responsible for higher current flows, which makes the distribution system less efficient (Energy Sector Management Assistance Program, 2007). According to the Overseas Japan Electric Power Investigation Committee (2000), the power delivery loss rates in Kenya amounted to 16.2% in 1997. In the Kenyan Renewable Energy Master Plan of 1997 the following loss factors are stated: 0.34% for a 55 km line with 132 kV (50 MW capacity) between Mombassa and Kilifi and 6% for a 495 km 132 kV line between Nairobi and Mombassa (50 MW capacity) (Ministry of Energy et al., 2009).

The latest electricity infrastructure development in Kenya is the Mombasa-Nairobi Transmission Line Project. It serves as a reference for future projects and also as a guideline for the model developed in this thesis especially concerning grid extension costs.

The planned 450 km line from Mombasa to Nairobi will pass through six districts including Machakos, Kajiado, Makueni, Taita Taveta, Kwale and Kilifi. This project is financed by the ADF (African Development Fund), AFD (African Development Fund), EIB (European Investment Bank) and GoK (Government of Kenya). It includes the construction of the following double-circuit transmission lines:

1. The construction of a 450 km 400 kV transmission line connecting Rabai and Isinya.
2. The construction of a 19 km 220 kV overhead transmission line connecting Isinya and Embakasi.

3. The construction of a 4 km 220 kV underground transmission line connecting Isinya and Embakasi.

In the planning phase of the project the subsequent alternatives have been taken into consideration and have been declined for the following reasons. Firstly, it was suggested to construct a 330 kV transmission line from Mombasa to Nairobi instead of the 400 kV line. This proposal was declined because the 330 kV possesses a lower transfer capacity and shows higher system losses compared to the 400 kV line. It was argued that the 400 kV lines are used on a global scale combined with 220 kV lines. This results in lower costs for the technology. Furthermore, the planned interconnections between Kenya and Tanzania will be 400 kV lines and will end at Isinya substation. Therefore, it will be advantageous if the substation at Isinya is at 400 kV. The second proposal was to construct a 220 kV transmission line for the connection of Mombasa with Nairobi instead of the 400 kV line. However, the amount of power which would have been possible to carry with a 220 kV would not have been satisfactory to deliver the planned power from Mombasa (African Development Fund, 2008).

2.1.1.3. Costs of photovoltaic systems and grid extension

The costs of a PV system are composed of the following components (International Energy Agency and Renewable Energy and Efficiency Partnership, 2008):

1. Planning and project development,
2. Capacity building and training,
3. Capital costs (hardware and equipment),
4. Transportation and installation,
5. Operating and maintenance, replacement component costs (e.g. batteries), and
6. Monitoring and evaluation costs.

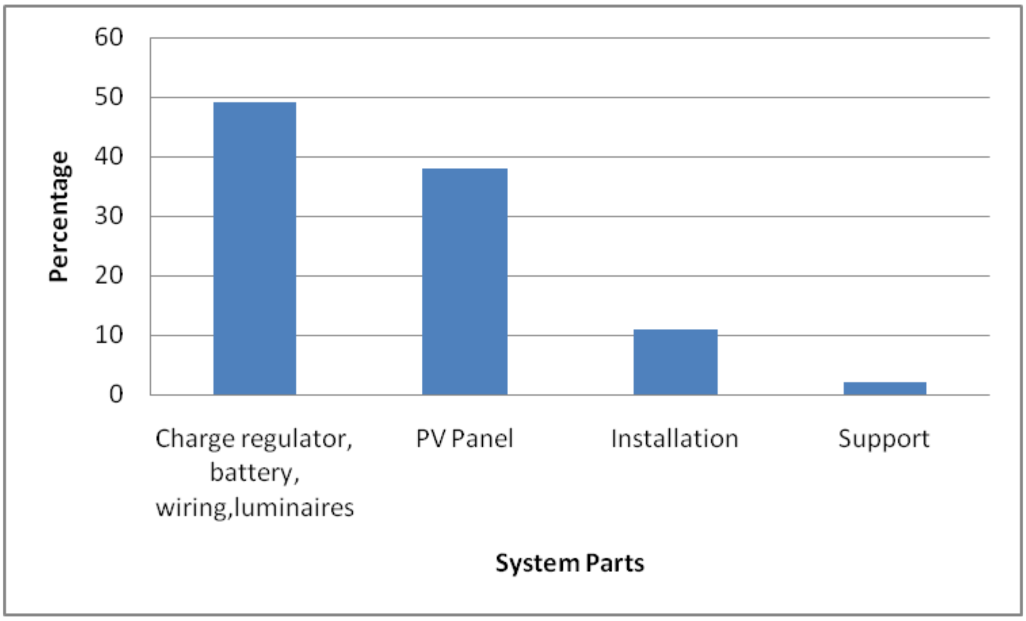

Figure 2: Share of costs for a solar home system (Source: International Energy Agency, 2003)

The costs of a PV system depend on the size and number of components, the number of systems purchased (volume discount), the level of competition in the local market, duties and taxes, subsidies available in the installation market, project planning and marketing needs and financing costs such as interest and fees. For solar home systems the costs are composed of the following components: Charge regulator, battery, wiring, lighting costs, PV panel costs, installation costs, and support costs. The costs for the charge regulator, battery, wiring, and lighting already account for half of the total costs. Panel costs are responsible for 38% of the total costs, whereas installation and support costs account for 13% of the total systems costs (see Figure 2) (International Energy Agency, 2003).

The price of a solar power installation is significantly based on the size of the whole system. A system only used for lighting, which powers two or three fluorescent tubes needs about 50 W. This kind of installation would cost around USD 500. A refrigerator used for cooling vaccines requires an array of around 200 W and amounts to about USD 5,000. The costs for PV systems often appear comparably elevated due to the high capital costs. Yet, when comparing life cycle costs, PV systems can become more favorable compared to alternatives with lower investment costs but high operating costs (International Energy Agency, 2010). Other sources speak of costs for solar home systems depending on the local market size, the share of imported components and governmental policy, between USD 500 and USD 1,500 per system. Life cycle cost analyses generally project that this type of system will produce power at USD 0.30 to 0.50 per kWh (Goetzberger and Hoffmann, 2005). In a study of the Columbia Earth Institute, which was also used for the development of the "Rural Electrification Master Plan", the following costs are given. The smallest panel is designed for 50 Wp. This costs USD 150 for the panel and the fixing, USD 150 for the batteries and USD 150 for the regulator, lamps and accessories. For a 1 kWp system costs amount to USD 6,000 for the panel and fixing, USD 3,000 for the batteries and USD 3,000 for the regulator, lamps and accessories (Columbia Earth Institute, 2007). The PV system has recurring costs due to the replacement of batteries (Kohle et al., 2002). These costs amount to 5% of the initial investment. The lifetimes are assumed to be 20 years for the panels, three years for the batteries and ten years for the balance of the system (Columbia Earth Institute, 2007). The balance consists of structures for mounting the PV arrays or modules and power-conditioning equipment that adjusts and converts the DC electricity to AC electricity (U.S. Department of Energy, s.a.). Leading solar photovoltaic module producers offer the following average prices not including freight and transport costs for a PV system which supplies a Kenyan household with 60 kWh of electricity per month. Solar modules cost around USD 250, a battery approximately USD 250 and a charge controller around USD 100.

In the following section costs for the extension of the national grid are discussed, therefore different sources are compared.
The costs for the building of electricity infrastructure consist of generation costs, transmission costs (from the power plant up to 33 kV lines, or in some countries 11 or 66 kV) and distribution costs (downstream from 11 to 440 V) (Victor and Heller, 2006; World Bank, 2002; Rufin et al., 2003). In rural areas the costs for energy infrastructure are higher. In Africa, a large proportion of its inhabitants live in rural areas such that the supply of electricity to its population is further decelerated (Haanyika, 2006).
The costs for grid extension used in the model are derived from the Mombassa-Nairobi transmission line project. The total costs of the project without tax duties and interest; however including physical contingencies (10%) and price contingencies

(5% per annum for foreign exchange cost and 10% per annum for local costs) is estimated to amount to approximately UA 183.83 million. These costs are composed of foreign exchange costs of UA 154.86 million and local costs of UA 28.97 million. The costs for the construction of the transmission line system itself is made up of the 440 kV transmission line and the 220 kV transmission line comprising of overhead and underground cables: The costs for the 440 kV transmission line are UA 124.9, which is composed of 90% foreign costs. 80% of the expenses for the 220 kV line are foreign costs and amount to approximately about UA 8.67 million (African Development Fund, 2008). This amounts to USD 413,000 per kilometer

In a World Bank study the costs for transmission lines were collected. The authors concluded that the costs of labor and materials for the construction of a three-phase line vary between USD 8,000 to USD 10,000 per kilometer. The cost of materials already amount to USD 7,000 with the cost of poles accounting for about 40% of the materials costs. The second most costly component is the conductors (wire and cables). However, the costs depend on the load being served and the voltage used. One can save 30% to 40% of the costs when using a single-phase construction. Annually, operating costs of the transformers can outweigh capital costs. As smaller transformers are often not available, the use of extra-large transformers can increase the costs per user when electrifying small rural populations. The study gives the following options to decrease costs for grid extension (United Nations Development Programme and World Bank, 2000):

1. Use of higher voltage.
2. Use of higher quality poles to reduce life-cycle costs.
3. Wider use of single-phase distribution.
4. Considering the life-cycle costs of transformers rather than simply the initial capital cost.
5. Properly sizing and placing transformers.
6. Considering alternative pole designs.
7. Standardizing materials and designs.
8. Implementing quality assurance programs.
9. Developing manuals and specifications for staking and design.
10. Using small transformers to serve small load centres adjacent to MV lines.

When implementing these recommendations, the cost of a three-phase construction (including both materials and labor) over normal topography in developing countries can decrease from USD 8,000 to USD 5,000 per kilometer. This does not include site-specific import duties and transportation costs. Furthermore, the construction of single-phase distribution line can be reduced to USD 4,000 per kilometer. However in countries with expensive labor, the costs are increased by up to USD 2,000.

In another study, the financial costs of providing centralized PV are compared with the cost of grid extension for a remote village in Nigeria. The costs for a 185 mm^2 high tension 33 kV cable are assumed to amount to USD10,300 per kilometer. Costs for the cable account for 90% of the component costs and cost of transportation and installation represent 20% of the materials cost. 1% of the capital costs have to be foreseen for maintenance activities (Oparaku, 2002).

A study by the World Bank on the technical and economic assessment of grid, mini-grid and off-grid electrification technologies divides the costs into distribution and transmission system costs and applies them to the case of India. The result is that a high voltage (33 kV-11 kV) distribution line costs around USD 5,000 per kilometer and a low voltage (230 V) line approximately USD 3,500 per kilometer. The costs for the transformer amount to USD 3,500 per kilometer. Circuit-kilometer of distribution conductor and the rated output of the generation source determine the capital costs for the distribution system. A power output smaller than 60 kW requires only a low voltage distribution network.

In a further step, distribution capital costs are levelized. Operation and maintenance costs are 2% of the initial capital cost annually. Both can be expressed on a per circuit-kilometer basis. The levelized capital costs for a high voltage line amount to USD 535 per kilometer and year and operation and maintenance cost amount to USD 100 per kilometer and year. For low voltage lines levelized capital costs add up to 376 USD per kilometer and year and operation and maintenance cost to USD 70. The levelized costs for a transformer are calculated as USD 375 per unit and year with additional operation and maintenance costs of USD 70 per unit and year.

Costs for the transmission line depend on the rated output of the power station. An output between five and ten MW requires a voltage line of 69 kV, whereas a generation plant of 30 to 50 MW needs a line of 138 kV and an output of 150 to 300 MW of 230 kV. Levelized capital costs of the 69 kV line amount to USD 3,015 per

kilometer and year and operation and maintenance costs to USD 845 per kilometer and year. The 138 kV line implies capital costs of USD 4,675 and operation and maintenance costs of USD 1,311 per kilometer and year. For an output of 150 MW, the capital costs of the 230 kV line amount to USD 11,578 and operation and maintenance costs to USD 3,246 per year, compared to capital and O&M costs of USD 16,259 and USD 4,559 per kilometer and year respectively for an output of 300 MW (Energy Sector Management Assistance Program, 2007).
Tab. 1 summarizes the previous section by showing the per-kilometer costs of grid extension and line type according to the studies discussed.

Table 1: Costs per kilometre of grid in USD according to different studies and type of line

Study	**Two-phase line**	**Three-phase line**	**230V**	**11kV-33kV**	**33kV**	**69kV**	**138kV**	**220kV**	**230kV**
African Development Fund, 2008								413,000	
Energy Sector Management Assistance Program, 2007			3,500	5,000					
Oparaku, 2002					10,300				
United Nations Development Programme & World Bank, 2000	4,000	5,000-10,0000							
World Bank, 2002						28,177	43,687-78,036		108,205-151,956

In order to calculate the percentage of distribution losses, the average percentage of transmission and distribution loss is multiplied with the distribution loss rate. This results in a loss of electricity of 12%. Transmission losses are incorporated by decreasing the net power delivery depending on the generation type in accordance with the circuit-kilometer associated with each type of power generation (Energy Sector Management Assistance Program, 2007).

When calculating the costs of grid extension in rural areas one needs to take into consideration the relationship between network expansion cost and penetration rate. One assumes that marginal costs increase significantly when connecting the last few households. A study on the impacts of geography on energy infrastructure costs conducted by Zvoleff et al. (2009) confirmed this assumption. However, the effect is negligible when the settlement pattern is nearly homogeneous.

Yet connection costs do not monotonically increase with penetration rate. It is argued that energy planners should optimize local penetration rates in order to guarantee cost-effectiveness of the national grid. This means “ensuring full penetration in those areas where it is optimal, while reducing unnecessary costs in areas where it is not” (Zvoleff et al., 2009).

The cost elasticity in connection with population density is negative. Average distribution costs decrease for densely populated areas. A study assessing the Slovenian electricity distribution system concluded that if customer density increases by 1%, costs will drop by about 0.60% (Filippini et al., 2004).

2.1.2. Electrification in Kenya

In Kenya, like in most Sub-Saharan African countries, the majority of people do not have access to modern energy sources. On average in Sub-Saharan Africa (SSA) only 23% of the population has access to modern forms of energy. The situation worsens still when looking at rural areas. The percentage of electrified people in rural areas amounts to only 8%, compared to 51% in urban areas (International Energy Agency, 2002). The rate of electrification in Kenya is even lower. In total 14% of Kenyan inhabitants are connected to the grid. This figure can be divided into 42% in urban and 4% in rural areas (Kenya National Bureau of Statistics, 2000).

Figure 3 shows that in Kenya the main sources of energy are traditional fuels. For cooking, firewood is still the principal resource. On average, 68.3% of the households use firewood for cooking. In rural areas, 80% of all households use firewood for cooking compared to only 10% in urban areas. Charcoal is the second most important fuel for cooking; however it is often not replaced but added to the use of firewood. The third fuel used for cooking is paraffin followed by gas LPG. The last two sources are primarily utilized in urban areas. When looking solely at urban areas the most important source of cooking fuel is paraffin, followed by charcoal, gas and only on the fourth rank firewood can be found (Kenyan National Bureau of Statistics, 2007).

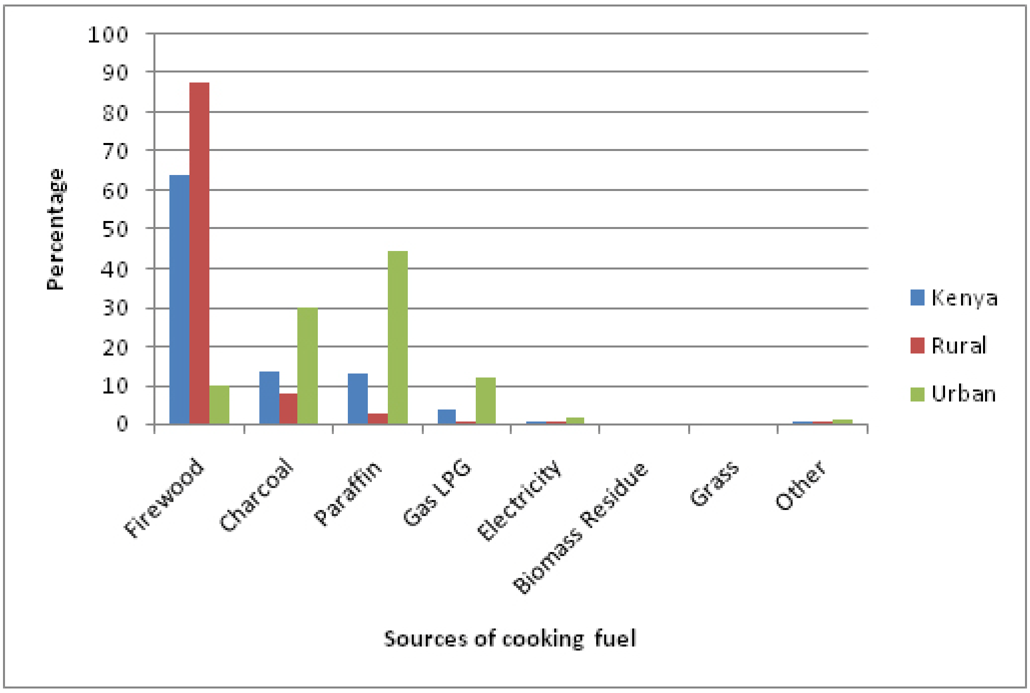

Figure 3: Sources of cooking fuel in Kenya (Source: Kenyan National Bureau of Statistics, 2007)

As can be seen in Figure 4, for lighting, paraffin lamps are used in 76.4% of the households. Electricity represents the second most common source of lighting with 15.6%. Differences between urban and rural areas are significant. In rural areas, paraffin accounts for 86.4% and electricity for 3.9% of the fuel choice. In rural areas however electricity is the main source of energy used for lighting accounting for 51% and paraffin for 46.3% (Kenyan National Bureau of Statistics, 2007).

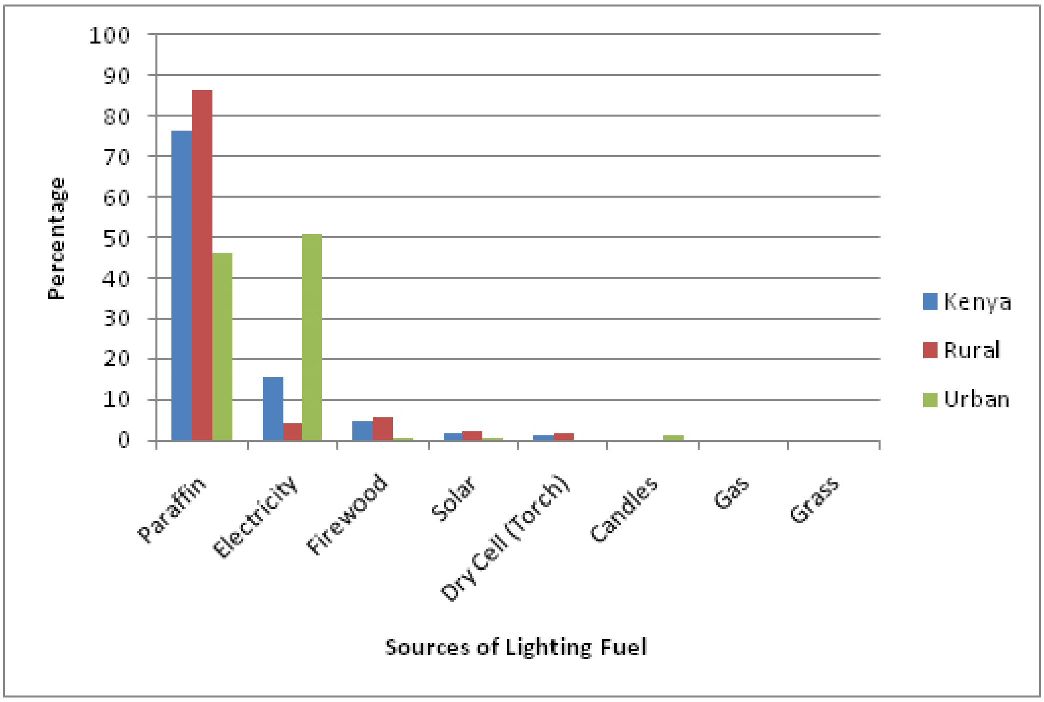

Figure 4: Sources of lighting fuel in Kenya (Source: Kenyan National Bureau of Statistics, 2007)

Challenges facing the power sector are a low per capita consumption (less than 160 kWh) and a low access rate. Furthermore a weak transmission and distribution infrastructure is responsible for high system losses of about 16.5% and a poor quality of supply characterised through intermittency, blackouts and brownouts. Generation projects feature very long lead times. When looking at reasons for the current power crisis in Kenya, history was marked by least cost power planning and very long delays in completion of committed projects (Imitira, 2009). Reasons for the low electrification rate are the lack of finance to cover capital and operating costs for generation, transmission and distribution of electricity, which is very high for rural areas. Moreover incentives to invest into rural areas are rather low caused by high connection and low electricity consumption and income (Abdullaha and Markandya, 2009).

Electricity in Kenya is supplied by the Kenyan Power and Lighting Company. According to the Kenyan government the total installed capacity amounts to 1,357 MW of which 146 MW is emergency power (Kiva, 2009). Firewood and charcoal are the most important energy sources for Kenya and account for 68% of the national energy supply (Energy, Environment and Development Network for Africa and Heinrich Boll foundation, 2009). In 2000 the biomass demand in Kenya amounted to 34.3 million tonnes. However the amount of sustainable supply of forest biomass was 15 million tonnes, a loss of 19.3 million tonnes for that year. The rapidly growing demand has led to extensive deforestation, de-vegetation and land degradation (United Nations Development Programme, s.a.b).

Figure 5 demonstrates the share of energy sources used in Kenya for electricity supply. Nearly all of it is supplied domestically. About half of the supply is generated by hydropower, about one third by oil and one sixth by geothermics.

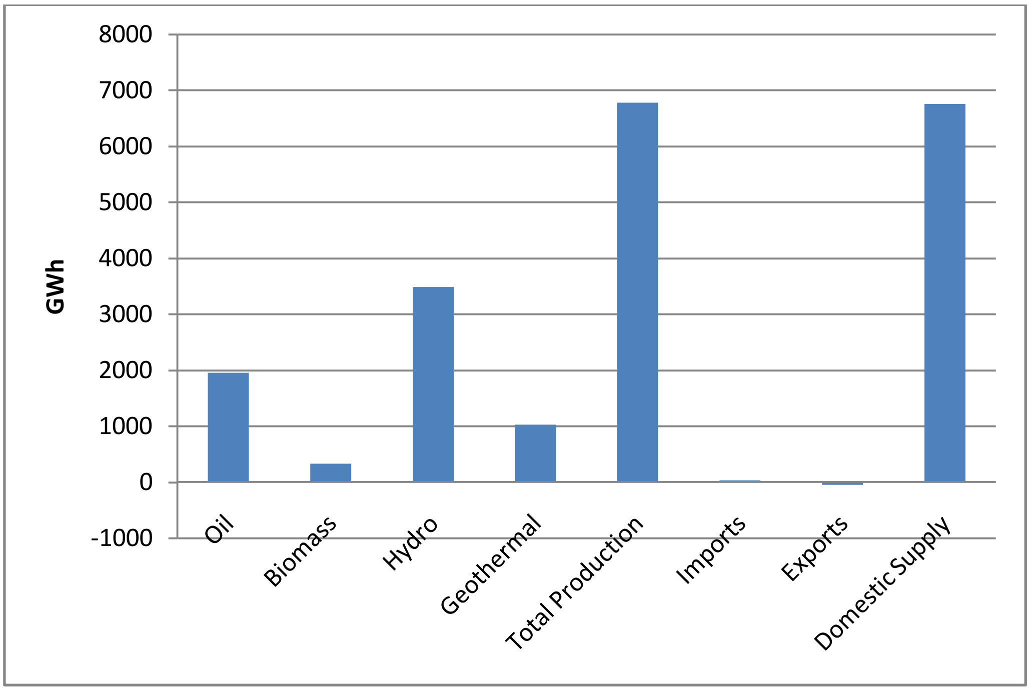

Figure 5: Electricity in Kenya in 2007, (Source: IEA, s.a.)

Figure 6 illustrates that electricity generation has strongly increased since the 1970s. The generation from hydropower has continuously increased, compared to the use of oil which decreased until the mid-90s and since then increased considerably. Combustion of biomass stagnated, whereas the generation of electricity from geothermal, solar and wind energies started in the mid-80s and has slowly increased since.

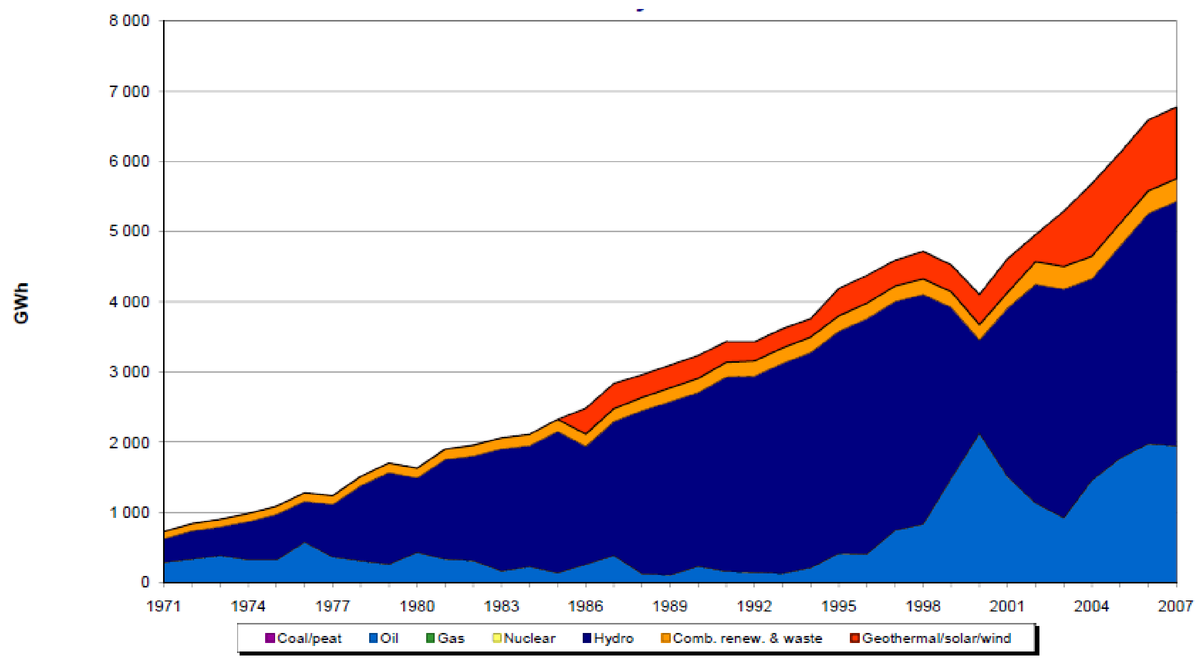

Figure 6: Development of electricity generation by fuel from 1971 to 2007 in Kenya, (Source: Organisation for Economic Co-operation and Development and International Energy Agency, 2009)

During average rainfall more than 53% of the electricity is generated from hydropower. The drought of the year 2009 led to a severe decrease in water levels. One of the hydropower plants in Masinga, with a capacity of 40 MW, had to be closed and all the others operated below their maximum capacity. As a result this disequilibrium was matched by importing 146 MW of expensive emergency power (Kiya, 2009). In 2006, the emergency capacity of Kenya amounted to 100 MW, which equalled about 8.3% of the total installed capacity. The costs associated with the emergency power amounted to about 1.45% of the GDP (Eberhard et al., 2008). The power crisis during the last year resulted in poor, unreliable and costly electricity supply. Power shortages affect especially low income users such as the informal sector manufacturers, small-scale farmers, and rural and semi-urban service institutions like schools and health clinics. In addition regular voltage fluctuations which are a result of rationalizations can break small electronic devices (Energy, Environment and Development Network for Africa and Heinrich Boll Foundation, 2009).

According to the Kenyan Power and Lighting Company (KPLC), total maximum demand in Kenya amounted to 1,070 MW in 2008/09. In 2008/09 KPLC sales to domestic costumers represent 1,254 GWh, to small commercial 823 GWh and 3,020

GWh to commercial and industrial customers. In total 5,432 GWh have been sold in 2008/09 (Kenya Power & Lighting Company, 2009).

2.1.2.1. Renewable energies

The potential for renewable energies in Kenya is very high.
Kenya features high irradiation values (between 4,600 and 6,500 Wh/m^2/day). Moreover, it has an average of five peak sunshine hours. These are very good conditions for the implementation of photovoltaic technologies. Kenya has one of the most advanced and growing PV markets in the developing world with a growth rate of 170% in 8 years even with government intervention or policies. Today the installed capacity amounts to 4 MW and around 200,000 rural households have their own solar system. Every year between 25,000-30,000 PV modules are sold on the Kenyan market. At present grid connected PV systems are of the size of 15 to 20 km^2 (Deutsche Gesellschaft für Technische Zusammenarbeit, 2010).
Throughout the country wind speeds of three to ten meters per seconds have been measured. The installed capacity however, amounts to only 0.55 MW. The technical geothermal potential is around 3,000 MW, today of which 127 MW are used. Concerning biomass most of the potential lies in generating electricity from agricultural residues such as bagasse and rice husks. Today six Kenyan sugar factories use bagasse to generate electricity with a capacity of 38 MW (Energy, Environment and Development Network for Africa and Heinrich Boll Foundation, 2009). Renewable energies technologies need to be expanded in order to create a larger mix and reduce the dependence on hydropower. Geothermal, small hydro, biomass cogeneration and wind are widely available in Kenya and still under-exploited. Furthermore the implementation of renewable energies implies the creation of jobs in all educational levels ranging from manual labour to management level positions. Another positive impact is that manual and informal labour is created in rural areas (Energy, Environment and Development Network for Africa and Heinrich Boll Foundation, 2009).

The Renewable Energy Department which is part of the Ministry of Energy has been given the task to promote and develop renewable energy technologies and to formulate, review and analyse the renewable energy policy of Kenya (Energy, Environment and Development Network for Africa and Heinrich Boll Foundation, 2009).

2.1.2.2. Government program

The government stated its goal to work towards connecting at least one million more people to the grid by 2012. This will result in an increase of peak power demand from 1,188 MW to 1,838 MW (Kiva, 2009).

The Kenyan Power and Lighting Company (KPLC) is a limited liability company which is responsible for the transmission, distribution and retail of electricity in Kenya. KPLC is a public company and the majority shareholder in KPLC is the Government of Kenya and its institutions (Kenya Power & Lighting Company, s.a.). To avoid future power crises the government intends to increase the reserve margin to 30% by 2012. In order to achieve this target, the aim is to install generators in Embakassi and Naivasha with a generation capacity of 80 MW and 60 MW each. A second measure undertaken by the KLPC was the introduction of load management. This action was launched in August 2009 and entails power interruption for three alternate days in a week, from 6 am to 6.30 pm. Furthermore the government launched a task force on accelerated development of green energy. The aim is to generate an additional 2,000 MW of green electricity by June 2012. Another measure by the government is to decrease the energy peak demand by 49 MW, through the distribution of 250,000 energy saving lamps (Kiva, 2009).

A key player in the energy system of Kenya is the Ministry of Energy. Its role is to be in charge of energy planning by developing strategic 5-year plans (Energy, Environment and Development Network for Africa and Heinrich Boll Foundation, 2009). The 51% government owned Kenya Power and Lighting Company (KPLC) is responsible for electricity transmission, distribution and sale. Two thirds of electricity is generated by the state owned Kenyan Electricity Generating Company (KenGen). Due to the liberalisation of the oil market in 1994, a mix of state-owned and private companies is active in the petroleum sector. The Energy Act of 2006, which was assented into law on the 30th of December 2006, established the Energy Regulatory Commission. The Commission's goal is to regulate the energy sector. Through it, the Minister of Energy is empowered to promote renewable energies (Energy, Environment and Development Network for Africa and Heinrich Boll

Foundation, 2009). The Energy Act awarded the mandate to the Rural Electrification Authority to develop and update the rural electrification master plan and promote the use of renewable energy sources (Energy, Environment and Development Network for Africa and Heinrich Boll Foundation, 2009).

The Rural Electrification Master Plan (REM) became effective in August 2009. In it, it is stated that the target electrification rate for rural households is set at 20% by 2010 and 40% by 2020. This translates into 650,000 new grid and off-grid connections in rural areas between 2008 and 2013 (i.e. 130,000 per year) and 850,000 connections from 2014 to 2018. The major focus of the rural electrification master plan is to electrify all target loads (district headquarters, trading centres, secondary schools and health centres, etc.) by 2012/2013. Today about 6,000 of the target loads do not have access to electricity. Furthermore through the connection of the target loads about 850,000 households will be automatically electrified.
The plan distinguishes between the following three types of rural electrification projects (Ministry of Energy et al., 2009):

1. National grid extension projects (at constituency level), schemes (connecting localities along one MV line) and subprojects (at locality level, most frequently trading centres and sometimes stand-alone load centres).
2. National grid densification projects (at constituency level), requiring transformers (as far as necessary) and service drop line.
3. Projects off the national grid which can either be electrified through regional grids supplying small to large-sized areas or through local supply of single trading centres / stand-alone landmark loads.

In the Rural Electrification Master Plan (REM) it is stated that on average it costs USD 1,100 to connect a household to the grid. However, this does not include cost for equipment inside connected loads and cost for transmission system upgrades. The government aims that at the end of the 5-year Action Plan the rural load will amount to 735 GWh. This means that 8.5% of the electricity demand on the rural grid results from the demand of rural households. In other words the effect of the REM is rather small compared to the fact that there is a strong increase in demand in urban areas from people which are not connected to the grid today.

The REM includes the following projects (Ministry of Energy et al., 2009):

1. Off-grid projects:
   The investment costs for off-grid projects in remote rural areas will amount to about USD 150 million. The off-grid projects will result in about 63,000 connections until 2018. About half of these households will be eligible for the social tariff. This tariff is set at KSh 14per kWh.
2. Grid extension RE projects:
   The investment of grid extension projects amounts to about USD 429 million, which will result in the connection of about 341,000 households until 2018. About 37% of households will be entitled to obtain the social tariff.
3. Grid densification RE projects:
   The investment into grid densification projects amounts to about USD 193 million. This investment will allow the connection of 240,000 households until 2018. Out of these 240,000 connections, 34% are eligible for the social tariff.

In the Kenyan Rural Electrification Master Plan it is stated that for rural areas where solar resources are abundant, solar technologies represent the cheapest option and are particularly well suited for hybrid applications. For example for North-Eastern districts, PV-diesel hybrid schemes will represent the best option for a decentralised grid or mini-grid (e.g. in North-Eastern Province). For towns in districts located in the North-West, Northern and North-East and along the coast, the supply with fuel represents a major challenge. This problem further deteriorates during the rainy season.

Therefore for remote areas and for small stand-alone loads, stand-alone PV systems have two advantages over grid extension. Firstly, they represent the least cost option and secondly they can be used as a pre-electrification solution (Ministry of Energy et al., 2009).

2.1.2.3. Electricity price

The Kenyan current energy supply is largely based on hydropower. A long drought in 2009 has led to a constant increase in electricity price and rationalization of electricity supply. The media stated that prices have increased by 60% within 10 months (Shah, 2010).

Figure 7 shows that the highest price increase took place between March 2009 and November 2009. In this period the price rose from 14.7 KES per kWh to 19.5 KES per kWh, which translates to an increase of 33%. However when looking at the entire year of 2009 the price rose by 28%. From October 2009 until January 2010 this was "only" 6%.

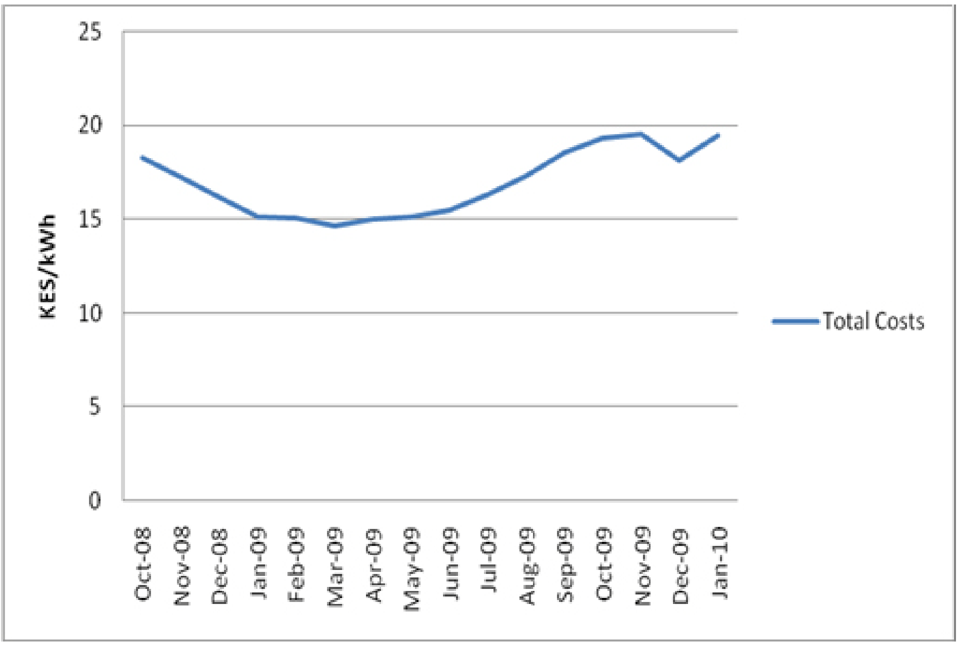

Figure 7: Trend of the electricity price from October 2008 until January 2010 in KSh (Source: Shah, 2010)

One can therefore assume that media reports only took into consideration the increase of the fuel cost charge as it shown in Figure 8 (Shah, 2010).

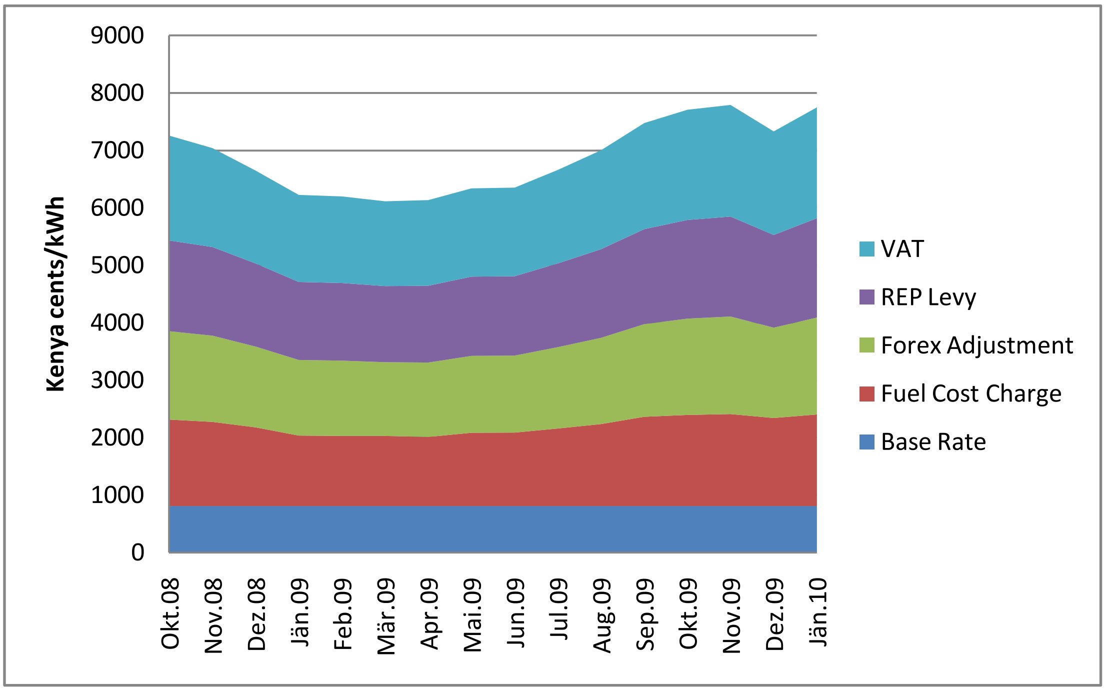

Figure 8: Composition of the electricity price from October 2008 until January 2010 in Kenyan Cents (Source: Shah, 2010)

2.1.3. Energy demand of not electrified households

In Kenya the average electricity consumption per month amounts to 189 kWh per electrified household. However this depends largely on the district and on the number of people living in the households. The average consumption per household is between 78 kWh in Central Kenya and 450 kWh in the North-East region. Before the price increase the average monthly electricity costs amounted to KSh 2,028. However costs per region and household vary strongly. They range from KSh 556 per household and month in Western Kenya and KSh 4,355 per household and month in North-West of Kenya (Ministry of Energy et al., 2009).

The International Energy Agency states that low income households mainly use biomass, batteries and candles for cooking, heating and lighting. Besides biomass, middle income households can afford kerosene and LPG (liquefied petroleum gas) for cooking. For heating they do not rely only on biomass but also use coal. Lighting may be provided by biomass, kerosene, or electricity. Apart from cooking, heating and lighting they may also make use of water pumps through diesel and electricity. Furthermore, middle income households use refrigerators with batteries, basic appliances functioned by electricity batteries or oil and lastly transport operated by oil (International Energy Agency, 2002).

In order for poor households to invest in appliances which are run by electricity and result in an increase of demand, poor households need to gain confidence that

- Prices do not increase over a longer period of time, and
- Electricity supply is sustained.

The World Bank states that the transition from traditional energy forms such as the use of biomass to modern energy is not a straight process and not only based on the possibility of electrical services. Poor households use electricity mainly for lighting and communication devices and continue to use wood, dung, fossil-fuels like liquefied petroleum gas (LPG) and kerosene for cooking and heating.

According to the World Bank the transition process is determined by availability and affordability (International Energy Agency, 2002)

- Availability: If no grid or other distribution system is in place households cannot access electricity even if they would be able to afford it.
- Affordability: Affordability can be overruled,
    - In case traditional energy forms such as biomass are free or cheaper, a change to modern energy forms will only very slowly take place.
    - The initial costs of appliances discourage households from switching away from biomass.
    - Cultural preferences: in some cases traditions and not income or availability determine the choice of fuel.

The government of South Africa launched an electrification program. In rural areas, the program was based on a combination of grid, mini-grid and off-grid connections. As a result of this program the government was expecting a constant increase in demand to 350 kWh per month for each connected household (Department of Minerals and Energy, 2001). However, for low income households the electricity demand remained below 50 kWh per month, compared to a nationwide average consumption of 132 kWh per month (Prasad, 2006).

A study by Howells (Howells et al., 2005) conducted in South Africa found that the demand for electricity was income inelastic. An increase in the price for paraffin only triggers small changes in the demand for electricity. This is largely due to the fact that appliances for the use of paraffin are already available in the households. The model further shows that low income households use electricity for appliances which are cheap to purchase and for which per unit electricity costs are low, such as lighting, ironing and entertainment. Moreover, the possibility to obtain credit also plays a significant role. Credits give households the chance to purchase electrical devices which newly electrified households would not be able to pay for at once. In the instance that costs for appliances are subsidised an increase in demand is most likely (Louw et. al., 2008). In Kenya, the monthly average electricity demand of existing electric devices in non-electrified households operated by own energy sources amounts to 28.7 kWh (Ministry of Kenya, 2009).

The South African government introduced a poverty reduction policy which will provide households with a monthly 50 kWh free basic electricity (FBE) subsidy (Howells et. al., 2005). About 50 kWh are an adequate amount of electricity provide access to basic lighting, a small black-and-white television, a small radio, basic ironing and boiling of water using an electric kettle. If energy efficient technologies, such as compact fluorescent lighting are used, 50 kWh can provide more services than the ones mentioned above. However, as already mentioned one needs to take into account that the initial costs of energy efficient technologies often exceed the households' possibilities (Department of Minerals and Energy, 2003). As traditional alternatives for cooking and heating such as coal and firewood are in most cases cheaper than electricity, electricity is often only used for television, lighting, electric irons, and a few other applications for which fuel substitutes are inferior or absent (Afrane-Okese, 1998). Therefore, purchase energy is at about 20 kWh per month (Williams et al., 1996). Howells et al. (2006) undertook a study which focuses on a shift of free electricity used for cooking. Cooking amounts to about 17 kWh of the 50k Wh. Cooking takes place in the afternoon when it is most expensive and the marginal costs of new service on the electric power system are high (Cowan, 2004). The study assumes a 70% probability that cooking takes place during peak periods and that cooking equipment is used on average on 50% of their rated full power. The study concludes that an electricity-only approach is not always the best as it may trigger power shortages on the national grid due to current peak reserve limits

(Howells et. al., 2006).
Another study reinforces the importance to simplify the access to electricity at the level of consumption in poor households. This can be ensured by decreasing the lifeline tariff consumption unit for poor households to 25 kWh or less. This group only consumes a very small amount of electricity; however they benefit most from changes in their possibilities of electricity consumption (Abdullaha and Markandya, 2009).
According to the Rural Electrification Master Plan domestic energy use is “defined as electricity consumption inside the home to power light bulbs, radios, TVs, etc.” The total domestic demand in a district is the sum of household demand and as a result correlates with the penetration rate. The penetration rate signifies the percentage of households which are connected to the electricity grid. The electricity demand of newly connected households is divided into four stages: Shortly after the household is connected to the electricity grid the electricity consumption remains very low. The demand in the first month after connection corresponds to the devices available in the households. During the first year the perception of needs governs the purchase of additional electronic devices. Therefore a higher perception translates in a higher multiplier. The growth rate between the first year and the adaption to average rural demand levels ranges between 5% and 10% per year. This can, however in poor areas only amount to between 2% and 3%. With time, energy demand will increase and meet the demand of rural household, which had already been connected. This process takes about ten years and can be seen as a multiplier of the demand of the first month (Ministry of Energy et al., 2009).

2.1.3.1. Willingness to pay

A study concluded that in Kenya the willingness and affordability of households to pay for improved electricity services is between USD 3 and USD 10 per kWh (Kammen and Kirubi, 2008). Another study conducted in the Kisumu district stated that the willingness to pay for photovoltaic systems is lower than for grid extension. However, in this case the households were located in close distance to a transformer and as a result grid extension seemed easily realizable (Abdullaha and Markandya, 2009). Another reason for a lower willingness to pay for solar PV is that people know that in comparisons to grid connection, PV systems often only offer limited supply (Abdullaha and Markandya, 2009). The study showed a high WTP for grid connections. It also applies to poor households who are willing to spend a large share of their income on grid electricity. However, in most of the cases, the difference between the willingness to pay and the total costs for grid electricity exceeds those of PV. Therefore, lower subsidies are required for off-grid PV options and it can be seen as the better option for market penetration (Abdullaha and Markandya, 2009).

In terms of payment the sampled population preferred monthly payments. However, the WTP of these monthly payments is still lower than actual connection costs. In order to overcome this problem it is essential to extend the period of monthly payments to at least ten years and at the same time reducing the interest rate to about 5% (Abdullaha and Markandya, 2009).

A socio-economic survey conducted by the government of Kenya revealed the amount of money households are maximum willing to pay for electricity connection:

- 9% of the households are maximum willing to pay KSh 32,500,
- 88% of the households are maximum willing to pay KSh 50,000,
- 3% of the households are maximum willing to pay KSh 75,000,
- 1% of the households are maximum willing to pay KSh 100,000.

However, the connection fee of KSh 32,500 which according to the survey 97% of the households are willing to pay is still not affordable to most of the households. On average, households are willing to pay KSh 720 per month for electricity services. This means consumptions of between 32 and 65 kWh per month depending on the electricity price. Contingent on the region, households are willing to pay 2% and 6% of the monthly income for electricity services. The avoided energy costs which are due to a switch to electricity from conventional types of energy amount to KSh 1,166 per month on average (Ministry of Energy et al., 2009).

2.2. Review of studies on grid-connected and stand-alone energy systems

Most of the studies focus on either assessing grid connected or stand-alone systems in a particular often isolated context. There are only a few studies which compare techno-economic-environmental feasibility of grid connected and stand-alone systems (Kaundinya et al., 2009). One exception is the study of Parshall et al. (2009), which develops a model for spatial national electricity planning in settings with low existing grid coverage with the objective of minimising costs. The model is in a further step applied to Kenya. In the model, the option of grid electrification is compared with off-grid solutions. More precisely, two off-grid possibilities are evaluated. Firstly, diesel mini-grids with low voltage distribution lines and medium-voltage lines, and secondly, stand-alone solar photovoltaic systems for households combined with a diesel generator in the market centre. Costs of grid extension are composed of the costs for the extension of the MV line from an existing distribution network to an MV to LV transformer. The second parts of the costs are those for connecting households and institutions which are located within the demand node. In demand nodes which are already equipped with an MV backbone, the option of extending the grid is less costly. Small demand nodes can be grouped together so that grid extension can become an option. The following two rules are determining:

1. Connect each non-connected demand node n if the distance between the node and the closest point on the grid g (part of the existing grid or a node just connected by the algorithm) is smaller than the maximum length of the MV backbone is cost-effective.

   $$distance_{n,g} \leq MV_{maxn}$$

2. For each newly connected group of nodes the maximum length of the adjusted MV backbone (for a demand group containing nodes i and j) is equal to the maximum length of the MV backbone of node i plus the maximum backbone of node j minus the distance between node i and node j.

   $$MV_{maxk} = MV_{maxi} + MV_{maxj} - distance_{i,j}$$

   MV_{maxk} is the adjusted MVmax value for a demand group containing nodes i and j.

Demand was divided into four demand categories which represent a combination of population density and wealth. The model simplifies the demand in representing households in demand nodes by using the smallest administrative units in the country. Model inputs include electricity demand, costs and geographic characteristics. The result of the model is that "under most geographic conditions, extension of the national grid is less costly than off-grid options". Another outcome of the study is that in most of the cases the penetration rate, which is exogenously chosen by planners, affects the average connection costs greater than inter-household distance, per-household demand, and closeness to the national grid. This finding can be translated into the policy recommendation to strengthen regional connection programs (Parshall et al., 2009).

3. Data and Methodology

In this chapter the input data and the model organisation is described, so that the results of the model can be reconstructed.

3.1. Data presentation

In the following part, all the input data which will be used in the model is explained: solar irradiation, electricity demand, stand-alone photovoltaic costs, grid-extension costs, photovoltaic efficiency, energy generation costs, distances between the districts, maximum solar panel area and maximum grid capacity.

The first data input described is the solar irradiation. The data for solar irradiation determines the output of energy to be harvested with the photovoltaic technology and consequential costs per kWh. Solar irradiation data has been collected by the Center for Energy and Processes (CEP) which is located in Sophia Antipolis, France. The data is available from 1985 to 2004 with a spatial resolution of 30 km^2. Solar irradiation is given in Watt hours per square meters per day. Seasonal variations in solar irradiation have an important effect on the suitability of stand-alone systems. In order to determine if seasonal differences in irradiation values are significant, weekly mean irradiation levels were calculated. It can be observed that the mean irradiation value of all districts is lowest around June and July.

When looking at the mean irradiation values the lowest value with 6,133 Wh/m^2 can be observed in week 24, whereas the highest value of 6,598 Wh/m^2 can be found in week five. The lowest value of the low curve is in week 30, amounting to 3,226 Wh/m^2. Its highest value is in week 8 amounting to 5,580 Wh/m^2. For the high curve the highest level of irradiation amounts to 7,285 Wh/m^2, the lowest is in week 24 adding up to 6,133 Wh/m^2 (see Figure 9).

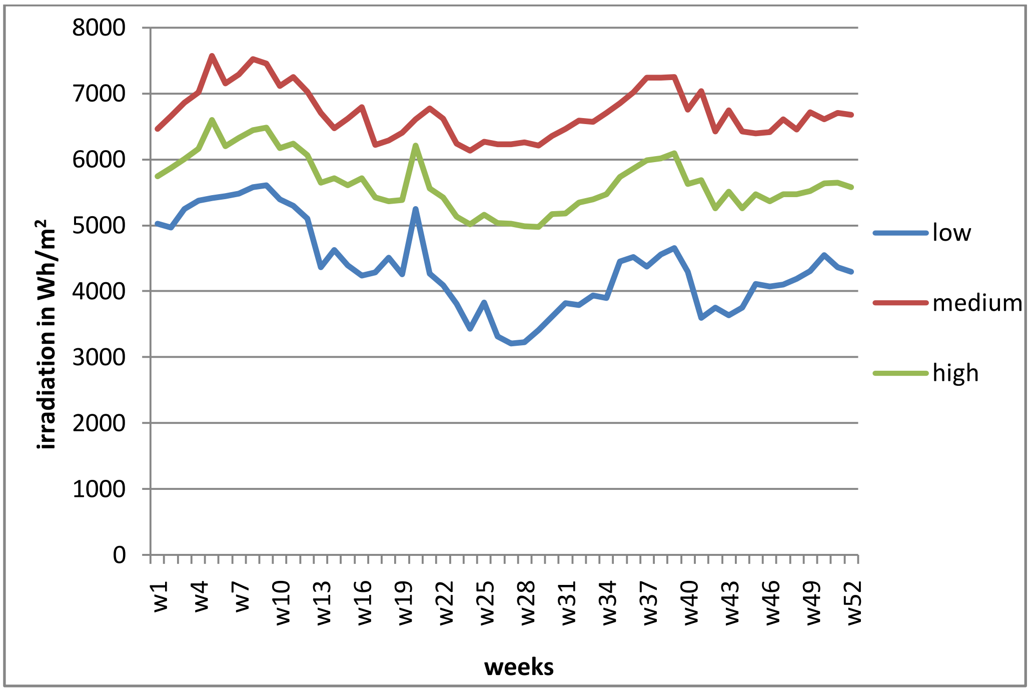

Figure 9: Seasonal change in irradiation as a mean of all districts in Wh/m^2

Differences in irradiation are the highest for the low values ranging from 3,000 Wh/m^2 to 5,500 Wh/m^2. The discrepancy for the high values lies within 1,000 Wh/m^2 ranging between 6,000 Wh/m^2 and slightly more than 7,000 Wh/m^2. (see Figure 10)

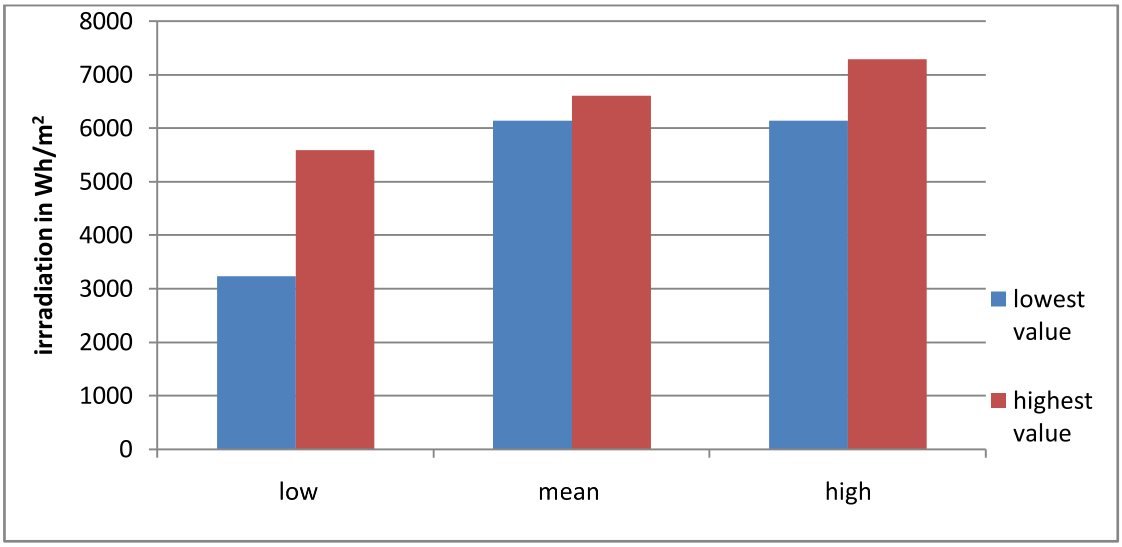

Figure 10: Lowest and highest annual mean irradiation value for low, mean and high data

In a next step the mean irradiation value for every district was calculated. In Figure 11 we can see the distribution of mean irradiation levels across Kenya. The district of Samburu with 6,447 Wh/m^2 features the highest mean irradiation level and Mandera with 4,870 Wh/m^2 the lowest level. This is a difference of more than 1,550 Wh/m^2 and could therefore disfavour in each case either the off-grid PV or grid extension option.

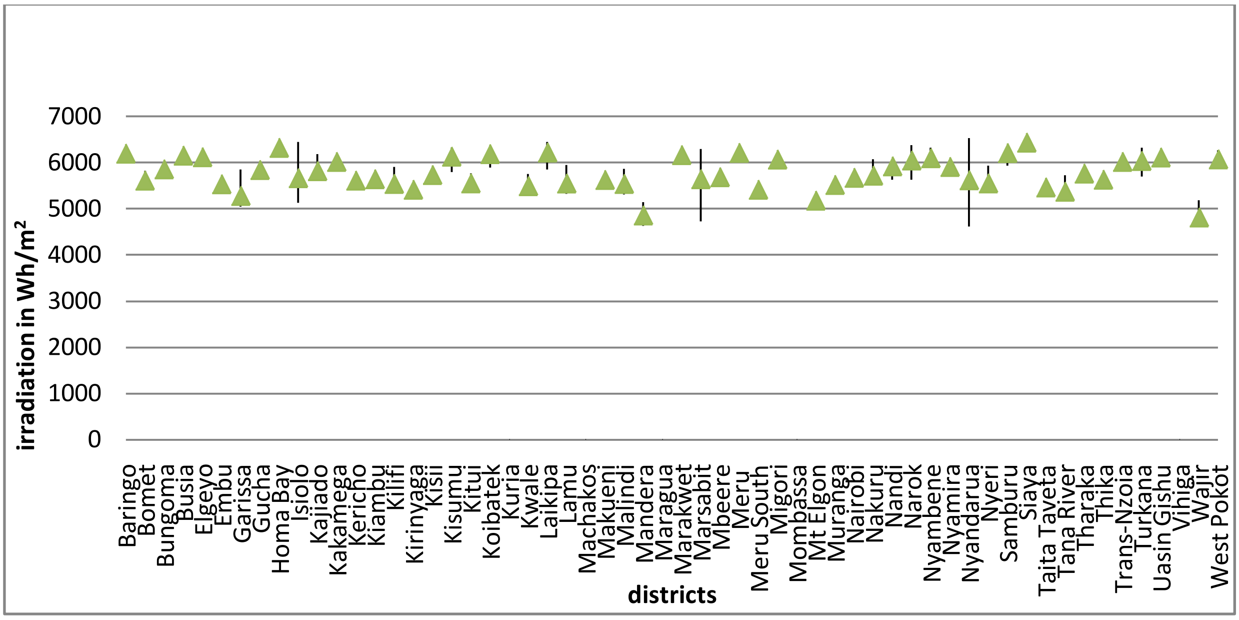

Figure 11: Mean irradiation values for Kenya's districts in Wh/m^2 per day

Figure 12 shows that there is a strong difference in irradiation between Eastern- and Western Kenya when looking at the long term average of solar irradiation. Central, North-Western and South-Western Kenya feature the highest values of solar irradiation. These regions reach mean values of up to 6,500 Wh/m^2/day. In Eastern-Kenya and especially in the North-East values of as low as 4,600 Wh/m^2/day are measured.

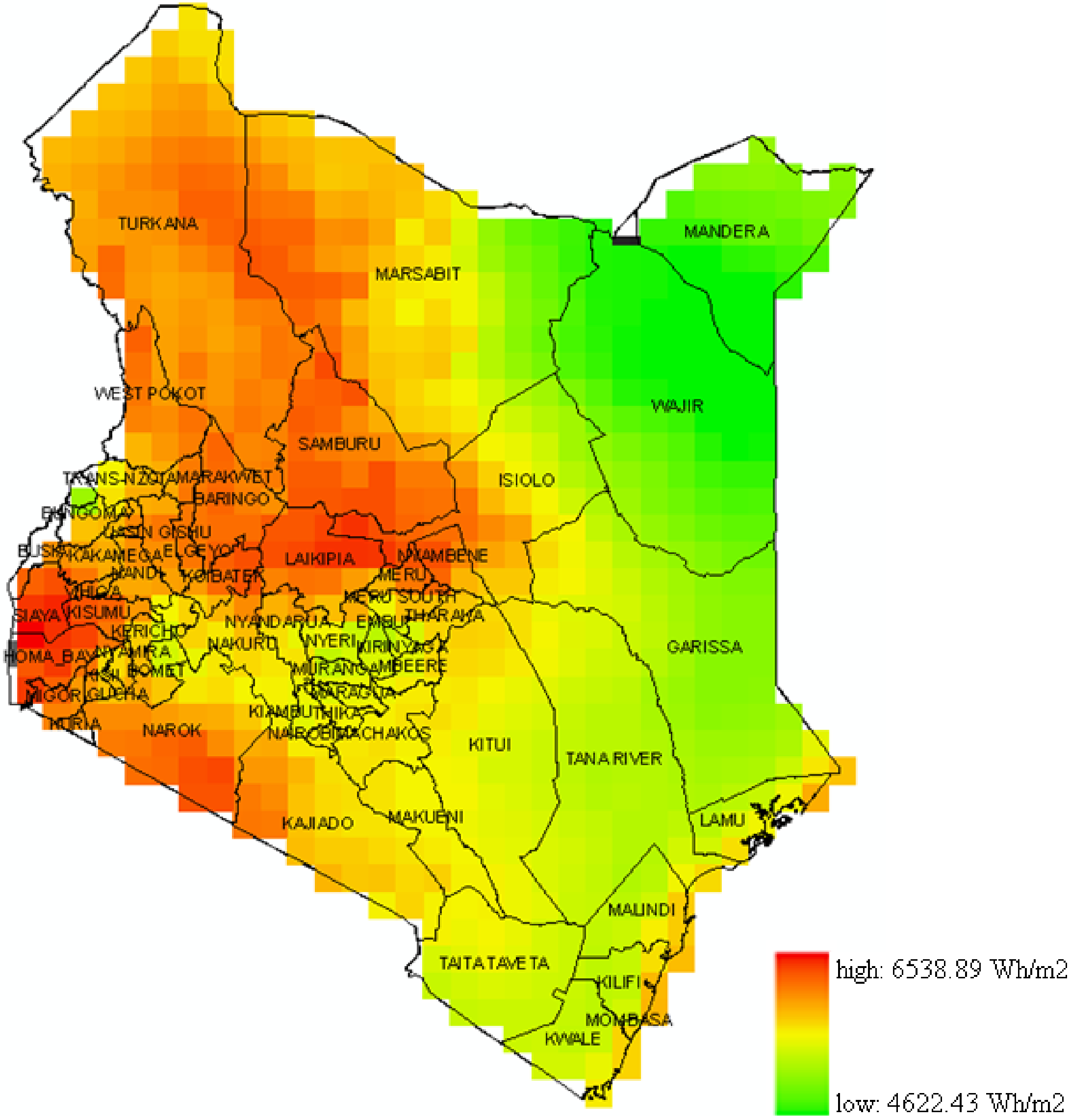

Figure 12: Long-term (1985-2004) average of solar irradiation in Wh/m^2/day

The second parameter depicted is the electricity demand. This model does neither take income differences between households nor economic differences between districts into account. To derive the electricity demand per capita simply the amount of electricity needed to cover a basic demand is taken into account. In the literature this value is set at 50 kWh per household (see 2.1.3.). The average household size in Kenya amounts to five people. Again, regional differences are not taken into account.

Therefore, to derive the electricity demand per district, the number of inhabitants is divided by five and then multiplied by 50 kWh.

The third input data are the costs. Costs in the model include both stand-alone PV systems as well as grid extension costs.
Solar modules with a capacity of approximately 60 Watt cost around USD 250, a battery costs approximately USD 250, and additional equipment costs about USD 100. The battery of this system is a 12 V lead-acid battery with approximate capacity of 60 to 120 ampere- hours (Ah). The lifetime of the PV module, the battery and the extra equipment is set at 20, ten and five years and the interest rate at 14%. Annual solar panel installations costs amount to USD 128 per m^2.
Grid extension costs are composed of transmission line and distribution costs.
The lifetime of the transmission grid amounts to 40 years and the interest rate is fixed at 14%. According to the project costs of the Kenya-Mombassa Transmission line project, the annual per meter costs for the construction of a transmission line amount to USD 58.128.
The reference costs for the distribution grid amount to USD 0.1027 per kWh (Ministry of Energy, 2009). In the model, these costs will be added as a distribution charge. A 1% increase in population density leads to 0.6 % decrease in distribution costs (Filippini et al., 2004) Therefore, the distribution charge will be adjusted to the population density of each district. Distribution charges vary between USD 0.000114 per kWh in Nairobi and USD 0.1075/kWh in Isiolo.

The next input data is the photovoltaic efficiency. The following formula is used to calculate the energy produced from the photovoltaic system:

$E_{electric}=H_{solar}*f_{inclination}*Fs_{olarcells}*l_{cell}*PR$

Where:

$E_{electric}$= produced energy per year in kWh/year

H_{solar}=mean sum of the yearly radiation energy in kWh/year

$f_{inclination}$ = inclination factor (considers the orientation of the solar cells to the direction of the insolation, between 0.5 and 1) dimensionless

$F_{Solarcells}$ = Area of the solarcells in m²

l_{cell}= module efficiency (between 0.07 and 0,28; benchmark 0.15) , dimensionless

PR = Performance Ratio, correction factor for construction and maintenance of the solar system (between 0.5 - poor equipment and 0.85 - ideal construction and perfect maintenance), dimensionless.

The mean sum of the yearly radiation energy in kWh/year is taken as the mean irradiation value for every district as described in the first section of this chapter. For the inclination factor, a value of 0.95 is assumed because the optimal inclination of modules in Kenya amounts to zero degrees and this makes it relatively easy to orient the modules to the direction of the irradiation. The area of the solar cell amounts to one m^2. For the module efficiency a value of 0.175 and for the performance ratio of 0.77 are taken. It is assumed that the modules chosen feature a good efficiency and are constructed and maintained in a relatively correct manner. However. optimal values are not applied as correct construction and maintenance cannot be guaranteed, especially in remote areas.
The result for the kind of systems used in this model is a photovoltaic efficiency of 12.8%.

The fifth parameter is the costs for the energy generation. In 2010, costs of energy generation amount to KSh 10 according to the reference scenario in the rural electrification master plan. The REM includes a low, a reference and a high economic scenario based on the price of crude oil. In the reference scenario, the price for crude oil stays at USD 100. In the high scenario it increases on average to USD 150, whereas in the low scenario the price for crude oil decreases until it reaches USD 50. The scenarios are similar for coal and natural gas. In 2010, in the low and high energy scenario, costs account for KSh 5 and KSh 12 respectively. In the reference scenario, costs will increase to more than KSh 13 (USD 0.166816) until 2014/2015. In the model, costs are taken as KSh 10 based on the reference value for 2010. This amounts to USD 0.12938 as of May 2010.

The sixth input data represent the distance between the districts. The distances between all districts are calculated in the following way: In a first step the mean centre of every district using ArcGIS is determined. In the next step, through ArcGIS the distance between all district centres is calculated through ArcGIS.

The seventh parameter integrated into the model is the maximum solar panel area. The maximum solar panel area is the total land area of every district. This model does not take any other land uses into account. However, the area which will be used for electricity generation from photovoltaic systems will not be large enough to cause opportunity costs, as one square meter per household is considered sufficient to cover the electricity demand. Small systems can be installed on the roof. However, when demand increases and therefore modules are added, other land uses will have to be taken into consideration and opportunity costs need to be calculated.

The last input data is the capacity of the grid. For simplicity, grid capacity is regarded as infinite.

3.2. Model organization

In this part of chapter three the methodology is described, starting from explaining optimization and energy models in general to the methodology applied in this thesis.

3.2.1 Methods

Like other models, energy models characterize reality in a simplified way. They help us to perform tests or experiments for cases for which these would be impossible or too expensive to perform in the real system (Hirematha et al., 2005). A study reviewing energy models divides them into the following types: energy planning models, energy supply-demand models, forecasting models, optimization models, energy models based on neural networks and emission reduction models (Jebaraj and Iniyan, 2006). In order to answer the research question, an optimization model is most appropriate.

Economics can also be defined as a “science of choice.” In general, an economic project can be accomplished by different options. However, depending on the criterion, one option will be more optimal than another one. Hence, an optimization model aims to find the best option based on a specified criterion. In economics, this criterion applied is mostly to maximise (e.g. profit) or minimize (e.g. costs) a specific variable. From an economic point of view, maximization and minimization problems are called optimization problems, i.e. the search for the best solution. Yet, when looking at it from a mathematical angle, maximisation and minimisation problems do not imply optimality but an extreme value. When formulating an optimization problem, i.e. the first step is to define an objective function. The dependent variable embodies the object of maximization or minimization. The independent variables are the choice variables. In summary, an optimization process is to find the set of choice variables which will defer the wanted extreme value of the objective function (Chiang, 1984).

A linear programming problem consists of “determining all activities of the system which are:

a) non negative
b) satisfy the material balance equations
c) minimize the total costs.“ (Dantzig, 1963)

These characteristics pertain to this model.

The model represents an extended version of a transportation problem, such as one developed by Dantzig in 1963. The model will answer the question of whether it is more beneficial to electrify a particular district by extending the grid or implementing off-grid photovoltaic technologies. In order to come to this result, it will compare the costs of grid extension with the costs of solar PV systems.

Problems in the real world are mixed integer programming (MIP) problems, composed of continuous and integer variables. For MIP the discrete requirements are enforced which means that the discrete variables must assume integer values between their bounds (Rosenthal, 2010). GAMS and CPLEX are used for solving the mixed integer programming (MIP). The General Algebraic Modeling System (GAMS) was developed at the World Bank by Alexander Meeraus and his colleagues (Kendrick et al., 2005). It is a modelling system for mathematical programming and optimization designed for modeling linear, nonlinear and mixed integer optimization problems (GAMS, s.a.).

CPLEX solves integer programming problems, large linear programming problems, and quadratic programming problems. CPLEX is supported amongst other with GAMS (IBM, s.a.).

3.2.2. Model overview

Districts are divided into demand and supply districts depending on the existence of a grid. In the next step, the mean centre of every district is determined and the distances of all mean centres to another are calculated. The model then compares the annual costs of grid extension with the annual costs for off-grid solar PV technologies. From this analysis, the more cost-effective option is selected. This process is graphically represented in Figure 13.

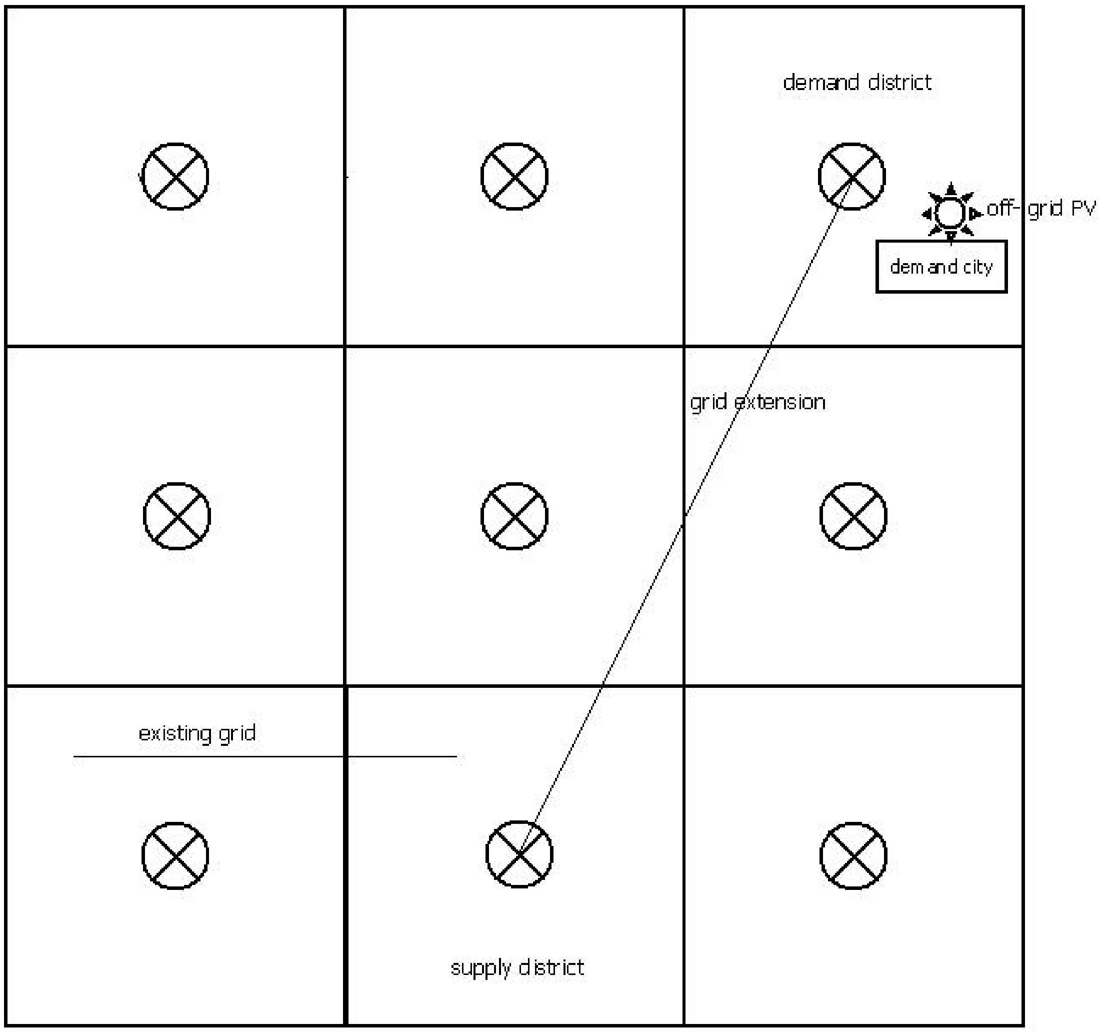

Figure 13: Graphic representation of the optimization model

3.2.3. Algebraic representation

Kenya is divided into 58 administrative districts. The divisions are depending on the availability of an electricity grid and are then declared either a supply district (*i*) or demand district (*j*).

Indices:

i= supply districts

j= demand districts

Given data:

a_i= supply of electricity in districts *i* in kWh

b_j= demand of electricity in districts *j* in kWh per month

d_{ij}= distance between districts *i* and district *j* in m

p_j= maximum solar panel area in districts *j* in m^2

i_j= solar irradiation in districts *j* in $kWh/m^2/a$

c_j= distribution charge in districts *j* in USD per kWh

c^f= solar efficiency in percentage

c^t=costs of building of power transmission lines in USD per m

c^s= solar power installation costs in USD per m^2

c^e= energy generation costs in USD per kWh

g= grid capacity in kW

Positive variables:

x_{ij}= amount of grid electricity transported from *i* to *j*,

where $x_{ij} \geq 0$ for all *i*, *j*

s_j= size of solar panel area

where $s_j \geq 0$ for all *j*

Binary variable:

w_{ij}= electricity transport from *i* to *j*

where w_j= 0,1

Constraints:

Observe supply limit in *i*: $\sum_j x_{ij} \leq a_i$, for all *i*

Satisfy demand in *j*: $\sum_i x_{ij} + c^f * i_j * s_j \geq b_j$, for all *j*

Limit the transportation of energy in the grid $x_{ij} \geq g * w_{ij}$ for all *i*, *j*

Observe solar panel limits: $s_j \leq p_j$

Minimize $\sum_{i,j}(c^e + c_j) * x_{ij} + \sum_{i,j} c^t * d_{ij} * w_{ij} + \sum_j s_j * p_j$

3.2.4. Modelling

Kenya is divided into 58 administrative districts (see Figure 14)[1].

---

[1] Baringo, Bomet, Bungoma, Busia, Elgeyo, Embu, Garissa, Gucha, Homa Bay, Isiolo, Kajiado, Kakamega, Kericho, Kiambu, Kilifi, Kirinyaga, Kisii, Kisumu, Kitui, Koibatek, Kuria, Kwale, Laikipa, Lamu, Machakos, Makueni, Malindi, Mandera, Maragua, Marakwet, Marsabit, Mbeere,

Figure 14: Kenya and its districts

Meru , Meru South, Migori, Mombassa, Mt Elgon, Muranga, Nairobi, Nakuru, Nandi, Narok, Nyambene, Nyamira, Nyandarua, Nyeri, Samburu, Siaya ,Taita Taveta, Tana River, Tharakam, Thika, Trans-Nzoia, Turkana, Uasin Gishu, Vihiga, Wajir, West Pok

In the model, they are classified as demand or supply districts. The size of the districts varies significantly. However, the decision was taken to integrate this classification into the model for the following two reasons: Firstly, most of the data is available on a district level. Secondly, political decisions are often based on a district level classification.

Supply districts are those which dispose of an electricity grid. Demand districts are districts which are not electrified. They represent the majority of districts.

The model will answer the question if it is more beneficial to electrify a particular district by extending the grid or implementing off-grid photovoltaic technologies. Therefore as already mentioned, it will compare the costs of grid extension with the costs of solar PV. The most important factors, influencing the costs for grid extension are the distances from the existing grid and the population density. Other decision parameters for grid electrification are the generation costs and the grid capacity. It is therefore necessary to calculate the shortest distance between the town or city to be electrified and the existing grid. Firstly, the mean centre of every district is defined. Secondly, the distance from every centre to another is calculated. Thirdly, the model will find the closest supply district's centre from the centre of the demand district in which the particular town is located. Decision parameters for the PV option are the efficiency of the modules, the costs of the system, the maximum amount of solar area and the level of solar irradiation. Capital costs are accounted as annuities in the model. Figure 15 shows the districts of Kenya with its mean centres (red dots) and the existing electricity grid (blue lines).

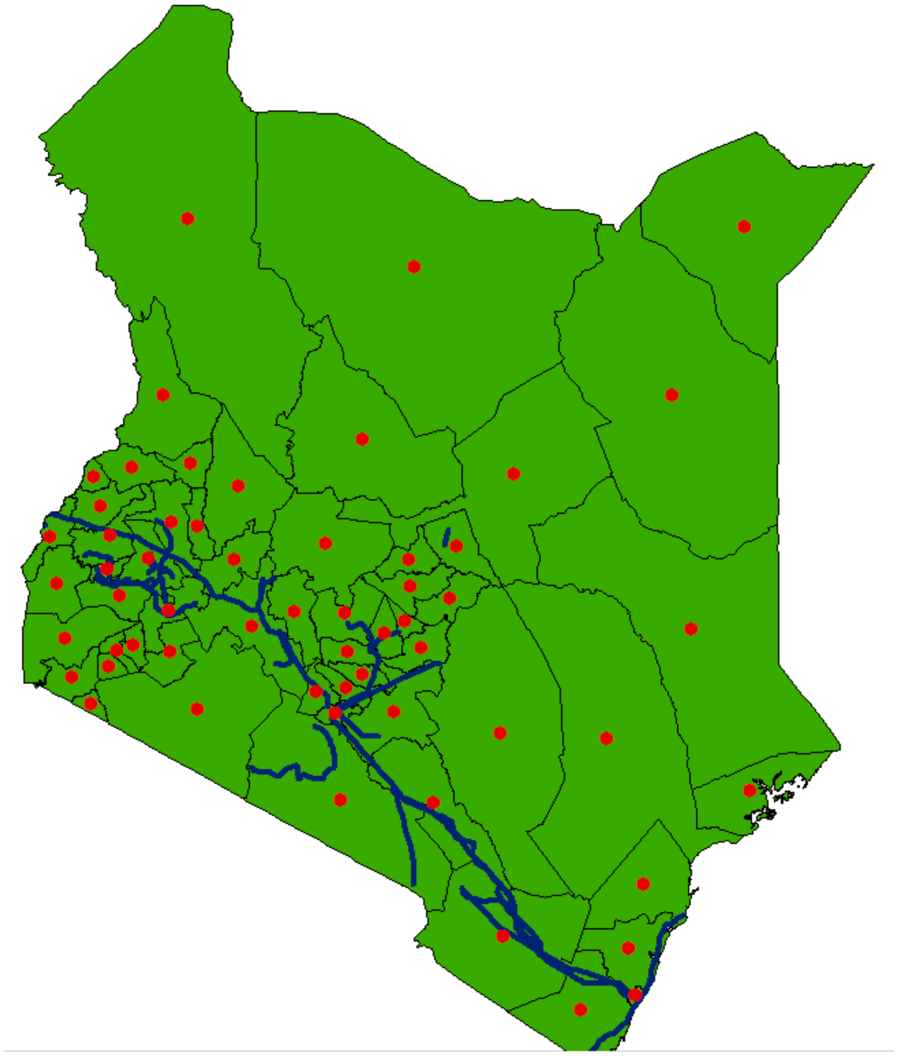

Figure 15: Map of Kenya with its districts and the existing grid

The aim of the model is to minimize the total energy system costs. Total costs are composted of distribution costs, transportation costs and solar panel costs. Distribution costs are the sum of the energy price and the distribution charge multiplied with the amount of electric energy transported from one grid to another. Transportation costs are defined as the sum of investment costs for one meter of transmission grid multiplied by the distances from supply to demand districts. The grid electricity transported from supply to demand locations is defined as a binary variable (taking on values of zero or one only). In other words, transport does either occur or not. The third component are the solar panel costs. These are the sum of the solar panel costs multiplied by the solar panel area.

Besides the minimization of the total costs, the following constraints need to be fulfilled: Firstly, the electric energy transported from one grid to another needs to be less than the supply of grid energy. Secondly, in case electricity is transported, it can not exceed the grid capacity. Thirdly, the area used for the construction of solar panels cannot be larger than the maximum area provided for solar panels, in this model the total district area. Finally, the sum of the amount of electricity transported from one grid to another, plus the electricity gained from photovoltaic systems (area used for the construction of solar panels multiplied with the solar PV efficiency and the annual solar radiation) must be greater than the electricity demand.

If there are binary variables in the model, it can be solved either as a MIP or as a RMIP. The difference between the MIP and the RMIP is that for the MIP discrete requirements are enforced: the discrete variables must assume integer values between their bounds. This model uses the MIP solver CPLEX.

4.2.5. Model Scenarios

The model will be tested under four scenarios. The first scenario is based on the data described in chapter 4.1. The second scenario assumes an increase in electricity price. The third one presumes advancements in the photovoltaic technology leading to a higher solar efficiency and solar panel lifetime. Lastly, the fourth scenario postulates GDP growth resulting in a higher electricity demand.
Table 2 shows the parameter variations in the four scenarios.

Table 2: Parameter variations in the four scenarios

Scenarios	Solar efficiency	Solar Panel lifetime in years	Energy generation costs in USD/kWh	Energy demand per household in kWh/month
Scenario 1	0.128	20	0.12938	50
Scenario 2	0.128	20	0.22	50
Scenario 3	0.2	25	0.12938	50
Scenario 4	0.128	20	0.12938	100

For the first scenario the input data as described in section 4.1. are used. The second scenario assumes a further increase in electricity price mainly due to climate change and changes in land cover. Studies revealed that changes in land cover have significant impacts on water resource availability (MacMillan and Liniger, 2005).

Moreover, climate change according to model predictions will have a significant impact on Africa, predominantly on arid and semi-arid regions (Hulme et al, 2001). Hydropower represents the primary source of energy generation in Kenya. An increase in temperature and decrease in precipitation leading to dehydration of rivers and as a result a decrease of output from water power would significantly increase the price for electricity. A region of Kenya which has been investigated intensively concerning its hydrology is the area around Mount Kenya. In this region, population increased by a factor of ten between 1960 and 2000. Due to the significant increases in population, an intensification of irrigated agriculture and an increasing water demand for livestock and domestic purposes led to an overall growth in water demand (Liniger et al., 2005). However, according to another study, climate change has a much larger effect on water resources in the area of Mount Kenya than land use change. It can be expected that dry periods are more severe and enduring which reduces water levels to nearly zero. Nevertheless, an increase in floods during rainy seasons can be expected. This signifies that the availability of the already scarce supply of water will be even more variable in the years to come (Notter et al., 2007). The extent, to which the changes in precipitation can be traced back to greenhouse gas emissions, however remains uncertain (Hulme et al., 2001).

Scenario three presumes advancements in the photovoltaic technology. A further decrease in the price for solar PV modules, longer life time for batteries and an increased efficiency will be achieved through an increase in research and development leading to advanced and inexpensive technologies. Watanabe et al. (2002) analyse the behaviour of technology in reducing prices of innovative goods on the basis of PV technology state that "technology both indigenous and assimilated spillover technology contributes significantly to reduce the prices of PV modules." The performance of the respective modules (conversion efficiency) affects the variance of module prices while the size of the module provides no significant effects on price distribution (Watanabe et al., 2002). The first solar cell was developed over 50 years ago and until today significant improvements in efficiency and price reductions have been achieved (European Renewable Energy Council, 2008; Office of the Deputy Prime Minister, 2004). Prices are to a very large extent only capital costs and its decrease will continue by as much as 50% within the next couple of years. Today, electricity from PV costs about USDD 0.22 to 0.30 per kWh, depending on the location (PricewaterhouseCoopers et al., 2010) and the quantities purchased. PV prices are currently decreasing. The moment of competitiveness depends on the country. In countries where grid power is expensive, PV can already compete with grid power (Foster et al., 2010). The European Photovoltaic Industry Association (EPIA) states that grid parity[2] of photovoltaic technologies will already be attained by 2010 in countries with high solar irradiation. By 2020, PV electricity will be competitive in all European countries. However, in order to achieve this goal, a continuous technology improvement needs to take place. Cost reductions will be reached through economies of scale caused by an acceleration of PV use (European Renewable Energy Council, 2008).

Scenario four assumes an increase in GDP per capita. In Kenya, economic growth contracted from 1992 onwards. In the 1990s GDP increased on average by only 2%. Between 1990 and 2004, during the time when Kenya´s economy was liberalized, real capita income was falling. This was mainly due to bad governance of the economy and the financial sector (Roe, 2004).
One study states that further financial development in the form of reforms and policies in the financial sector could trigger economic growth in Kenya (Wolde-Rufael, 2009). The Kenyan economy had only slowly recovered from the political crisis before the financial crisis hit the world. The most important sector, agriculture declined due to unfavourable weather conditions. Compared to agriculture and manufacturing, wholesale, retail trade, transport and construction were able to grow. In order for the economy to recover, the government adopted an expansionary fiscal policy including a fiscal stimulus targeted at infrastructure. Predictions, however, foresee that improvement will be retarded due to the ongoing consequent food, energy and water crisis. The overall growth for 2008 amounted to 1.7%, the lowest growth rate recorded since 2003 (World Bank, 2009). The International Monetary Fund however expects real GDP to grow until 2011. (International Monetary Fund, 2009). In a recent report "Kenya economic update" the World Bank predicts Kenya's growth rate to reach 4% and 5% in 2010. This enables Kenya to again reach high growth

[2] Photovoltaic electricity is equal or lower than the retail electricity

levels similar to the time period from 2004 until 2007 before the domestic political and global financial crisis (World Bank, 2010).

4. Results and Discussion

In the first part of this chapter, results of the four scenarios are presented. Secondly, the influence of four different input parameters, namely the costs of grid energy, the interest rate, the efficiency rate and the amount of irradiation will be assessed. This chapter concludes with a discussion of the results.

4.1. Results

Firstly, this chapter gives the result of the modelling process according to the four different scenarios. Secondly, the input parameters are discussed.

4.1.1. Scenario 1

The first scenario using input data described in the previous parts gives the following results: Ten of the 58 districts are supplied with photovoltaic technologies, 48 with grid electricity. Figure 16 shows the districts supplied with grid electricity in grey and those with photovoltaic technology in yellow.

The districts for which PV is chosen as the better options feature, except for two of them, similar characteristics. Tab. 3 indicates which characteristics are determining the decision to the supply through off-grid photovoltaic technologies: Firstly, they are located in the North-Eastern part of the country. Secondly, they are situated quite far away from the existing grid. Furthermore, the districts selected for the PV option comprise the largest ones, which account in sum for more than half of the area of Kenya and consist of a very low population density. The average population density amounts to 358 inhabitants per km^2. However, the population density in the solar districts is with one exception between 2.4 and 12.5 inhabitants per km^2.
Comparisons in the distributions charge which depends on the population density, give similar results. Solar districts strongly deviate from the mean value, resulting in higher distribution charges and increasing costs per about USD 0.1 per kWh.
Differences in solar irradiation are not the main reason for the choice of system

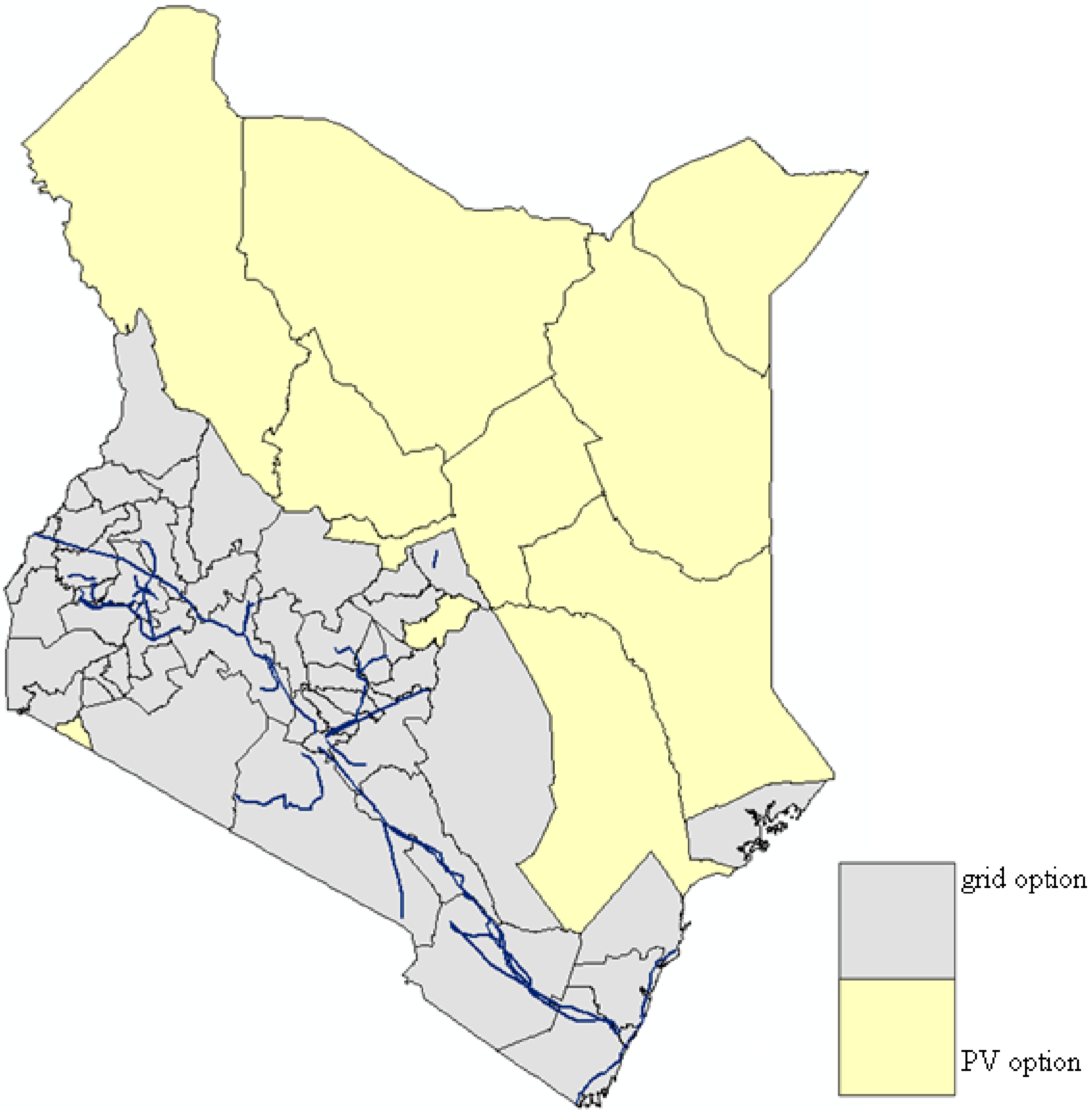

Figure 16: Districts supplied with PV and grid extension in scenario 1

Table 3: Deviation of parameters from mean value in districts where the PV option is chosen

Districts	Solar irradiation (Wh/m^2)	Deviation from mean value (Wh/m^2)	Demand (GWh/month)	Deviation from mean value (GWh/month)	Distribution Charge (USD/kWh)	Deviation from mean value (USD/kWh)	Population density	Deviation from mean value
Garissa	1931.72	-153.53	48.30	68.63	0.107	0.017	11.66	346.34
Isiolo	2072.17	-13.08	12.10	104.83	0.106	0.108	5.13	352.88
Kuria	2085.25	-3.63798E-12	18.24	98.70	0.087	0.087	349.62	8.38
Mandera	1777.46	-307.79	30.04	86.88	0.106	0.106	6.03	351.98
Marsabit	2064.07	-21.18	14.58	102.35	0.108	0.108	2.41	355.59
Samburu	2270.81	185.55	17.23	99.71	0.107	0.107	8.33	349.68
Tana River	1965.13	-120.13	21.71	95.22	0.107	0.107	6.18	351.82
Tharaka	2108.48	23.23	12.12	104.81	0.103	0.103	79.83	278.18
Turkana	2208.16	122.91	54.10	62.83	0.107	0.107	7.80	350.21
Wajir	1761.55	-323.71	38.31	78.62	0.107	0.107	12.51	345.50
Mean	2085.25		116.93		0.090		358.01	

4.1.2. Scenario 2: Increase in the electricity price

In the Kenyan Rural Electrification Master Plan the total average electricity generation costs are predicted to increase until the years 2014 and 2015 until they reach nearly KSh17 (USD 0.22) per kWh. An increase in the generation costs to USD 0.22 signifies that the model decides to build off-grid photovoltaic technologies in 15 districts (see Figure 17)

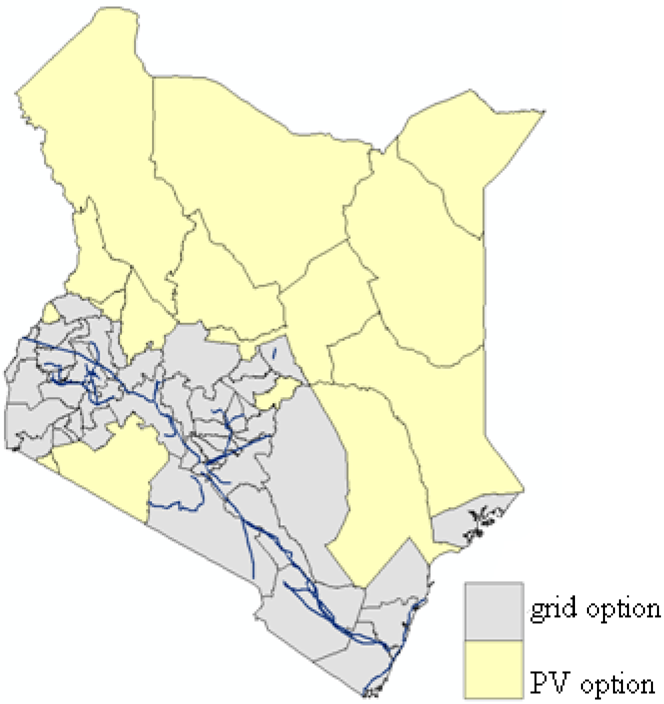

Figure 17: Districts supplied with PV and grid extension in scenario 2

4.1.3.: Scenario 3: Advancements in the photovoltaic technology

The report “Technology Roadmaps-Solar photovoltaic energy” of the International Energy Agency outlines that the efficiency of commercially used modules will increase to up to 23% by 2020. At the same time the operational lifetime will amount to 30 years. This is an increase of 10 years compared to today’s lifetime of 20 years. For scenario 3 an efficiency of 20% and a lifetime of 25 years are assumed, as in rural Kenya not the same possibilities of maintenance can be presumed. This assumption leads to the result of 24 districts being supplied with stand-alone photovoltaic electricity (see Figure 18).

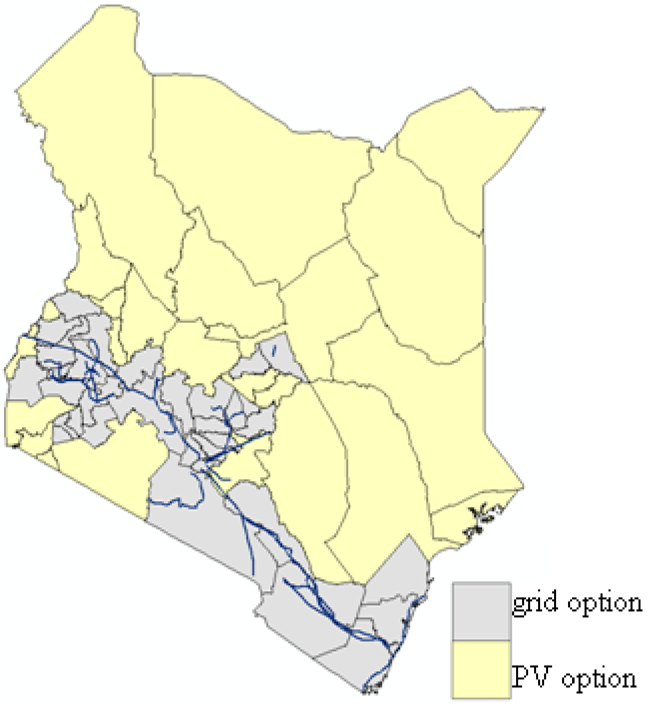

Figure 18: Districts supplied with PV (yellow) and grid extension (grey) in scenario 3

4.1.4. Scenario 4: Increase in demand

In scenario 4 an increase in demand due to a higher GDP per capita is assumed. A doubling in demand to 100 kWh per household and month will make the supply with PV technology competitive in only five districts (see Figure 19).

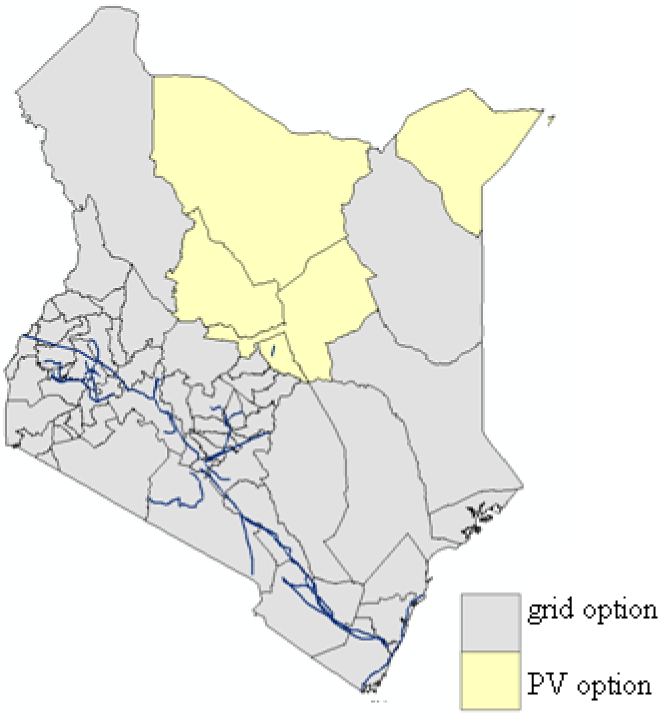

Figure 19: Districts supplied with PV (yellow) and grid extension (grey) in scenario 4

4.2. Sensitivity Analysis

In the following section some of the input parameters are analysed in terms of their impact on the outcome. How does a change in the parameter change the number of districts supplied with photovoltaic energy?

The costs of grid energy correlate strongly with the number of PV districts. Figure 20 shows that the higher the costs for grid energy, the more districts are selected for a supply with solar energy.

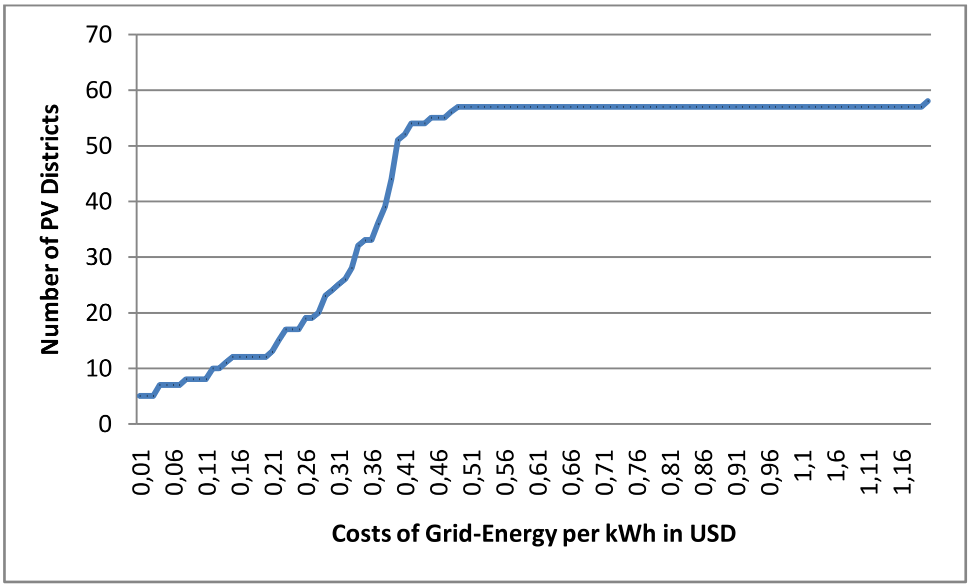

Figure 20: Correlation between number of PV districts selected and costs of grid energy

There is a strong correlation between the interest rate and the number of photovoltaic districts (see Figure 21). The higher the interest rate the more districts are supplied trough grid extension. This can be explained by a lower system lifetime of photovoltaic technology compared to the electricity grid and by higher investment costs of PV technology, resulting in total higher capital costs for PV than for grid.

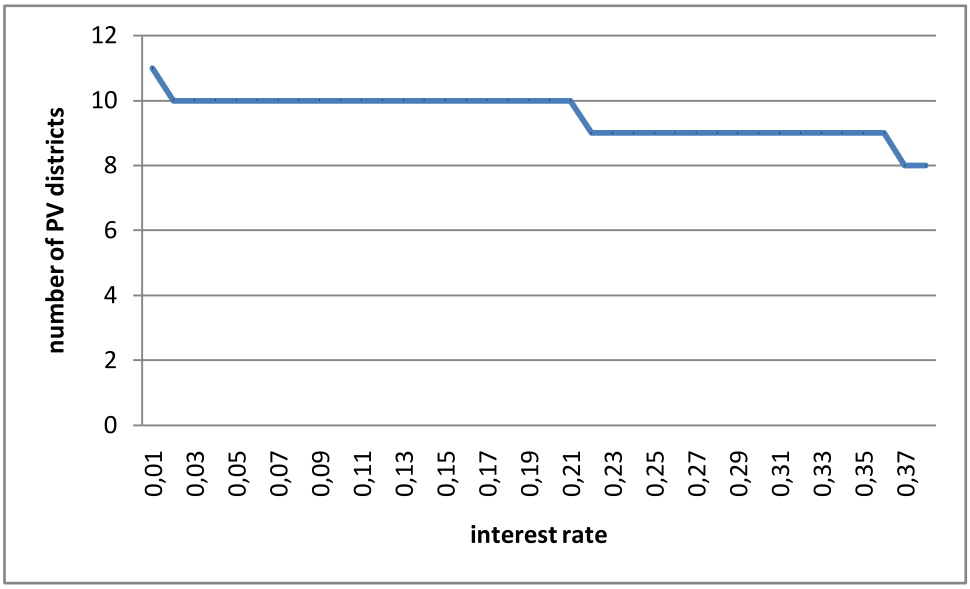

Figure 21: Correlation between number of PV districts selected and interest rate

In scenario one, we assume an efficiency of photovoltaic cells of 12.8%, which leads to the result that ten districts are supplied with PV energy. When increasing the efficiency, the number of PV districts increases strongly until an efficiency of 29% is reached. This can be seen in Figure 22. Today, commercially available cells convert between 7% and 20% of solar irradiation into electric energy. However, under laboratory conditions values of more than 40% have been reached. Thus, in the future it might be more economical to opt for the solar option for the supply of the majority of districts.

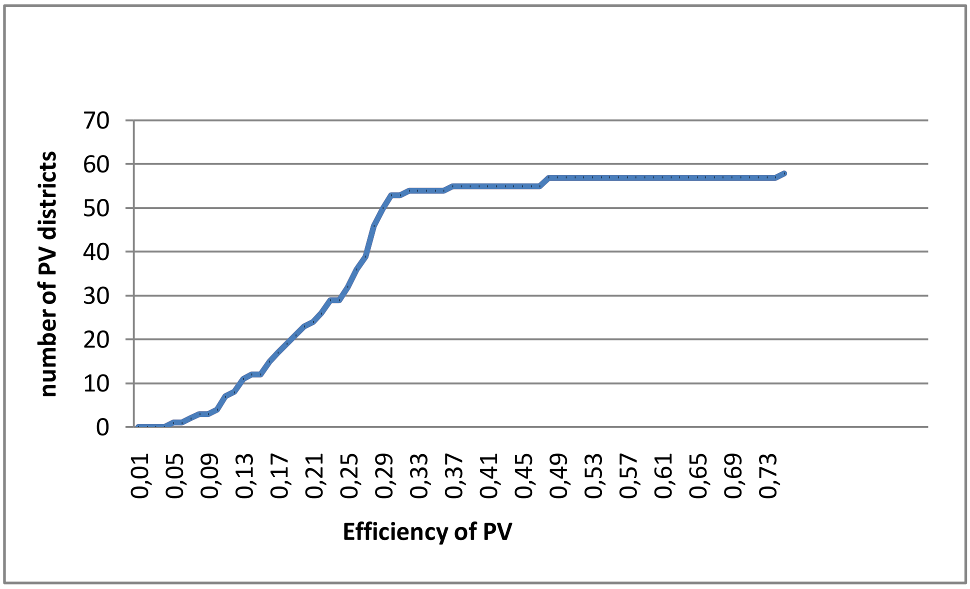

Figure 22: Correlation between numbers of PV districts selected and PV efficiency

Figure 23 shows which districts will already be supplied with solar PV when efficiencies are very low and which require a very high efficiency in order for the model to prefer the PV over the grid extension option. In this map, the dark green indicates a district, which only requires a low PV efficiency for the PV option to be realized. The districts coloured in red will only be electrified with PV when the efficiency is very high. In other words, the greener the colour the more likely it is that the PV option represents the optimal solution for this district.

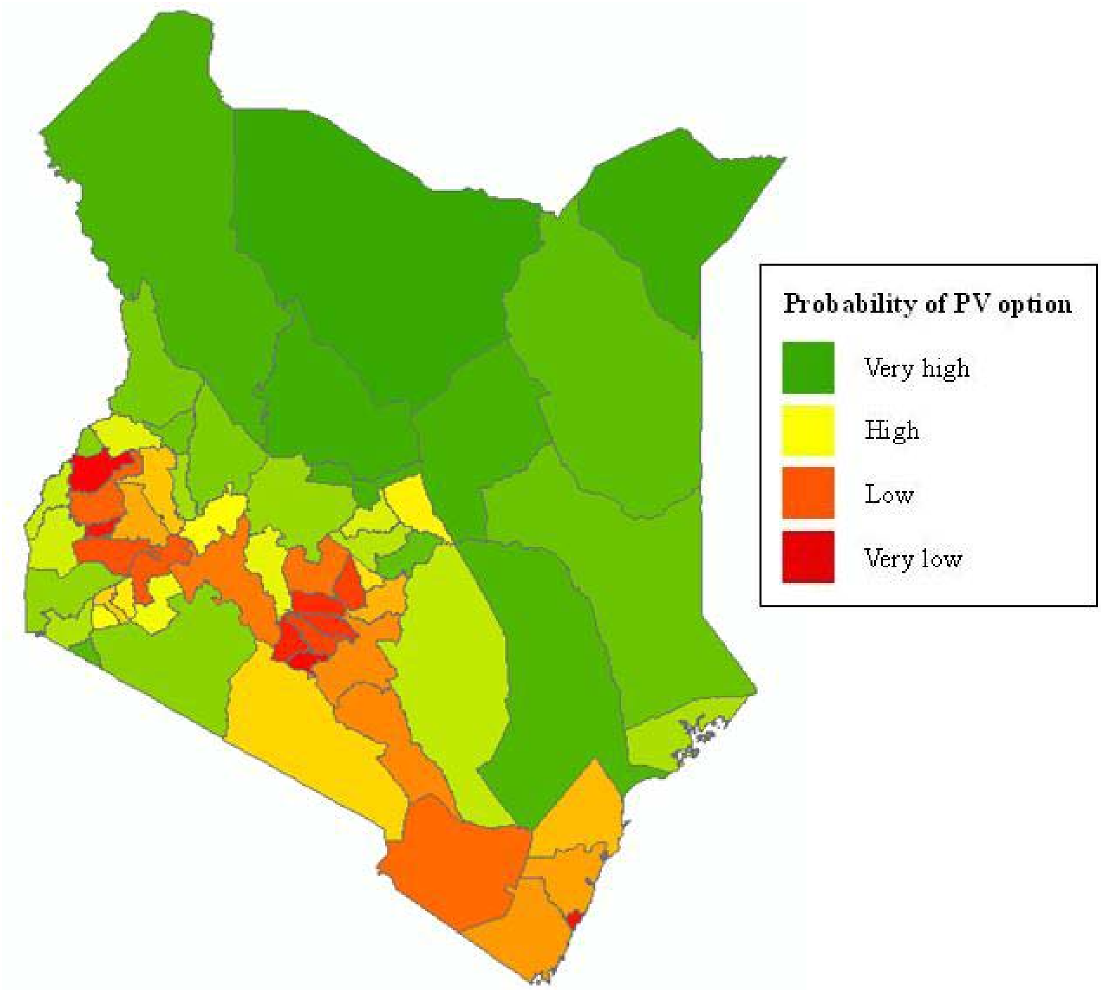

Figure 23: Map indicating the likeliness of the PV option, green (very likely) vs. red (very unlikely)

Solar irradiation strongly correlates with the number of districts selected for the PV option (see Figure 24). This can be interpreted in the sense that solar irradiation has an influence on the result; also when not visible at first sight as the likeliness of the PV option is particularly high in North-Eastern parts of Kenya which feature a lower solar irradiation.

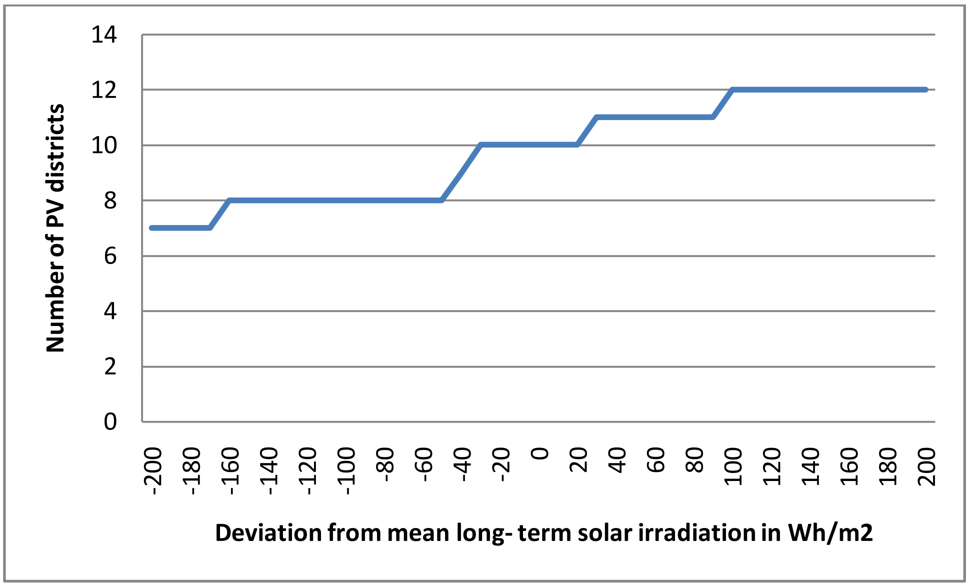

Figure 24: Correlation between numbers of PV districts selected and solar irradiation

4.3. Discussion of the results

For the majority of the districts, electrification via grid extension represents the least-cost option. In scenario one, only ten out of 57 districts are supplied with grid energy. Due to a long lifetime and large population, costs on an annual per kWh basis are small compared to solar photovoltaic technologies. The solar battery lifetime is only a couple of years and investment costs per household are rather large. Yet, distribution network costs determine largely the costs for grid extension. Therefore, differences in population density are the parameters which influence the outcome the most. For districts, which feature a low population density, PV systems represent the better option. The low demand per household is one important explanation factor for the choice of PV in some districts. However, one needs to add that the demand side represents a weak part of the model. In poor and especially areas, demand is even lower, which could lead to a shift towards the PV option. An adjustment, giving a more realistic picture of the demand would possibly change the outcome in one way or another. The supply with electricity will in the long run imply an increase in wealth and financial possibilities for the households concerned. This in turn will eventually give rural households the possibility to pay for a wider range of electricity usages and eventually result in a growing demand for electricity. This means that at long-sight grid electrification will become economically viable.

An increase in electricity supply cannot be covered by the current generation infrastructure. Therefore, electricity planning needs to target the building of new power plants. The results show that the present price of generation does not significantly favour the photovoltaic option. In cases where electricity planners neglect the demand side, without thorough planning and actions, the outcome of the model could change and lead to grid parity of PV within a short time.

It is also worth mentioning that differences in solar irradiation amongst districts do not have a significant effect on the model result.

An important result is that development, which can not be influenced by national energy planners or the Kenyan government can have large effects on the result: An increase in solar efficiency, which is very likely for the future, quickly changes the outcome. This new situation will make it more beneficial for a larger share of the districts to be supplied with off-grid photovoltaic technology. Furthermore, climate change which will lead to an increase in temperature and decrease in humidity will affect the hydro power generation output in Kenya. Hydropower accounts for more than half of the electricity generation in Kenya. A decrease in hydropower generation will lead to a rise in the price of electricity. This will also augment the competitiveness of photovoltaic energy. The third scenario which implies an increase in GDP per capita resulting in an enhanced demand for electricity would lead to an increase in districts supplied with the grid extension option. Yet, a decrease in GDP would imply the reverse effect, entailing that it is optimal to implement off-grid photovoltaic systems in more districts.

5. Conclusion and Outlook

5.1. Conclusion

In order for Kenya to meet the Millennium Development Goals major efforts and investments into its electricity infrastructure are required. None of the MDGs will be reached without a supply of electricity in sufficient quantity and quality. This requires households to be supplied with electricity in order to cover their basic needs. As already discussed, one option represents the extension of the national grid and another one the supply with off-grid photovoltaic systems. The second option is particularly important for rural households but might for certain areas also only serve as an interim solution. The model developed in this thesis gives a first guideline for which districts grid extension is more economical and for which it is more beneficial to concentrate on the implementation of stand-alone options. The result is that under current circumstances for ten districts covering more than half of the total land area of Kenya, implementation of stand-alone photovoltaic systems represents the better solution. This finding leads to the conclusion that the population density is a very important decision parameter. Another significant outcome of the model is that changes in the electricity prices have a significant effect on the result. It implies that in order to supply a larger share of the population with grid energy, infrastructure planning is of utmost importance in order to avoid the outcome of very costly solutions. However, Kenyan's government can not influence all parameters and therefore has to react to developments coming from outside the country. For example, an increase in solar PV efficiency, which would very likely come as a result of research and development within developed countries, will strongly change the results and planning requirements of the government of Kenya.

The model is designed for national planning. For single towns or households which decide to invest into electrification, in most cases off-grid PV will be the best choice.

5.2. Outlook

The improvement of the input data and the integration of new decision variables into the model are needed in order to allow for more realistic decision-making and electricity planning. One needs to be cautious when taking recommendations of this model and apply them to single towns. It might be advantageous to electrify the district in general through grid electrification, but this can completely change for particular towns or regions within the district. Therefore, the next step would be to divide the country into smaller divisions in order to account for differences within the districts.

In its current version, the model is static and does not consider newly built grid lines. Furthermore, the model does neither take into account limits in grid transportation nor in generation capacities. Shortages in the electricity supply are already today a major problem. An increase in demand would automatically lead to power outages and increase in electricity prices. When taking this factor into account, the grid extension possibility would be automatically disfavoured. It is therefore necessary to include current power plants into the model and also to assess the potential of new generation possibilities, especially renewable energies into the model. An increase in

renewable energies however puts higher demands on the grid, requiring the implementation of a smart grid. Renewable energies, nevertheless also represent an option for stand-alone electrification. The model could be extended to include other renewable energies as an off-grid possibility. Besides, the two options national grid extension or stand-alone solutions, a third one, namely decentralized mini-grids could lead to a more modern and low carbon-technologies oriented energy system.
In the model we assume that all households have the same demand for electricity which is certainly set too low for many household, while it may be too high for poor, rural households. Further research is needed to better model the demand, distinguishing between incomes of households and also including other infrastructure apart from single houses. This could be achieved by using the data of the "Kenyan Integrated Household Budget Survey" of 2005.
In the current model geographic features are not taken into account. Its integration will increase grid extension costs, adding to a more realistic depiction. An improvement of the current model taking all these factors into account would improve electricity planning in Kenya and across Sub-Saharan Africa and ultimately help in the attainment of poverty alleviation and the attainment of the Millennium Development Goals.

6. Bibliography

Abdullaha S., and Markandya A. (2009): Rural electrification programmes in Kenya: Policy conclusion from a valuation study. Department of Economics Working Papers 25/09, University of Bath, Bath.

Aeschbacher J., Liniger H.P., and Weingartner, R. (2005): River water shortage in a highland-lowland system. A case study on the impact of water abstractions in the Mt. Kenya Region, Mountain Research and Development 25, 155-162.

Afrane-Okese Y. (1998): Domestic energy use database for integrated energy planning. Energy and Development Research Centre, University of Cape Town.

African Development Fund (2008): Project: Mombasa - Nairobi Transmission Line Project. Project Appraisal Report, Tunis.

Barnes D., and Floor W.M. (1996): Rural energy in developing countries: A challenge for economic development. Annual Review of Energy and Environment 21, 497-530.

Bouffard F., and Kirschen D.S. (2008): Centralised and distributed electricity systems. Energy Policy36, 4504-4508.

Chiang A.C. (1984): Fundamental Methods of Mathematical Economics. 3rd ed., McGraw-Hill, New York.

Columbia Earth Institute (2007): National Electrification Coverage Planning-Investment Costing Estimation Model- Kenya Final Report. Report to the World Bank by the Energy Group, Columbia Earth Institute, New York.

Dantzing, G.B. (1963): Linear Programming and Extensions. Princeton University Press, Princeton- New Jersey.

Deichmann U., Meisner C., Murray S., and Wheeler S. (2010): The Economics of Renewable Energy Expansion in Rural Sub-Saharan Africa. Policy Research

Working Paper 5193, The World Bank Development Research Group Environment and Energy Team, Washington.

Department of Minerals and Energy (2003): Electricity basic services support tariff for the Republic of South Africa.
http://www.dme.gov.za/pdfs/energy/electricity/fbe_policy.pdf - accessed on: 06.06.2010

Deutsche Gesellschaft für Technische Zusammenarbeit (2010): Solar PV (Kenya). http://regionalenergy-net.com/index.php?Itemid=33&id=27&option=com_content&task=view - accessed on: 01.06.2010.

Eberhard A., Foster V., Briceño-Garmendia C., Ouedraogo F., Camos D., and Shkaratan M. (2008): Underpowered: The State of the Power Sector in Sub- Saharan Africa. AICD, Background Paper, World Bank, Washington.

Energy, Environment and Development Network for Africa and Heinrich Boll Foundation (2009): Large Scale Hydropower, Renewable Energy and Adaptation to Climate Change: Climate Change and Energy Security in East and Horn of Africa. http://www.boell.or.ke/downloads/RenewableEnergyandAdaptationtoClimateChangePublication.pdf - accessed on: 05.04.2010.

Energy Sector Management Assistance Program (2007): Technical and Economic Assessment of Off-grid, Mini-grid and Grid Electrification Technologies. Technical Paper 121/07, Washington.

European Renewable Energy Council (2008): Renewable Energy Technology Roadmap 20% by 2020. Brussels.

Filippini M., Hrovatinc N., and Zoric J. (2004): Efficiency and regulation of the Slovenian electricity distribution companies. Energy Policy 32, 335-344.

Foster R., Ghassemi M., and Cota A. (2010): Solar Energy- Renewable Energy and the Environment. CRC Press, Boca Raton.

GAMS (s.a.): The GAMS System. http://www.gams.com/docs/intro.htm - accessed on: 28.05.2010.

Goetzberger A., and Hoffmann V.U. (2005): Photovoltaic Solar Energy Generation. Springer, Berlin Heidelberg.

Haanyika C.M. (2006): Rural electrification policy and institutional linkages. Energy Policy 34, 2977-2993.

Hirematha R.B., Shikhab S., and Ravindranath N.H. (2005): Decentralized energy planning; modeling and application-a review. Renewable and Sustainable Energy Reviews 11, 729-752.

Howells M.I., Alfstad T., Victor D.G., Goldstein G., and Remme U. (2005): A model of household energy services in a low-income rural African village. Energy Policy

Volume 33, Issue 14, September 2005, Pages 1833-1851.

Hulme M., Doherty R., Ngara T., New M., and Lister D. (2001): African climate change: 1900-2100. Climate Research 17, 145-168.

IBM (s.a.): IBM ILOG CPLEX Optimizer. http://www-01.ibm.com/software/integration/optimization/cplex-optimizer/ - accessed on: 28.05.2010

Imitira J.K. (2009): Power situation in Kenya- Reforms to Guarantee Security of Supply. http://www.boell.or.ke/downloads/Imitara_-_PowerSituationReformstoGuaranteeSupply.pdf - accessed on: 02.04.2010

International Energy Agency (2000): Energy and Poverty. In: World Energy Outlook 2002. http://www.iea.org/textbase/nppdf/free/2002/energy_poverty.pdf - accessed on 01.01.2009.

International Energy Agency (2002): World Energy Outlook 2002. Paris.

International Energy Agency (2003): PV for Rural Electrification in Developing Countries- Programme Design, Planning and Implementation. Report IEA- PV, Paris.

International Energy Agency (2010): Stand-alone PV power systems (off-grid). http://www.iea-pvps.org/pv/sa_syst.htm - accessed on: 25.03.2010.

International Energy Agency and Renewable Energy and Efficiency Partnership (2008): Renewable Energy Services for Developing Countries In Support of the Millennium Development Goals: Recommended Practice & Key Lessons, Report IEA-PVPS T9 - 09:2008, United Kingdom.

International Monetary Fund (2009): World Economic Outlook October 2009- Sustaining the Recovery. Washington.

Jebaraj S., and Iniyan S. (2006): A review of energy models. Renewable and Sustainable Energy Reviews10, 281-311.

Kaltschmitt M., Streicher W., and Wiese A. (2007): Renewable Energy- Technology. Economics and Environment, Springer, Berlin.

Kaundinya D.P., Balachandra P., and Ravindranath N.H. (2009): Grid-connected versus stand-alone energy systems for decentralized power—A review of literature. Renewable and Sustainable Energy Reviews 13, 2041-2050.

Kammen D. M., and Kirubi, C. (2008): Poverty, energy, and resource use in developing countries: Focus on Africa. Annals New York academic of science1136, 348-357.

Karekezi S., and Kithyoma W. (2005): Sustainable Energy in Africa: Cogeneration and Geothermal in the East and Horn of Africa - Status and Prospects. Energy, Environment and Development Network for Africa, Nairobi.

Kendrick D.A., Mercado P.R., and Amman H.M. (2005): Computational Economics. Princeton University Press, Princeton, New Jersey.

Kenya National Bureau of Statistics (2000): Household energy consumption Survey. Nairobi.

Kenyan National Bureau of Statistics (2007): Basic Report Kenya Integrated Household Budget Survey- 2005/06. Revised ed., The Regal Press Kenya Ltd., Nairobi.

Kenya Power & Lighting Company (s.a.): KPLC Fast Facts. http://www.kplc.co.ke/displayPageInside.asp?level_three_title_id=42&top_level_id=3&level_two_title_id=17 - accessed on: 28.05.2010.

Kenya Power & Lighting Company (2009): Annual Report & Financial Statements- for the financial year ended 30 June 2009. Nairobi.

Kiva N.I. (2009): GOK responses to the energy crisis. www.boell.or.ke/downloads/Kiva_-_GOK_Responses_to_Energy_Crisis.pdf - accessed on: 02.04.2010.

Kolhe M., Kolhe S., and Joshi J. C. (2002): Economic viability of stand-alone solar photovoltaic system in comparison with diesel-powered system for India. Energy Economics 24, 155-165.

Liniger H.P., Gikonyo J., Kiteme B., and Wiesmann U., (2005): Assessing and managing scarce tropical mountain waterresources. The case of Mt. Kenya and the Semi-Arid Upper Ewaso Ng'iro Basin. Mountain Research and Development 25, 163-173.

Louw K., Conradie B., Howells M., and Dekenah M. (2008): Determinants of electricity demand for newly electrified low-income African households. Energy Policy 36, 2812- 2818.

MacMillan L., and Liniger H.P. (2005): Monitoring and modelling for the sustainable management of water resources in tropical mountain basins - the Mount Kenya example. In: Huber U.M., Reasoner M.A., Bugmann H. (Eds.): Global Change and Mountain Regions: A State of Knowledge Overview. Kluwer Academic Publishers, Dordrecht.

Ministry of Energy, Rural Electrification Autrhority, MVV decon, and Re-Engineering Africa Consortium (2009): Rural Electrification Master Plan. Final Report Volume 1 - Main Report August 2009, Nairobi.

Modi V., McDade S., Lallement D., and Saghir J. (2005): Energy Services for the Millennium Development Goals. Energy Sector Management Assistance Programme, United Nations Development Programme, UN Millennium Project, and World Bank, New York.

Notter B., MacMillan L., Viviroli D., Weingartner R., and Liniger H-P. (2007): Impacts of environmental change on water resources in the Mt. Kenya region. Journal of Hydrology 343, 266- 278.

Office of the Deputy Prime Minister (2004): Planning for Renewable Energy- A Companion Guide to PPS22. Her Majesty's Stationery Office, Norwich.

Oparaku O.U. (2002): Rural area power supply in Nigeria: A cost comparison of the photovoltaic, diesel/gasoline generator and grid utility options. Renewable Energy 28, 2089-2098.

Organisation for Economic Co-operation and Development and International Energy Agency (2009): Electricity generation by fuel Kenya. http://www.iea.org/stats/pdf_graphs/KEELEC.pdf – accessed on : 02.03.2010

Overseas Japan Electric Power Investigation Committee (2000): Power Delivery Losses, In: ESMAP (2007): Technical and Economic Assessment of Off-grid, Mini-grid and Grid Electrification Technologies. Technical Paper 121/07, Washington.

Parshall L., Pillai D., Mohan S., Sanoh A., and Modi V. (2009): National electricity planning in settings with low pre-existing grid coverage: Development of a spatial model and case study of Kenya. Energy Policy 37, 2395-2410.

Prasad G. (2006): Social issues. In: Winkler H. (Ed.) Energy Policies for Sustainable Development in South Africa: Options for the Future. 1st ed., Energy Research Centre, Cape Town (2006) (Chapter 5).

PricewaterhouseCoopers, Potsdam Institute for Climate Impact Research, International Institute for Applied Systems Analysis and European Climate Forum (2010): 100% Renewable Electricity- A roadmap to 2050 for Europe and North Africa.

Roe A.R. (2004): Key issues in the future development of Kenyan banking. Paper to Stakeholders' Forum on Financial Sector Reforms, Mombasa.

Rosenthal, R. (2010): GAMS- A User's Guide. GAMS Development Corporation, Washington.

Rufin C., Rangan U.S., and Kumar R. (2003): The changing role of the state in the electricity industry in Brazil, China and India. American Journal of Economics and Sociology 62 , 649-675.

Shah S. (2010): The cost of electricity in Kenya. http://rayofsolaris.net/blog/2010/the-cost-of-electricity-in-kenya/ - accessed on: 29.03.2010.

United Nations (2006): The Millennium Development Goals Report 2008. New York.

United Nations (2008): The Millennium Development Goals Report 2008. United Nations Department of Economic and Social Affairs (DESA), New York.

United Nations Development Programme (s.a.a): Energy for Sustainable Development. http://www.undp.org/energy/engmdgtop.htm - accessed on 04.05.2010 – accessed on: 01.06.2010

United Nations Development Programme (s.a.b): MDGs report Kenya. http://www.ke.undp.org/download.php?f=571__UNDPKE-MDGs%20report%20Kenya.pdf - accessed on: 01.06.2010

United Nations Development Programme (s.a.c): Program document for Kenya. http://www.undp.org/africa/programmedocs/KENYA-CPD-2009-2013.pdf - accessed on: 06.06.2010

United Nations Development Programme (2009): Draft country programme document for Kenya (2009-2013). www.undp.org/execbrd/word/DPDCPKEN1.doc - accessed on: 05.04.2010.

United Nations Development Programme and World Bank (2000): Reducing the Cost of Grid Extension for Rural Electrification.Washington.

United Nations Energy (2005): The Energy Challenge for Achieving the Millennium Development Goals. s.l.

United States Department of Energy (s.a.): Balance of System. http://www1.eere.energy.gov/solar/bos.html - accessed on: 26.04.2010.

Victor D., and Heller T. (2006) The Political Economy of Power Sector Reform: The Experiences of Five Major Developing Countries Technical Report, Cambridge University Press, Cambridge.

Watanabe C., Nagamatsua A., and Griffy-Brown C., (2002): Behavior of technology in reducing prices of innovative goods-an analysis of the governing factors of variance of PV module prices, Technovation 23, 423-436.

Williams A., Eberhard A., and Dickson , (1996): Synthesis report of the biomass initiative. Biomass Initiative report PFL-SYN-01, Department of Minerals and Energy Affairs.

Willis H. L. , and Scott W.G. (2000): Distributed Power Generation. Marcel Dekker Inc.; New York.

Wolde-Rufael Y. (2009): Re-examining the financial development and economic growth nexus in Kenya. Economic Modelling 26, 1140-1146.

World Bank (2002): Private participation in infrastructure: trends in developing countries in 1990-2001. Technical Report, Washington

World Bank (2010): Kenya economic update- Running on one engine: Kenya's uneven economic performance with a special focus on the port of Mombasa. 2nd ed.

- accessed on: http://siteresources.worldbank.org/KENYAEXTN/Resources/Kenya-Economic-Update-June-2010.pdf

Zvoleff A., and Kocaman A.S., Huh W.T., Modi V. (2009): The impact of geography on energy infrastructure cost. Energy Policy37, 4066-4078.

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