Integrated Techno-Economic Comparative and Socio-Economic Impact Study for Increasing Energy Access in Rural Kenya

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Master Thesis

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Abstract

Kenya is a country with high energy poverty rates while millions of people, especially in the rural areas, rely on kerosene lamps as a source of lighting. The usage of kerosene is linked with the degradation of different social and economic aspects and parameters, such as health, education, income etc. At the same time, grid extension and connection to that require a very high capital. In other words, the state's limited financial resources do not allow the sustainable development of rural electrification while rural families cannot afford the installation and consumption costs of electricity in the areas where the national grid has reached.

The latest years, alternative solutions to grid connection such as solar lamps, larger solar kits and microgrids have made their appearance in Kenya and they offer the opportunity to people to turn into cleaner and healthier sources of lighting and electricity.

This MSc thesis has two goals. The first one is to measure and quantify various differences on socio-economic parameters between kerosene lamps and solar lantern users. The second one is to identify, design and compare alternative solutions to grid extension for rural electrification. Therefore, this work is separated in two parts. The first part is a socio-economic impact study, conducted in Kenya between May and July 2014 as an interview survey. The second part is a techno-economic comparative study between the different alternatives for rural electrification that exist nowadays in Kenya, which has as a base the designing and sizing of renewable energy microgrids for five remote communities in the country.

The results of the socio-economic study showed that the source of lighting has a great impact on people’s quality of life, aspects of development and escape from poverty. Families that use solar lanterns recorded better education, health and income levels while the kerosene lamp usage seem to have great connection to drudgery, high expenditures, bad school grades and degraded living conditions. As far as the techno-economic comparative study is concerned, it has been shown that both solar lanterns and microgrids have a significantly lower cost in comparison to the respective expenditures of rural families in Kenya for kerosene lamps and fuel. As a result these technologies are able to cover the gab that is left by the low or zero rates of grid extension in remote areas and they can be an affordable, healthier and more sustainable solution for those rural households that rely on kerosene as a source of lighting and lack at the same time access to essential services such as phone charging, radios and other appliances.
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**Abbreviations**

GDC: Geothermal Development Corporation
KenGen: Kenya Electricity Generating Company
KES: Kenyan Shilling
KPLC: Kenya Power and Lighting Company
NGO: Non-Governmental Organization
NOCK: National Oil Corporation of Kenya
PAYG: Pay As You Go
REA: Rural Electrification Authority
SE4ALL: Sustainable Energy for All
SHS: Solar Home System
USD: United States Dollar
N/A: No Availability

*Optimal microgrid: The most cost effective microgrid strictly among the ones designed under this MSc thesis

**Solar lanterns, solar lamps and solar lights are considered the same kind of energy system
Introduction

Nowadays in Kenya, only 19% of the total population has access to electricity (1), which means that more than 34 million people mainly rely on polluting and dangerous sources of lighting. The majority of these people live in rural communities, far away from the national grid which is extended under very slow rates. That lingers the development of rural electrification and these communities will continue to live under energy poverty for the following years.

For households that have lack of access to electricity, the main source of lighting is kerosene lamps. The usage of kerosene has critical consequences in the quality of rural families and condemns them to poverty. More specifically, kerosene fumes are highly toxic and they lead to death more than 400,000 people annually (2). This is a result of lung cancer and other respiratory system diseases, while since the process of affection by the exhaust gasses is slow and most of the times people do not realize it, kerosene lamps are also known as “silent killers”. Except the health effects, the usage of kerosene lamps is connected to other poverty related and socio-economic factors such as high expenditures on fuel, drudgery, education, social and productive activities.

Therefore, important questions arise. Can the impact of kerosene lamps be measured and quantified? Which are the different aspects of people’s lives that are affected by kerosene lamps and condemn them to poverty and how much do they impact on them. What would be the difference in the daily life of rural families if the kerosene lamp was abolished?

In order to answer these questions, a socio-economic impact study was conducted under this MSc thesis. The study aimed to examine the impact of kerosene lamps on various socio-economic factors and the difference that can be done by replacing kerosene lamps with the simplest alternative source of lighting which is solar lanterns, under the specific case study of rural Kenya. In order to collect data, a field trip was performed in Kenya between May and July 2014. The research was conducted as a questionnaire survey, while the participants were asked in two different ways, phone interviews and field interviews in rural communities of West Kenya.

The scope of that socio-economic study which measured and quantified the great differences in various aspects between kerosene lamp and solar lantern users in Kenya, was to show and promote the importance of abolishing the kerosene lamp and eliminating energy poverty by increasing energy access for rural households.

At the moment in Kenya, there are some efforts towards the direction of increasing energy access for poor and unelectrified areas. The country is participating in the Sustainable Energy for All - UN initiative, while also one of the main goals of the national development plan VISION 2030 is to secure electricity access for all the Kenyan citizens until 2030. Moreover, Kenya is a country with increased renewable energy potential and specifically solar, wind and geothermal energy. However, it is a developing country with limited financial resources while corruption infests the national economy and progress. That means achieving the goals of SE4ALL and VISION 2030 for energy access is a difficult or even impossible task for the current and next governments.

In practice, rural electrification faces more problems. Grid extension requires a very high capital as the development of new MV lines cost $10,000 USD per km (3). In addition to that, the installed
power capacity of the country is less than half of the country’s power load demand, which means that in order to achieve rural electrification by extending the national grid not only requires new transmission lines but also new power plants. At the same time, connection to the grid is very expensive for the majority of rural households, thus the phenomenon of “under-grid” houses, which are houses very close to the grid but they cannot afford the connection fee and charges, is very frequent. Nevertheless, solar home systems (SHSs) are an expensive solution which corresponds to middle to high income households and not to the bottom of the economic pyramid.

The limitations of electricity grid extension emerge the need of finding alternative ways in order to increase energy access for remote communities. In order to investigate through which solutions this can be achieved, a techno-economic comparative study in combination to a market research in Kenya was conducted under that MSc thesis. That happened as one of the basic principles of that thesis was to include data and produce results that correspond to the current situation and available technologies in Kenya, while also propose solutions that are directly implementable and affordable for rural families. The best three alternatives that were identified in Kenya were renewable energy microgrids, solar lanterns and larger solar kits.

The purpose of that techno-economic comparative study was firstly to design renewable energy microgrids for five rural communities in Kenya, which were selected according to the climate characteristics of the regions they belong. Then, the cost of microgrids was compared to solar lanterns and larger solar kits. Thus, the feasibility of different energy systems was assessed and for each community the optimal solution for increasing the energy access was derived. Nevertheless, the comparison is expanded to technical, social, entrepreneurial and other factors that concern the applicability of renewable energy technologies in Sub-Saharan Africa.

The results of the techno-economic study address to the involving stakeholders in Kenyan rural electrification, the government, public and private organizations and they intend to direct them to alternative paths of eliminating energy poverty in the country. Moreover, they aim to provide a detailed design of microgrids to organizations with the capacity to implement it such as the Rural Electrification Authority, Kenyan Power and private energy companies. In general, this study is an effort in contributing as much as it can be possible to the goals of Sustainable Energy for All – UN initiative and Kenya VISION 2030 to a brighter and cleaner future for rural Africa.

Chapter 1 of the MSc thesis, the energy background and potential of Kenya is presented, while also a reference to previous socio-economic and techno-economic studies and their weaknesses is done. Chapter 2 concerns the socio-economic impact study, methodology and results. Chapter 3 is a review on the current technologies, ownership and payment schemes that can be found for rural electrification in Kenya. In chapter 4, the techno-economic comparative methodology and aspects are extensively analyzed. Chapter 5 presents the results and conclusions of the techno-economic impact study. Lastly, chapter 6 is a summary of the general conclusions and lessons learned from that MSc thesis.
1 Background and literature review

1.1 Kenya outlook and energy poverty

Kenya is a country of 580,367 km$^2$ which makes her the 49th biggest country in the world and 23rd in Africa. The country’s population is 45,010,056 while more than 43.4% of it lives under the poverty line (4). With total GDP of $41.117 billion USD and GDP per capita of $976 USD (5), Kenya is the largest economy of East Africa but still one of the poorest countries in the world even if it has a high potential of natural resources exploitation and development of productive sectors such as heavy industry, tourism and energy generation, that could create wealth and increase the living standards.

Even if in Kenya there is an emerging energy market that is highly based on renewable sources, the energy poverty continues to be one of the biggest problems in the country. According to the World Bank (1), only 6.7% of the rural population has access to electricity. In the urban areas, the percentage of people that has access to electricity is 58.2%. In total, only 19.2% of the total population has access to electricity, which equals to more than 34 million people.

1.2 Energy Sector in Kenya

1.2.1 Energy Mix

Kenya has an installed effective capacity of 1,664 MW. The main electricity generation sources are hydro, geothermal and thermal power while the small wind power share is expected to be increased the following years (6). The total penetration of renewable energy sources is more than 80%, which makes Kenya one of the most sustainable countries in the world, as far as the power generation is concerned (7). As hydro is a fluctuating source of energy, it creates instabilities in power generation.

In addition to that, insufficient investment in country’s energy infrastructure has led to the need of diesel power plants installation, that have a high cost of energy generation, between $26 and $36 USD/kWh. The installed capacity per energy source is the following:

<table>
<thead>
<tr>
<th>Energy Source</th>
<th>Installed capacity (MW)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hydro</td>
<td>770</td>
</tr>
<tr>
<td>Thermal</td>
<td>622</td>
</tr>
<tr>
<td>Geothermal</td>
<td>241</td>
</tr>
<tr>
<td>Cogeneration</td>
<td>26</td>
</tr>
<tr>
<td>Wind</td>
<td>5.1</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>1664.1</strong></td>
</tr>
</tbody>
</table>

Table 1 Installed capacity in Kenya by source of energy
1.2.2 Electricity Consumption profile

Urban Kenyan households consume annually 844 kWh in average while the respective amount for rural households is 544 kWh. As far as the average per capita energy consumption, urban population per person consumes 216 kWh while rural population consumes 115 kWh per person (8).

There are four categories of electricity consumption schemes, domestic, small commercial, interruptible and street lighting. All schemes have a fixed charge of 1.41 US$ while this covers consumption up to 15,000 kWh per month. For domestic customers, there are three tiers of consumption, 0-50kWh, 51-1500 kWh, higher than 1,500 kWh per month, which add an extra cost of $0.024, $0.096 and $0.22 USD per kWh respectively. For small commercial, interruptible and street lighting schemes, the price of kWh is $0.11, $0.06 and $0.09 USD respectively.

1.2.3 Energy Sector Stakeholders

The stakeholders of the electricity in the country are the following (9):

- **The Ministry of Energy (MoE)** develops the energy policy of Kenya, the least cost energy plans, while also it administrates the Rural Electrification Scheme. Part of MoE is the renewable energy department which is consisted by the following divisions: solar, wind, mini & micro hydro and energy conversion.

- **The Kenya Electricity Generating Company (KenGen)** is the public and main power producer that holds more than 75% of the total installed capacity. KenGen sells electricity in bulk to KPLC which then distributes it to the customers.

- **Kenya Power and Lighting Company (KPLC)** which owns all transmission and distribution assets, buys electricity in bulk from KenGen and independent power producers (IPPs), in order to transmit, distribute and retail it to the customers.

- **Independent Power Producers (IPPs)** build, own and operate power stations and sell the power in bulk to KPLC. IPPs in Kenya hold only thermal power plants. There are four IPPs namely:

<table>
<thead>
<tr>
<th>IPP</th>
<th>Operating Capacity (MW)</th>
</tr>
</thead>
<tbody>
<tr>
<td>IberAfrica</td>
<td>56</td>
</tr>
<tr>
<td>Tsavo Power</td>
<td>74</td>
</tr>
<tr>
<td>OrPower</td>
<td>48</td>
</tr>
<tr>
<td>Mumias</td>
<td>2</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>180</strong></td>
</tr>
</tbody>
</table>

*Table 2 Independent Power Producers (IPPs) in Kenya*

- **Energy Regulatory Commission (ERC)** reviews electricity tariffs and enforces safety and environmental regulations on electrical energy, petroleum and related products, renewable energy as well as safeguarding the interests of electricity consumers. ERC is also active in collecting data and handling statistics while also prepares country’s energy plans in cooperation with the Ministry of Energy and ensuring the implementation of the principles for competition in the energy sector.
The Rural Electricity Authority (REA) develops and implements the country’s rural electrification plan under the administration of the Ministry of Energy. In addition, REA manages small projects based on renewable energy, such as hydro, solar and wind power. Furthermore, the authority manages the Rural Electrification Program Fund.

Kenya Electricity Transmission Company (KETRACO) is government owned and it is mandated to construct, plan, design, build and maintain electricity transmission lines and associated substations with government funding to accelerate infrastructure development.

Geothermal Development Company (GDC) is tasked to promote rapid development of geothermal electric power and to manage geothermal resources. GDC aims to expand its activities in other utilities except electricity, such as hot water for residential usage such as space heating and for industrial and agricultural applications, such as seed drying and pasteurizing.

Figure 1 The Kenyan energy sector

In order to decrease the lack of electricity in areas where it is not cost effective to extent the grid, there are isolated power plants called Isolated Power Stations (IPSs). The IPSs work either with thermal power or renewable energy. Moreover, as there are many fluctuations and failures in the grid, there are several installed Emergency Power Plants (EPPs). The current installed independent power stations (IPSs) in Kenya are the following (10):

<table>
<thead>
<tr>
<th>Location</th>
<th>Diesel Capacity (kW)</th>
<th>Wind Capacity (kW)</th>
<th>Solar Capacity (kW)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Baragoi</td>
<td>128</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Eldas</td>
<td>184</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Elwak</td>
<td>360</td>
<td>0</td>
<td>50</td>
</tr>
<tr>
<td>Habaswein</td>
<td>800</td>
<td>50</td>
<td>30</td>
</tr>
<tr>
<td>Hola</td>
<td>800</td>
<td>0</td>
<td>60</td>
</tr>
<tr>
<td>Lodwar</td>
<td>1440</td>
<td>0</td>
<td>60</td>
</tr>
<tr>
<td>Lokichogio</td>
<td>520</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Mandera</td>
<td>1600</td>
<td>0</td>
<td>300</td>
</tr>
<tr>
<td>Marsabit</td>
<td>2400</td>
<td>500</td>
<td>0</td>
</tr>
<tr>
<td>Merti</td>
<td>138</td>
<td>0</td>
<td>10</td>
</tr>
</tbody>
</table>
1.3 Renewable energy status and potential

1.3.1 Hydro Power

Hydro power counts for 42% of the total installed capacity in Kenya while there are 14 large scale power plants of 759.68 MW and 31 MW of small scale plants across the country. The potential is much higher as it is estimated that the total potential capacity is between 3000 MW and 6000 MW (7). However, the future energy policy in Kenya will turn in other sources in the future because of the fluctuations and uncertainties that are caused by the poor rainfall. KenGen is the only operator of hydro power in Kenya.

<table>
<thead>
<tr>
<th>Hydro Power station</th>
<th>Installed capacity (MW)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gogo</td>
<td>60</td>
</tr>
<tr>
<td>Gitaru</td>
<td>225</td>
</tr>
<tr>
<td>Kamburu</td>
<td>93</td>
</tr>
<tr>
<td>Kindaruma</td>
<td>72</td>
</tr>
<tr>
<td>Kiambere</td>
<td>72</td>
</tr>
<tr>
<td>Masinga</td>
<td>40</td>
</tr>
<tr>
<td>Mesco</td>
<td>0.38</td>
</tr>
<tr>
<td>Ndula</td>
<td>2</td>
</tr>
<tr>
<td>Sagana</td>
<td>1.5</td>
</tr>
<tr>
<td>Sondu Miriu</td>
<td>60</td>
</tr>
<tr>
<td>Tana</td>
<td>20</td>
</tr>
<tr>
<td>Turkwel</td>
<td>106</td>
</tr>
<tr>
<td>Wanjii</td>
<td>7.4</td>
</tr>
<tr>
<td>Sosiani</td>
<td>0.4</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>759.68</strong></td>
</tr>
</tbody>
</table>

Table 4 Hydro power stations in Kenya

Pico and small hydro power can have a big impact in decreasing energy poverty in Kenya, and especially in remote areas where the extension of the grid is not feasible. More specifically, the potential of small hydro power plants up to 10 MW is approximately 3000 MW (7) while the potential for pico hydro power units up to 5 kW is 3 MW (11).
1.3.2 Geothermal Power

Along with Ethiopia, Kenya is the only country in Africa that has exploited a part of its available geothermal energy. Researches claim that the total potential is between 4000 MW and 15000 MW (7; 12) as there is significant volcanic activity in the area. For that reason, the Kenyan government has founded the Geothermal Development Company, which has the goal to promote and develop further the respective power sector. The largest existing power unit is the Olkaria power station which has an installed capacity of 163 MW and is operated by KenGen and OrPower. In 2012, the new Eburru Geothermal Power Plant was synchronized with the grid providing 2.52 MW of electricity. Moreover, the new Olkaria IV unit that is supposed to be commissioned in 2014 will add 140 MW to the national grid, while the Menengai plant will supply it with 100 MW and Olkaria VI & VIII with another 420 MW.

1.3.3 Solar Power

As Kenya is located on the equator, there is a significant potential of solar energy harvesting. More specifically, the country’s irradiation is between 4 and 6 \( \frac{kWh}{m^2\text{day}} \), with a mean value at 5 \( \frac{kWh}{m^2\text{day}} \). The following picture and table indicate the solar energy potential that could be exploited for electrification:

![Figure 2: Annual sum of hourly Direct Normal Irradiation (DNI) for Kenya (2000-2002 averaged) (7)](image-url)
The significant potential of solar energy harvesting has resulted in an emerging solar energy market. That market is consisted by import and manufacturing companies, vendors, NGOs, installers and after sale service providers. The household solar system installations per year, which are more than 3000 systems between 20 W and 100 W is the highest in the world (7).

More specifically, there are 15 to 40 solar equipment suppliers in Kenya while also three batteries manufacturers and nine lamp manufacturers. The sellers are a few hundreds and there are also more than 2000 technicians (7). In 2009, the total installed capacity of PVs was 8 MW to 10 MW which equals to 320,000 solar home systems (SHS), while the estimated annual increase rate is 1-2 MW (13). It should be mentioned that the installation of SHSs is not taking place as a part of the governmental energy plan; therefore, it is not considered part of the national energy policy as it is owned by privates and does not supply neither the national grid nor any isolated grids.

Solar energy will play an important role in the energy future of Kenya. Even if there is an ongoing extension of the grid, there is an estimated total penetration of 30 MW for SHS, and especially at remote and rural areas (13). In a large scale level, the Kenyan government has invested more than 500 million dollars in the construction of solar power plants across the countries. The total cost of the projects is 1.2 billion US$ while they will also be funded by the private sector. They are expected to have finished until 2016 and they will consist the 50% of the total power generated in the country (14).

### 1.3.3.1 Solar Water Heaters (SWHs) new regulation

A notable new regulation that concerns the solar water heaters (SWHs) installation was introduced in 2012. According to that, all premises that have an exceeding requirement of 100 litters of water per day are obligated to install SWH equipment in order to cover their needs. In addition, all electric power distributors and suppliers will not provide electricity to new premises that do not comply with the regulation, while all installations should be performed by certified technicians or constructors.
1.3.4 Wind Power

Most parts of Kenya are characterized as low wind sites where wind speeds vary between $1\,\text{m/s}$ to $5\,\text{m/s}$. However, in the northern region Marsabit there is a significant potential of wind power, since there are measured average wind speeds between $4.6\,\text{m/s}$ and $11.6\,\text{m/s}$ while the maximum measured wind speed is $22.3\,\text{m/s}$ (7). The following wind atlas summarizes the wind speed profile of the country:

The low wind in most parts of the country makes the implementation of large scale wind projects not feasible but it can provide the essential wind energy for powering pico and mini wind turbines, especially in areas where the extension of grid is not currently possible. Also, there is a small number of companies based in Nairobi that work on small scale wind power which they even manufacture themselves.

At the moment, there is an uprising large scale wind power sector in Kenya. The first wind farm was the Ngong Hills, built in 1993 with maximum capacity of 5.1 MW. KenGen plans to extend the capacity of the wind farm up to 25.5 MW. Except the extension of Ngong Hills farm, there are several other wind power projects. Isiolo wind farm project, which is a part of the Kenya Vision 2030 initiative, is expected to be delivered by 2016 and will supply the national grid with 50 MW. In addition, the Lake Turkana project will be the biggest wind power unit in Africa since it will have a total capacity of 300 MW, while it is planned to be commissioned in 2016.
1.4 Vision 2030

VISION 2030 is Kenya’s development plan between the years 2012 to 2030. The goal of the development plan is to transform Kenya into an industrialized middle-income economy with increased quality life, infrastructures and services for the citizens. The goals of VISION 2030 are based on three main pillars, political stability, social development and economic growth. Political stability refers to a democratic society where the rights of citizens are respected and laws are the core of governance. Social development corresponds to the establishment of a society that is based on equality and a secure and clean environment while economic growth refers to a 10% growth rate of GDP until 2030 (15).

As access to energy is an essential factor of prosperity and development, VISION 2030 has specific goals in order to change drastically and fundamentally the country’s energy profile. More specifically, there are six main pillars that are set for VISION 2030 (16):

1. Improvement of quality and reliability of electricity supply throughout the whole country
2. Installation of new power plants that will support the national grid
3. Access to electricity for areas that are currently not connected to the national grid
4. Creation of an interconnected grid with neighbouring countries in order to facilitate power exchange and develop electricity trade in the region
5. Reduction of transmission losses that currently have a total cost of US$17 million per year
6. Reduction of the cost of electricity for consumers

As it is mentioned above, a number of power plants funded by both public and private investments will be built in order to electrify the national grid. The following table summarizes the power generation projects that will be developed by VISION 2030 (17; 18).
<table>
<thead>
<tr>
<th>Project</th>
<th>Cost (million USD)</th>
<th>Capacity</th>
<th>Promoter</th>
</tr>
</thead>
<tbody>
<tr>
<td>Olkaria V</td>
<td>504</td>
<td></td>
<td>KenGen</td>
</tr>
<tr>
<td>Olkaria VI &amp; VIII</td>
<td>2 billion</td>
<td>420 MW</td>
<td>KenGen</td>
</tr>
<tr>
<td>Turkana Wind</td>
<td>623</td>
<td>300 MW</td>
<td>KenGen</td>
</tr>
<tr>
<td>Transformer Manufacturing</td>
<td>60</td>
<td>-</td>
<td>Ministry of energy</td>
</tr>
<tr>
<td>Solar PV Panels manufacturing</td>
<td>40</td>
<td>2 MW</td>
<td>Ministry of energy</td>
</tr>
<tr>
<td>Menengai Phase I-I</td>
<td></td>
<td>200 MW</td>
<td>GDC</td>
</tr>
<tr>
<td>Wind Energy - Isiolo</td>
<td>150</td>
<td>50 MW</td>
<td>KenGen</td>
</tr>
<tr>
<td>Mombasa Petroleum Trading Hub – Single Buoy Mooring (SBM)</td>
<td>400</td>
<td>800 GT</td>
<td>NOCK</td>
</tr>
<tr>
<td>Liquefied Natural Gas (LNG) storage and Regasification facility with associated power generation</td>
<td>830</td>
<td>450 MW</td>
<td>Ministry of energy</td>
</tr>
</tbody>
</table>

Table 5 List of power plants to be developed under VISION 2030

1.5 SE4ALL framework

In 2011, the UN Secretary-General Ban Ki-Moon, launched the Ban Ki Moon global UN initiative, Sustainable Energy for All (SE4ALL). The initiative targets to build cooperation between governments, the private sector, non-governmental organizations (NGOs) and other involving players of the energy sector in order to achieve the following three goals until 2030 (19):

1. Ensure universal access to modern energy services
2. Double the global rate of improvement in energy efficiency
3. Double the share of renewable energy in the global energy mix

Energy access is an essential and fundamental principle for a sustainable way of living and development. Therefore, the first goal of SE4ALL is to ensure that until 2030 all people universally will have access to clean and reliable energy sources. Approximately 40% of the earth’s population rely on unhealthy and expensive sources of lighting and cooking such as wood, kerosene, animal dung, charcoal etc. This has a crucial both on people’s health, quality of life and productive activities. More specifically, the incineration of these sources produces toxic fumes, which are dangerous as they can cause from simple irritation of eyes to serious illnesses and death, while only kerosene is responsible for the death of more than 4.3 million people annually (20). Except the impact on health, people have not only a poor quality of life but even be led to extreme poverty, as lack of electricity deprives from households essential appliances for development and growth and prosperity, such as lighting, phone charging, fan cooling etc.

Energy efficiency means that the available processes of power generation on the one side and the energy utilization on the other side are used in a sustainable, cost effective and clean way. Innovation is a key point in order to achieve that, as residential, transportation and industrial appliances minimize their needs for electricity or fuels, while new technologies are developed in order to extract more energy by conventional and renewable sources. This can be translated to
decreased costs for the consumers, creation of jobs, economic growth, less emissions and increased energy access as the wasted energy can be shared in electrified households. As a result, energy efficiency is an essential goal of the SE4ALL framework.

The third goal aims to the doubled penetration of renewable energy sources in the energy mix. On the one hand, renewable energy will contribute to the reduction of greenhouse gases emissions, pollution and therefore, it can play a critical role against the climate change. On the other hand, the lowering cost of renewable energy technologies will make access to electricity easier while investments on that sector increase the countries’ economic growth, create jobs and ensure better energy security by decreasing the dependence on fossil fuels the conflicts.

The three goals of SE4ALL framework are interrelated and in order to achieve them, simultaneous step have to be done. More specifically, energy poverty and climate change can only be eliminated through increased energy efficiency and energy sources that cost and pollute less. In addition to that, energy efficiency is highly related to renewable energy, as it is the only way to cover the energy needs without relying on fossil fuels. However, the innovative development of renewable energy technologies is the only way to make solar, wind and other sources cheaper than oil, charcoal, natural gas etc.

1.6 Vision 2030, SE4ALL and rural electrification in Kenya

It is notable that Vision 2030 development plan of Kenya and SE4ALL initiative goals that concern the energy sector coincide. More specifically, both schemes target to achieve global energy access which is based on more reliable, cheaper and cleaner energy sources until the year 2030. In addition to that, both emphasize on increased penetration of renewable energy technologies and sustainable energy management. This fact is expected to act promotionally for increasing rural electrification in Kenya as under cooperation they can mutually support each other in order to eliminate energy poverty in the country.

1.7 Solar Aid/Sunny Money

The conduction of the field trip in Kenya and collection of data for that MSc thesis was done under the cooperation with Solar Aid and Sunny Money as an internship. Solar Aid is the biggest NGO in Africa that works with rural electrification and increasing of energy access. The overall goal of the NGO is to abolish from Africa until 2020 the kerosene lamp. Solar Aid has established operations in five countries, Kenya, Tanzania, Malawi, Zambia and Senegal while it plans to expand further. Until today, Solar Aid has changed the lives of millions as it has distributed more than 1,400,000 solar lamps in Africa, making a step forward to the elimination of energy poverty. In 2006, Solar Aid founded a social enterprise, Sunny Money in order to catalyse its operations, create income and jobs for the involving customers and implement a revolutionary approach in the solar light market. Nevertheless, Solar Aid conducts and implements all its operations through Sunny Money as the model of distribution has been proved successful.
1.7.1 The Sunny Money model

The model of Sunny Money operational model has introduced an innovative way of approach. As that thesis was done under cooperation with Sunny Money, a chance was given to participate, help and assess that model in the field. Sunny Money model of operations is the following:

Organized field trips, in which Sunny Money employees participate, are performed in different parts of Kenya. The purpose of the field trips is to organize demonstrations of the solar lamps to teachers in rural areas. Usually these demonstrations take place in a central school of a bigger town where teacher from around villages and smaller communities are gathered.

![Figure 6 Sunny Money products' demonstration to teachers](image)

The reason of organizing demonstrations specifically to teachers is that Sunny Money involves them in its operations as its agents. More specifically, after each demonstration, every teacher is supplied with a solar lantern and information on the function, impact and benefits of the lamps in comparison to kerosene lamps. After leaving the demonstration, the teachers use the provided solar lamp and information in order to transfer to their students their newly adopted knowledge on that technology. In continuity, the teachers create a detailed list of the students that express interest to buy a solar lamp from Sunny Money.

Thus, a list of customers is created in every school while the teachers are turned to Sunny Money agents. In addition, for every solar lamp that is bought by students, the teacher receives a small financial reward. Through this way, Sunny Money gives motivation to the teachers in order to raise awareness for solar lamps, creates income for them and catalyses its operations in order to replace kerosene lamps to cheaper, healthier and more modern sources of lighting. Finally, except that model, Sunny Money contributes to the elimination of energy poverty by supporting solar lamp entrepreneurs, providing marketing and training campaigns and helping with the shipment of products.
1.8 Previous techno-economic studies

Modelling and sizing energy systems and optimizing their performance are the most important procedures in order to study and find solutions for rural electrification. Until today, research has been done in order to define different approaches and ways of modelling, sizing and optimization. Most of them are based on mathematical or empirical models that focus on climate data such as solar irradiation and wind speed, while others focus on the control strategies of the energy system. In addition, optimization can be done either on harvesting the available energy sources or minimizing the cost of the system, while many studies focus on combination of the previous aspects.

A variety of software that uses these models is available nowadays and has been used extensively. These software commonly utilize climate data, technical specifications, equipment costs and electrical or thermal loads as inputs and produce outputs that concern the Net Present Value (NPC), the levelized, salvage, operation and maintenance (O&M) costs, while also the optimal sizing of the energy system according to the available technologies.

As far as the electrification of rural areas in developing countries is concerned, a number of studies that uses the referred models have been performed. The following section is an overview of aspects, parameters and limitations of those studies that examine the optimization of small hybrid or renewable energy systems and have similarities with the MSc thesis.

1.8.1 Studies based on HOMER Energy software

In 2011, Bekele G. and Tadesse G. (21) published a techno-economical study of a hybrid PV/Wind/Hydro energy system for electrification of six cities in Ethiopia and performed the sizing of the system and to obtain the cost of it with HOMER Energy software (22). In a similar research, Shaahid and El-Amin (23) use HOMER energy in order to optimize the hybrid Diesel/PV energy system of a remote village in Saudi Arabia. The study compares a diesel system with the hybrid one and finds that the second one can improve the efficiency and minimize the while also a reduction in the capacities of diesel and battery can take place (23). In addition, it shows that solar energy can play an important role in the energy mix because of the country’s high potential. Hrayshat (24) designs with HOMER energy a hybrid diesel/PV system for a remote village in Jordan and defines the price of diesel fuel per litter that makes it economically feasible. Himri Y. et al. (25) propose a comparable solution for a remote village in Algeria but they investigate a hybrid diesel/wind energy system. Shaahid and Elhadidy (26) investigate through HOMER Energy the effect of the size of the battery bank on the operation hours and on the energy provided by the diesel generator in Wind/Diesel energy system. More recent publications that work on relevant subjects are Asrari et all (27) for an Iranian village and Kobayakawa and Kandpal (28) for rural India.

These publications are the most relevant studies with that master thesis as they use HOMER Energy software in order to design and optimize off-grid energy systems for rural electrification in developing countries. However, there are certain aspects that have been taken under consideration in this thesis, while they are missing from the previous publications. First of all, in rural electrification, transmission losses that are not calculated in those studies should be taken under consideration as power has to be shared in households that they are far from each other. Therefore, if they are not taken under consideration during the definition of the load at HOMER Energy, this will conclude in a
smaller system. Furthermore, in the installation of energy systems and especially in rural areas, there are other non-negligible costs such as wiring, PV or wind turbines mounting while also transportation and labour costs, which affect significantly the budget of projects. In the previous publications, these costs are not counted. Moreover, none of those studies have included or sized the charge controller, which is an essential component in stand-alone energy systems. Nevertheless, all of them propose for the battery bank, the Surrette 6CS25P type, which is a pre-existing battery on HOMER Energy components library. However, not only this type might not exist in certain countries’ energy markets but also there might be more efficient and less costly option. In general, it can be seen that the studied components of the energy systems are not included after market research but more on the library of the software.

1.8.2 Previous studies on rural electrification of Kenya

An MSc thesis from Gotland University (29) focuses on a hybrid diesel/wind energy system for rural electrification in Kenya, while also it utilizes HOMER energy software. However, it has certain strong weaknesses. More specifically, the diesel generator price is based on a 7 years old research and is obtained from the Canadian energy market. The same happens, with all the other components as batteries, wind turbines and converters. In addition to that, the research does not clarify if components as the proposed wind turbines and batteries exist in the Kenyan market. The generic 20kW model and Fuhrlander 30kW are only used in the research because their specifications exist in the software’s. However, they cannot be found in the Kenyan energy market and they have never been used, which means that their installation would add importation and transportation costs that would increase the initial capital of the project.

A significant drawback of the thesis is that, it has not included a charge controller for the batteries, which as mentioned before, is an essential part of off-grid energy systems. The definition of load is based on 2005 statistics for Kenyan households but it does not take account the transmission losses of the electricity. Furthermore, the initial capital of the proposed system excludes labour, transportation, wiring, mounting and other costs that exist in every renewable energy project and are a significant part of the overall cost. Nevertheless, the study does not examine if and how such an system can be financially funded either by the users or by the Kenyan government in order to be implemented. In general, the thesis has a good approach on rural electrification; however the lack of technical and economical parameters and realistic information on technologies and costs does not make the proposed system a considerable solution.

Lukuyu and Cardell in their research on hybrid systems for Northern Kenya (30) introduce a different and more integrated approach. They perform a multi-attribute trade-off analysis according to which a system planning problem can have several optimal solutions instead of one (30). Multiple combinations between PV, wind and diesel hybrid systems with and without batteries are modelled on HOMER Energy, in order to examine the replacement of current diesel generators with a hybrid system for the electrification of Marsabit town. After, they compare the different hybrid systems in order to find the most cost effective solution of replacement. The question is that since HOMER Energy software has the ability to compare all those different solutions in a single optimization procedure, why the researchers choose to do separate optimization procedures for each system and after compare the solutions. In addition, again as previously research does not include several costs
such as transportation, wiring and labour while also they exclude the charge controllers which are essential for an off-grid system and for the respective size it would significantly increase the cost.

Nevertheless, both this MSc thesis and Lukuyu and Cardell’s research (30) focus on electrification of Kenya and they even use the share a region as a subject of study. Someone could extract a rough conclusion that the publication partially overlaps the subject of this MSc thesis. However, the difference is significant as the publication studies a very large system that intends to cover the needs of a town, while in that thesis focuses on remote communities.

Such a large system is not affordable by the users, while the funding of such a project either by the public or the private sector could make its implementation extremely hard or impossible. Moreover, the size of systems’ components is totally different while no mention is done on the sources of pricing. Also, communities that are far from the town will continue to leave without access to electricity as their connection to the regional grid is not included in the research. On the other hand, this MSc thesis intends to compare solutions that are affordable for the users, without relying on the bureaucracy and lack of funding of the public or private sector, while also they are immediately accessible and implementable. Nevertheless, this study is extended to five different parts of Kenya and not only one region.

Lastly, Rabah (31) published in 2005 a study for integrated solar systems for Kenya. In this publication, a reference has been done on the solar potential of Kenya, a common sizing method of solar energy systems is referred and finally a practical implementation is proposed for a household in Lodwar, Northern Kenya is done. However, this study has several limitations as the only pragmatic relation with Kenyan rural electrification is the solar data that are used. No reference is done on technologies that correspond to Kenya and the researcher proposes a theoretical size, while also no equipment or external cost is mentioned.

1.9 Previous Socio-economic studies

A number of socio-economic studies that examine the impacts of rural electrification in developing countries have been published the previous years. They examine how different aspects of people’s lives, such as health, education, behaviour and productive activities change when they have access to modern energy sources. Usually these studies are based on literature work, statistics, questionnaires, direct observation and interviews. This section is an overview of those studies that focus on Kenya while also those that have similar methodology that has been followed in that MSc thesis.

1.9.1 Previous socio-economic studies on Kenya

In 2007, Arne Jacobson published an extended research (32) that focused on the ways solar electrification and SHSs are used by Kenyan households and how it affects and changes their activities. In his research, Jacobson exports three main conclusions. First of all, solar electrification benefits mainly middle class households. By middle class are meant business owners, rural professionals, school teachers, civil servants, clerics etc. Secondly, SHSs are treated more like consumer goods that can provide to the user services and applications such as televisions and cell phones. Thirdly, even if children’s studying conditions are improved by the use of SHSs, many times
the available energy is used on the previous applications instead of extending the studying hours during the evening.

Kirubi et al. (33) published a remarkable research in 2009 on how a diesel powered micro-grid in Mpeketoni, coastal Kenya boosted the development of the community. More precisely, the research examines how electrification has improved small enterprises, agriculture, banking and communication services and education. Productivity of small businesses was increased as electrification allowed people to use electrical tools. This resulted in higher revenues, not only by the greater production rates but also because of the improved quality and design of products.

Moreover, there were differences in agricultural sector. On the one hand, people hesitated to bring heavy tools such as tractors before electrification as in case of damages they had no repair services in a distance closer than 100 km. On the other hand, refrigeration of products allowed farmers to preserve goods such as milk and meat. The access to internet services and electronic equipment such as computers, printers and fax made the communication and banking sector of the area to develop. Finally, students extended the studying hours as not only they had better quality of lighting in comparison to kerosene lamps but also they could use their available time more efficiently and not on collecting wood or clean water. Nevertheless, teachers could improve the quality of homework material and give evening lectures while also students have the opportunity to work on computers.

1.9.2 Previous socio-economic studies on rural electrification

Several studies have been studying the factors and results of rural electrification in developing countries. Kanagawa and Nakata (34) developed an energy-economic model in order to examine the possibilities of electrification for rural areas in India and according to that they extract results on the increase in children’s literacy. In 2001, Wamukonya and Davis (35) published a socio-economic impact comparative study between grid connection, SHSs and unelectrified households in Namibia that has a similar method of attack with that MSc thesis. Interviews were carried out and 371 questionnaires were filled in order to make a statistical analysis of the research question.

As other studies, Wamukonya and Davis (35) found that electrification improve studying conditions and safety, while also it provides access to services such as television, refrigeration etc. However, in contradiction to Kirubi et al. (33), they conclude that access to electricity does not change income and growth activities, while also there is no impact on immigration to urban centers and nurturing. Contrary to that, a related research of Waerras et al. (36) on the impact of renewable energy projects for Southern Mediterranean countries was carried out through questionnaires and showed that the most positively affected socio-economic aspects are education, security and migration. Similar benefits of access to electricity where found in the following publications with similar methodology. Liu et al. (37) focused on the case study of Tiber, Gustavsson and Ellegard (38) (39) on the case study of Zambia, Wijayatunga and Attalage (40) and Khandker et al. (41) on the case study of Bangladesh.
2 Socio-economic impact study: The importance of abolishing kerosene lamp

2.1 Introduction

Until today, there are a number of socio-economic studies that have tried to identify the impact of rural electrification in developing countries. However, a very limited research has been done on the specific case of Kenya. Solar Aid, which is the leading NGO for solar lamps in Sub-Saharan Africa, has been measuring the health, environmental, educational and social benefits of solar lamps distribution. Nevertheless, further research is needed in order to extract solid results on the change that increased energy access can have. Moreover, until now, no socio-economic study was found in the literature and research review, that tries to compare kerosene lamps and solar lanterns extended also to the specific background of Kenya. The conduction of such a study is of paramount importance. The reason is that it can show to the different stakeholders, such as companies, governments and people around the globe, how easily they can improve the lives of millions of people.

That is the reason why one part of this MSc thesis was dedicated to assess the socio-economic impact of solar lanterns in rural households. The data for this study were collected during the field trip in Kenya, between May and June 2014. In addition, the survey was conducted under cooperation with Solar Aid/Sunny Money, NGO, which provided support in critical parts, such as interviews in rural areas. On the one hand, the study aims to examine and model the usage of kerosene lamps and solar lanterns, which were the two included lighting sources. On the other hand, the study identifies the differences and improvements that solar lanterns can bring on development and quality of life parameters, such as education, health, income, social and productive activities.

Therefore, this chapter focuses on the socio-economic impact study that took place in Kenya. Firstly, the lighting solutions that were included in the research are analyzed. After that, the methodology, which includes, the design of the questionnaires, the conduction of the field survey and the analysis of the findings, follows. Finally, the chapter closes with the presentation and the quantification of the results and conclusions.

2.2 Lighting solutions of the study

The lack of access to electricity and modern energy sources forces people to find other solutions for lighting. Nowadays in Kenya, the main conventional source of lighting is kerosene lamps. This is the most well spread device that people use in rural and remote areas, without connection to the electricity grid. In addition to that, other sources of lighting are used in Kenya, such as wood, candles, or even small LPG and diesel lamps. However, during the survey and interviews, no person indicated any other conventional source except kerosene lamps. As a result, kerosene lamps are the
conventional source of lighting that is studied in the socio-economic part of the thesis, even if during the interviews, people had the opportunity to state the differences of other fuel-based sources.

Moreover, the survey was conducted in cooperation with Solar Aid/Sunny Money, NGO. In addition, customers of the organization participated in the research. This allowed including people that have been using for a specific amount of time their solar lamps and are able to identify the differences with kerosene lamps. Furthermore, one of the most distributed products of the NGO is the d.light S2 lamp. Therefore, it was chosen to be the solar product that would be compared to kerosene lamps.

### 2.2.1 Kerosene lamps

In Kenya, kerosene lamps are the most popular source of lighting for unelectrified households. In the small rural commercial centers kerosene lamps and fuel can be found easily, as they supply the nearby communities that are not connected to the grid. There are three main types of kerosene lamps that can be found in rural Kenya, tin can lamps, hurricane lamps and pressure lamps (42). Tin-can lamps are made by used food cans and jars and they are the cheapest option as they are usually handmade and they have a very poor quality of lighting. Hurricane lamps and pressure lamps are more expensive as they are manufactured in an industrial level, they produce less smoke, use less fuel and are safer than tin-can lamps.

![Different types of kerosene lamps](image)

### 2.2.1.1 Health and environmental effects

The smoke that is produced by kerosene lamps is toxic and can cause several health problems. They are considered responsible for respiratory diseases, vision problems and lung cancer as it is estimated that an evening spent next to a kerosene lamp and breathing of fumes is equal to 40 cigarettes (43). Other dangers of kerosene lamps are skin burnings, fires and children’s poison by fuel. Even if there are many risks by the use of kerosene, people continue to use them as gradually they get accustomed to the irritating smoke. However, this source of lighting is responsible for the death of more than 400,000 people every year, only in Sub-Saharan Africa. That is why, the kerosene lamp is also known as the “silent killer” (43).

Except the health impact a kerosene lamp can have, there is also a considerable environmental impact. The reason is that, they emit black carbon, which is the second most effective climate forcing agent after CO₂ (44). In addition, according to Physics.org (45), black carbon emitted stays in the
atmosphere for only two weeks but one kilogram of it can cause the same warming that 700 kilograms of CO\textsubscript{2} can cause if they linger for 100 years. The estimated total emission of black carbon by kerosene lamps is 270,000 tons each year, which equals to 240 million tons of CO\textsubscript{2} (44).

2.2.2 D.Light-S2 solar lantern

D.Light-S2 is one of the most distributed solar lanterns in Sub-Saharan Africa and main product of Solar Aid/Sunny Money. S2 is a small solar-LED lamp, certified by Lighting Africa (46) that can provide a clear and bright light of 25 lumens for task or general lighting, while its battery can last 4 hours. It is durable and resistant to dust and mechanical stress but it cannot charge a mobile phone or plug in a radio (47). Because of these reasons, it is one of cheapest and most popular lamps available in the African solar lantern market.

![Figure 8 d.light Solar lantern](image)

2.3 Methodology

The socio-economic impact study is based on the questionnaire survey that was conducted in Kenya between May and July 2014. The survey was done under the cooperation with Solar Aid/Sunny Money, NGO as it was also part of the internship of the student at the organization.

During the field trip and internship in Kenya, 141 questionnaires were filled. The provisional first form of the questionnaire was created in Stockholm before the start of the field trip and it was designing according to the respective literature review and previous socio-economic studies. The final form was done in cooperation with the Sunny Money innovation manager and advisor of the internship as it was formulated in order to ease the survey and to add or remove the respective essential or unnecessary parts.

The target was to define the questions in such a way that they would combine both simplicity and the essential parameters, in order to facilitate the understanding and answers of the respondents,
while also to be easily handled by the interviewers. The questionnaire survey was performed in two ways and there were two main target groups that both do not have access to electricity, the kerosene lamp users and the solar lantern users. Both target groups of participants were coming from the same places and had similar wealth situations, in order to be comparable and to decrease the effect of those parameters in the results.

The first way was through phone calls to Solar Aid/Sunny Money customers, which were done by experienced employees of the NGO that specialize on that kind of research. In addition, an online based questionnaire with a user friendly interface was created in order to assist the interviewer and make faster the research that was done through phone calls, as it was filled directly from the employee without the use of printed forms. The choice to conduct the survey through this way was made on the one hand because the target group were customers of the NGO that had been using for a certain time and they could be easily reached through phone calls and on the other hand, as Swahili is the most used language in Kenya, it would be easier and more efficient to be done by a native Swahili person in order to reduce the time per interview and to avoid any mistakes as a result of the faulty communication.

The second way refers to direct interviews of people in the field which were done both by the student and the NGO employees. During the field survey, nine different rural areas in Western Kenya were visited in order to interview people that use kerosene lamp as a source of lighting. The visited areas were: Nandi, Kakamega, Kisumu, Koyulu, Masogo, Eldoret, Kisii, Chiga and Ahero.

![Map of the areas where socio-economic study was conducted](image)

2.3.1 Questionnaire layout and parameters

The socio-economic questionnaire was separated to three main parts. The first part of the questionnaire included general questions about the participant’s profile. The second part contained questions about the energy access and the related expenditures and costs of that. Finally, the third and biggest part had questions that concerned the different parameters of people lives and how they were affected by the respective sources of energy.
2.3.1.1 First part of the questionnaire

The first part of the questionnaire had questions of general interest. That would include the age, gender, profession and profession of the household. The purpose of these questions was to provide general statistical information on the total sample of population that participated. In addition, questions regarding the number of rooms per household, the number of adults and children and the monthly income of the household on the one hand aimed to provide general information of statistics interest but more importantly to provide useful data that would be used for the comparative techno-economic study that is analyzed in the next chapter.

2.3.1.2 Second part of the questionnaire

In the second part of the questionnaires, the respondents were firstly asked which sources of energy they use for lighting. The following questions were regarding the number of equipment they use, the expenditures on fuel or replacement of lighting equipment, the refueling and replacement frequency and the distance they have to cover in order to find fuels or new devices. Nevertheless, the participants were asked how much satisfied are they by the respective source of lighting. The main purpose of this part was to study the different aspects of usage that each source of lighting has and to examine how the respective they affect the income and quality of life of households.

2.3.1.3 Third part of the questionnaire

The third was the most essential and important part of the questionnaire as it provided the data that were used for the socio-economic research. This part was divided in four sections that concerned different aspects of the social and economic parameters of peoples’ lives and aimed to identify how they are affected by the respective energy sources. The four sections were:

1. Education
2. Social and household activities
3. Health, safety and indoor air quality
4. Income and business activities

2.3.1.3.1 Education

Children and adults’ education is highly affected by the source of lighting they use. Kerosene lamps provide a very poor quality of lighting while also they exhaust toxic fumes. These factors create poor reading and studying conditions for the users and eventually they prevent them to spend time one that. In addition, the kerosene is an expensive fuel especially for the rural households in Kenya which means that it is not always available while also both children and adults spend a great amount of time in order to find it.

The questions regarding the education were focused on source of the lighting that is used by the adults and children of the household. Moreover, questions were asked on the quality of lighting, the time spend on studying, the satisfaction of the users, the children’s’ school grades and the usage of radio for educational activities.
2.3.1.3.2 Social and household activities

The access to modern lighting equipment and services has a great impact on the social and household activities in rural Sub-Saharan areas. Poor lighting conditions create insecurity and migration tendencies for the users, they do not allow them to extend their productive activities in the evening hours, they force them to drudgery and they prevent them to socialize in a family or community level. In addition, people that relay on kerosene lamps for lighting are not able to charge their mobile phones and they are obligated to either visit a local store or a neighbor house that many times is located in a great distance.

The questions of this section concerned the safety and migration tendency people have in order to achieve access to electricity, the respective social and household activities they do in evening hours and the way the manage to charge, if they have, their mobile phones. In this point, it should be mentioned that mobile phones are an essential equipment that even the poorest households have, as it is the most popular, efficient and quick way of communication in both urban and rural Kenya. S2 lamp does not support phone charging but the majority of solar lanterns do.

2.3.1.3.3 Health

As it is explained before, health of people in rural areas is inseparably linked with the source of lighting they use. Participants were asked questions regarding the different health effects that kerosene lamps have on both children and adults and how these would be avoided if they changed to cleaner and healthier lighting sources such as solar lanterns. However, the overall health effects can be identified only under laboratory conditions and analysis. Therefore, the purpose of the health section was to identify the most obvious health problems that toxic fumes of kerosene cause, and therefore they affect people’s selection and behavior on sources of lighting.

Moreover, questions regarding the safety and indoor air quality were asked to the participants, in order to measure the dangers and discomfort kerosene lamps cause.

2.3.1.3.4 Income and business activities

The last section of the questionnaire concerned the activities that produce income to people. Many Kenyans and other people in Sub-Saharan Africa use kerosene lamps or candles in their small business activities. The small businesses are usually shops that sell a variety of agricultural or consumer products such as phone credit cards, and they are the main source of income generation. The source of lighting that is used in these small businesses affects their function and income as fuel-based devices such as kerosene lamps prevent people to run them during the evening hours because of the poor lighting conditions and the money they have to spend on fuel. The purpose of this section was to identify the differences of income and number of customers, for businesses that changed from kerosene lamps to solar lanterns.

2.4 Results of the socio-economic research

2.4.1 Statistical data and characteristics of the sample population

This section is referred to the general information of the participants in the survey and includes statistical data and characteristics of sample population.
2.4.1.1 Age range and gender

Figure 10 Age and gender distribution of interviews participants

2.4.1.2 Income

Figure 11 Income profile of the participants in interviews

2.4.2 Energy modeling - Profile of the participants

2.4.2.1 Solar lantern users

2.4.2.1.1 Usage

The average number of solar lanterns per household is 2.29 while ¾ of owners use their lamps for 3 to 4 hours per day. More specifically, 77% of them light their household with their PV device for that period. This is logical, as under normal to intensive mode, the d.light lamp’s battery lasts for the respective amount of time. The rest 20% uses the solar lantern for 5 to 6 hours which can be done under battery saving mode. In addition, 95% of the respondents use their lamps daily, allowing to extract the conclusion that solar lanterns are easily adopted by the users.
2.4.2.1.2 Satisfaction and maintenance of kerosene lamps

Solar lanterns release the household from toxic smoke, high expenses, drudgery and many other disadvantages of kerosene use has. As it is expected, the vast majority is declaring very happy or happy, while there is none that stated unsatisfied by the use of solar lamps.

It is interesting though, that 10% of the solar lantern users said they keep using kerosene and solar lamps simultaneously. This can be explained by the fact that, on the one hand people might not own enough solar lamps in order to satisfy the whole household needs, while on the other hand are accustomed to the use of kerosene and do not directly change to different sources of lighting.

2.4.2.2 Kerosene lamp users

2.4.2.2.1 Usage and expenditures

In this section, there can be seen the different costs and drudgery that follow the usage of kerosene lamps. According to the survey results, the households own an average of 1.73 kerosene lamps with a mean cost of 290 KES ($3.42 US) per lamp, while they change them approximately every 8 months.

The hours of daily usage are slightly different to solar users, but still Kenyans use basically for the whole evening their kerosene lamps. Also, as it can be seen in the graph, the usage of lamps takes

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![Figure 12 Hours of daily usage and usage frequency of solar lanterns](image)

![Figure 13 Satisfaction of solar lantern users and users that continue using kerosene lamp](image)

28
place in daily base, showing that is an essential device of the household, despite the inconvenience and health risks, as there is no other available means of lighting.

![Hours of daily usage and usage frequency of kerosene lamps](image)

**Figure 14** Hours of daily usage and usage frequency of kerosene lamps

### 2.4.2.2.2 Satisfaction and Drudgery
The mean walking time in order to find fuel is 33 minutes. This is explained by the fact that many respondents said they have to walk long distances, even for 1.5 hours, in order to buy kerosene as the retail shops can be significantly far. In addition to that, as it can be seen in the next graph the majority of people buy in a daily or a weekly level, fuel. As a result, the combination of walking time and frequency of purchase means that kerosene lamp usage results to drudgery for households. In general, people are very unsatisfied by the use of kerosene lamps, which is the result of high costs, poor quality of lighting, health effects and drudgery of finding fuel.

![Kerosene lamps users' satisfaction and frequency of kerosene purchase](image)

**Figure 15** Kerosene lamps users' satisfaction and frequency of kerosene purchase

### 2.4.2.2.3 Kerosene related costs and household budget
Except the drudgery that kerosene lamps entail, they also highly affect the monthly household budget. More specifically, the participating households spend on average 891.4 KES ($10.5 US) per month for kerosene fuel. This corresponds at least to 17.8% of the monthly household monthly
income for households that earn up to 5000 KES per month, 8.9% for households that earn between 5000 and 10000 KES per month, 5.9% for households that earn between 10000 and 15000 KES per month and 4.5% for households that earn between 15000 and 20000 KES per month. Also, the cost of kerosene lamps is not negligible, as households spent on average 494 KES ($5.8 US) per year for new devices.

In this part, it is very clear the great difference that would make for the household’s income to change from kerosene to solar. If the monthly kerosene expenditures of a household where spent only once on the purchase of a solar lamp, then the life of their family would be changed forever. The overall living conditions would be significantly improved, while the savings from kerosene would increase the monthly budget of the household, allowing for expenditures on education, food, goods etc.

![Kerosene expenditures as a percentage of the household monthly budget](Figure 16 Kerosene expenditures as a percentage of the household monthly budget)

### 2.4.3 Education and reading

#### 2.4.3.1 Adults

**Reading frequency and habits**

Both kerosene lamp and solar lantern users have strong reading habits. The most popular book among them is the Bible but they also read material of educational interest such as books, magazines and newspapers. As it can be seen in the following graphs, the source of lighting affects the frequency of reading, as solar lantern users seem to read much more regularly during the week in comparison to kerosene lamp users. This can be explained by the low availability of fuel, the poor reading conditions and the disturbing effects, such as eye irritation and cough. Eventually, conventional ways of lighting bereave reading from users, which results to lower literature levels. However, the second ones appear to have lower but still frequent reading habits too, which is good from an educational point of view, but as they choose to read regardless the respective source, they continue to bear the health effects and risks of kerosene lamps. At this point, it should be mentioned that the frequency of reading is affected by several social and economic factors and is different for
person to person. So, it cannot be concluded that solar lamps lead directly to more reading hours but it appears to be a strong and important connection between the source of lighting and reading habits.

![Reading frequency of kerosene lamp and solar lantern users](image)

**2.4.3.2 Satisfaction by source of lighting for reading**

As it is expected, kerosene lamp users are very unsatisfied by this source of lighting for reading. This is the result of a combination of factors, such as poor lighting quality, health effects and limited availability. On the other hand, solar lantern users avoid these problems and they are more satisfied by their source of lighting. Nevertheless, the satisfaction and reading habits seem to be related, as satisfaction is reflected on the frequency of reading.

![Satisfaction of kerosene lamp and solar lantern users by the source of lighting for reading](image)

**2.4.3.2 Children**

**2.4.3.2.1 Studying hours and grades**

The source of lighting plays a crucial role on their overall education and progress in school. First of all, the vast majority of the children study even at night or both day and night. That means no student avoids using an artificial source of lighting by using the daylight or does not have the availability to do that. All children study at least partially during the night either with a kerosene lamp or a solar
lantern. However, students that own solar lanterns appear to have significantly less difficulty to study during the night, while students with kerosene lamps try to take advantage of the daylight as 71% of them studies both in day and night.

<table>
<thead>
<tr>
<th>Kerosene users</th>
<th>Solar lantern users</th>
</tr>
</thead>
<tbody>
<tr>
<td>0% 29% 71%</td>
<td>3% 12% 85%</td>
</tr>
<tr>
<td>Day Night Both</td>
<td>Day Night Both</td>
</tr>
</tbody>
</table>

Figure 19 Children’s studying habits by source of lighting

More importantly, there is a dramatic difference in the educational progress between solar lantern users and kerosene lamp users and the following graphs can explain that difference. 79% of the students that do their homework with solar lanterns have in average good grades while the rest 21% has moderate grades. It is also important also to mention that no parent said that children have bad grades. On the other side, 91% of students that use kerosene lamps have moderate grades while 3% has bad grades. In contradiction with solar users, only 6% has good grades.

This can be explained by the distinct advantage of children with solar lanterns to study on average for 2.6 hours per day, while the respective time for children with kerosene lamps is 1.3 hours per day. In other words, the first ones study the double time or 1.3 hours more than the second ones and as a result they have better grades. The fact that kerosene lamps have a very poor quality of lighting and produce smoke that causes eye irritation and breathing problems makes the children reluctant to study and to dedicate time on their homework under the respective conditions, a fact that is more clear in the next paragraph. As it mentioned in the previous section of adults’ education, several socio-economic reasons can influence the children’s grades, however, there is an undoubtable effect between of the source of lighting on education habits. Nevertheless, the fact that both kerosene and PV participants have similar socio-economic profile as they come from the same areas and have comparable wealth situation tries to eliminate the impact of other socio-economic factors on the research results.
2.4.3.2 Satisfaction and complaints by source of lighting for studying

In this section, it can be seen the satisfaction of children by two sources of lighting, which is reflected on their grades and studying time. 82% of the children with kerosene lamps complain about the quality of light and studying conditions, while the percentage of the children with solar lanterns that complain for the same reasons is only 18%. In general, no student was found to be at happy by kerosene lamps as 91% stated sad or very sad. On the other hand, students with solar lanterns state by 92% very happy and 4% happy with their source of lighting.
2.4.4 Health, safety and indoor air quality

In this section of the survey, all participants were asked about the different health effects and safety aspects of kerosene lamps, regardless if they use them or other source of lighting. The reason is that the majority of Kenyan people had used in some point of their lives kerosene lamps for lighting, while solar lantern users relied on kerosene before they would turn to PV systems.

2.4.4.1 Breathing problems and eye irritation, adults

The use of kerosene lamps for lighting has two direct effects that people are able to identify. These would be breathing problems and eye’s irritation. Of course, the toxic fumes cause a number of more serious or even deadly health effects. However, these can be studied under laboratory conditions. Therefore, the health section of the survey was to examine the direct impact that people can feel on their health, which will affect the choices and behavior as far as the source of lighting is concerned.

43% of the respondents said that they have been facing breathing problems while 57% said they do not have breathing problems. The effect on eyes is more easily perceptual as 65% of respondents complained that the smoke causes eye’s irritation, while the rest 35% did not express any discomfort. These statistics can be explained by the fact that people have been using for many years kerosene as
a fuel and as a result they have got accustomed to the toxic smoke and they do not express and do not understand the effects on breath and eyes.

2.4.4.2 Breathing problems and eye irritation, children

The direct effect of kerosene on children’s health can be seen in the following graphs. 36% of the respondents said that kids in the house have breathing problems while the rest 64% has not. Respectively, 52% of children feel irritation in their eyes while 48% they do not. Again as in adults, the direct health effects do not seem to be as high as they would be expected. In contradiction, children seem to be affected less in comparison to adults when they use kerosene lamps. This can happen because children, who spend more time next to burning lamps in order to study, have been used to the smoke and they do not have obvious symptoms. However, the impact and problems on their health is reflected both by the study hours and their complaints that were analyzed in the education section.
2.4.4.3 House fire and burning from kerosene lamps

More easily can be counted the safety issues of kerosene lamps. 9% of interviewed persons reported that a fire has been started by a kerosene lamp in their house at least one time. Even if this percentage is relatively low, it shows there is a high danger of fire by kerosene lamps, which can even lead to death of many people especially in condensed areas like slums. Furthermore, one out of five people reported that they have been burned by lamps, which is another concern of safety.

![Fire in the house and skin burns by kerosene lamps](image)

2.4.4.4 Heat, smoke and dirt

Indoor air quality is also downgraded by kerosene lamps. More specifically, 60% of the people complained about the heat they feel when they use them, while 80% complained about the smoke and dirt is caused by the exhausting fumes. As a result, living conditions are significantly undermined, while also this fact can explain the low satisfaction and unwillingness of students to use kerosene as a fuel.

![Heat, smoke and dirt by kerosene lamps](image)
2.4.5 Social and household activities

2.4.5.1 Feeling of safety

A big difference is recorded between kerosene lamp uses and solar lantern users as far as the feeling of safety is concerned. Half of the respondents that use kerosene said that they do not feel safe during the night. On the other hand the vast majority of PV users, by 97% stated they feel safe during the night. It can be seen that more reliable lighting sources can have change on the feeling of safety. However, it should be mentioned here that safety, as many other aspects, is affected by many parameters, such as location and type of the house, local criminality and previous incidents. It can be considered though, that the influence of these parameters is decreased by the fact that, both kerosene and PV users come from the same areas and have similar wealth profile.

![Figure 28 Feeling of safety by source of lighting](image)

2.4.5.2 Migration

Migration tendency of people is highly dependent on access energy. In the following graph it is shown that the majority of kerosene lamp users would immigrate to another place in order to have access to electricity, while on the other hand, most of the solar lantern users would not think to immigrate in order to achieve that. In this part it is very clear how much the quality of people is upgraded by even a small step up to energy ladder. Nevertheless, migration tendency is a multi-factor parameter. However, the respondents were asked specifically if they would move to another place in order to have access to electricity. Therefore, it can be assumed that the effect of other socio-economic factors on the research results is minimized.
2.4.5.3  Gathering at night

In contradiction to migration tendency and safety, the gathering at evening hours does not seem to be dependent on the source of lighting that families use. Both categories responded by 70% to 76% that they do not gather during the evening hours with friends or family members. This can mean even that a further access to electrical appliances such as TV could increase the social activities levels, or that family and friends gatherings are more a social characteristic of each family is independent of the respective energy sources.

2.4.5.4  Domestic work and cooking

Similar to friends’ and family gatherings, domestic work and cooking activities seem not to be affected by the source of lighting. More specifically, 97% of the kerosene lamp users and 92% of the solar lantern users stated that they do domestic work during the night. Respectively 82% of kerosene lamp users said that the household cooks during the night while respective percentage of PV users was 90%. This fact on the one hand can be interpreted by the reason that if there is domestic work to be done, and mainly by the women of the house, it will be done even if the working conditions are
bad. Conclusively, these daily activities will not be postponed for daytime because of the poor lighting and members of the household will be exposed in a daily level in the toxic kerosene smoke.

<table>
<thead>
<tr>
<th>Kerosene users</th>
<th>Solar lantern users</th>
</tr>
</thead>
<tbody>
<tr>
<td>3%</td>
<td>8%</td>
</tr>
<tr>
<td>97%</td>
<td>92%</td>
</tr>
</tbody>
</table>

Figure 31 Practice of domestic work by source of lighting during the night

<table>
<thead>
<tr>
<th>Kerosene users</th>
<th>Solar lantern users</th>
</tr>
</thead>
<tbody>
<tr>
<td>18%</td>
<td>10%</td>
</tr>
<tr>
<td>82%</td>
<td>90%</td>
</tr>
</tbody>
</table>

Figure 32 Cooking in the night by source of lighting

2.4.6 Business activities and change from kerosene to solar

A very small number of people that changed their lighting source to their businesses from kerosene lamps to solar lanterns were actually found. The majority of people that buy small PV systems, they use them in their household. The businesses that responded to have changed from kerosene to solar where small kiosks and shops that retail food, goods, sim cards etc. All the respondents stated the following improvements as far as their businesses were concerned:

- The opening hours were extended during the evening
- The number of customers was increased as a result of opening hours’ extension and attraction of people by the different way of lighting
- The profit was increased by the extended opening hours and increased number of customers
The number of people that mentioned they changed from kerosene to PV in their businesses is very small in order to allow the extraction of solid results. However, these statements can give an idea of the impact that increased energy access can have to micro-entrepreneurs and shop keepers.

2.5 Conclusions

According to the overall results of the socio-economic study, eradication of kerosene lamps can improve the lives of millions of households in developing countries. For this change, solar lantern can play a significant role. The turn towards modern energy sources by the replacement of kerosene with solar, affects all the aspects of development and quality of life, such as, income, education health, social and productive activities.

More specifically, the average monthly expenditures that rural households in Kenya do on purchase for kerosene are enough to afford a solar light such as d.light S2. In other words, the expenditures on kerosene for a period of 2 months are more than enough in order to buy a solar lantern that has a lifetime of 5 years. This fact shows how easily change can happen, as the savings from fuel can be spent on education, food and other goods. In education, the study showed that children who do their homework under the light of solar lamps study on average 1.3 hours and have much better grades.

Furthermore, several health impacts and dangers where related to kerosene lamps. Breathing problems and eyes’ irritation where reported by many users while also a risk of house fire and skin burning is considerable. In addition, solar lamps make people feel safer during the evening hours, decrease the migration tendency and create more income for small businesses as they extend the opening hours and attract customers.

Finally, duration and timing of activities such as cooking, cleaning and gathering during the night did not seem to be affected by the source of lighting as people answered that they practice them independently of having kerosene or solar lamps. As a conclusion, changing kerosene lamps to solar lanterns would improve the domestic work and activities environment and decreasing the respective health problems.

2.5.1 Limitations

In this socio-economic research, there were two limitations identified. Firstly, 141 respondents participated in the research. This number can be assumed to be capable in order to support the validity of the results, but a higher number of people questioned would lead to stronger conclusions. In addition, the participants come from the wider area of Western Kenya. A population sample that would be chosen all across the country would be the desired. However, this was practically impossible to be achieved as there were time and cost limitations of the field trip to Kenya, while certain areas of the country are difficult to be reached because of security concerns or limited transportation access. By satisfying better those two parameters, the population sample would be more randomized, and so it could represent better the current situation in Kenya.

The second limitation is that many socio-economic parameters are affected by several factors. Therefore, even if the respective questions try to isolate the effect of the source of lighting on them
and minimize the impact of other factors, there cannot be extracted absolute conclusions on the change that would be achieved by a replacement from kerosene to solar lamps.
3 Rural electrification in Kenya

3.1 Available solutions for rural electrification in Kenya

There are several technical solutions in order to increase access to electricity in Kenya. The following solutions are the most common ways of rural electrification in Kenya:

1. Grid connection
2. Microgrids
3. Solar Lanterns and larger solar kits
4. Solar Home Systems (SHSs)

3.2 Grid connection

The extension of the Kenyan electricity grid has been one the most important priorities of Kenyan governments. Theoretically, grid connection can provide to households the ability to use appliances without any restrictions. However, the reality in developing countries like Kenya is different. A number of factors limit the extension of the grid, the connection of rural households and the reliable usage of that.

First of all, the unsuppressed demand of the country is calculated at 1700 MW while the effective power generation is 1664 MW (48). In other words, Kenya should double the total capacity of the country as even if all the households were connected to the grid, there would be the ability to generate the necessary power in order to cover the country’s demand. Furthermore, the construction of MV lines has an average cost of 10,000$ US per km (3). That means the extension of the national grid requires a very high capital which of course cannot be provided by the communities.

In addition to that, the fee for a new single phase connection is 391.92 $ US while for a three-phase connection it is 549.89 $ US. As a result, it is easy to understand that even if the electricity grid has reached a community, it is financially very difficult or impossible for a rural household to obtain access. That is the reason why in Kenya there is a very high number of “under-grid houses”, which are dwellings very close to the transmission lines but the residents cannot afford the connection.

The financial characteristics and parameters of grid expansion and poverty of rural households acquire the development and implementation of alternative solutions in order to increase the access to electricity in Kenya.

3.3 Microgrids

Microgrids are small scaled electricity grids that are not connected to the main electricity grids of countries or wider regions. Grid expansion requires a very high capital while also in some areas it can
be technically challenging because of the geographical characteristics and the spreading of rural communities. The main advantage of microgrids is that they bypass the grid extension in order to electrify regions or communities, which means that electrification requires less financial and technical resources.

Furthermore, an advantage of same importance is that through microgrids, the transmission losses of the main grid are minimized, resulting in lower operation and maintenance costs. As microgrids aim to provide the required energy needs of small communities, they have the technical ability to exploit the local micro-climate energy resources and maximize the power generation efficiency. For example, if a small region is characterized by high wind speeds, then wind power can be used in order to supply the energy system and minimize or count off the need of fossil fuels.

Therefore, microgrids that effectively harvest the local renewable energy resources, can be a sustainable and affordable electrification solution as they are do not require fossil fuels and they do not produce any emissions in order to generate power. However, many times the power generation of microgrids is based either on diesel generators or on hybrid diesel/renewable energy systems. There are several reasons that this happens, especially in Sub-Saharan rural areas. Usually, diesel or hybrid systems require a lower initial capital in comparison to renewable energy systems, but they have higher lifetime costs because of their dependence on fuels.

At the same time, governments adopt a short-term way of thinking as far as the policies are concerned in order avoid the political cost of high budgets or increased taxes during their governance. As a result, they choose to increase the access to electricity through the minimum initial cost choices, such as diesel generators, without considering the total life cycle cost of a project. Also, the stochastic nature of renewable energy sources sometimes makes necessary the installation of the parallel installation of renewable energy technologies and diesel generators in order to equilibrate the fluctuations in the power generation.

3.3.1 Notable microgrid projects in Kenya

In Kenya, there is a small number of microgrids that are either state or private owned. This section makes a reference in three microgrid projects that have special characteristics in terms of ownership, funding, technology and operation.

3.3.1.1 Lake Victoria islands

Access:Energy (49) and PowerGen (50) are two cooperating companies that have developed a unique project in Lake Victoria. On the lake there are several slum islands that even if they are not far from the mainland, they are not connected to the grid. The two companies have developed microgrids that are generating energy by harvesting the increased potential of wind and solar power in the region.

Until now the two companies have built three different microgrids to the following slum islands Takawiri Island, Mageta Island and Remba Island while the installed capacity of each system is 70W, 360W and 3kW respectively. The innovation of the projects lay on the fact that the three microgrids are developed and run under the PAYG scheme. It should be mentioned that until now, only
Access:Energy and PowerGen have been using that scheme for the development of microgrids. According to Energy Digest (51) this is the connection and consumption process the consumers follow under the respective scheme:

- Every customer is provided with code number that corresponds to his connection line and meter
- Through his mobile phone and M-PESA service, the customer buys electricity credits.
- Through bitHarvester, a technology developed by Access:Energy (49), the operators can control remotely the electricity consumption of each household and manage the credits purchases by turning them to available electricity for the customer.
- A local agent of the operating companies expands the operations of the microgrid by signing new contracts and maintaining the existing energy systems.

![Figure 33 Lake Victoria microgrids by PowerGen and Access:Energy (52)](image)

### 3.3.1.2 Kitonyoni Village Market

In 2012, the Kitonyoni Village Market microgrid was commissioned by Chloride Exide (53) and started to supply the off-grid area with renewable energy. The overall cost of the project was $140,000 USD and it was financed by the Kenyan Ministry of Energy and UK Aid (54).

The energy system provides with electricity twenty six small businesses, four churches, a primary school and a health center, while also 500 households have replaced the kerosene lamps with LED lighting. That has resulted to a boosted financial activity as people have the availability to work electrical tools and they have extended their working hours. The solar energy system is consisted by a total installed capacity of PV panels and a stand-by diesel generator.

The interesting part of the Kitonyoni Village Market project is its ownership, operation and maintenance scheme. The community founded a cooperative partnership where the consumers can buy at least 300 shares that value in total 36. Through this way, it is guaranteed that the system is managed and operated by the owners without involving external stakeholders and the whole
community is responsible for the viability of it. Moreover, there is a connection fee of $190 USD which consumers can pay with a deposit of $35 US and pay off the rest with a monthly fee of $6 USD while the price of electricity is $1.12 USD per kWh.

![Microgrid of Kitonyoni Village Market](image)

3.3.1.3 Katahmba and Thima pico-hydro grids

Kenya is a country that has a high potential of hydro power exploitation and the twin pico-hydro projects of Katahmba and Thima rivers are two excellent examples of that. In 2003, Maher et al. (55) published a research paper that compared the two projects with SHSs and battery only systems. In that publication, the researchers showed that the existing small streams of Kenya can be effectively used in order to electrify communities that do not have access to the grid.

In Kathamba river, a pelton hydro turbine of 1.1kW maximum power output was installed. In total, 65 households gained access to electricity while the furthest dwelling was 550 meters far from the power station. In Thima river, the usage of a pump was reversed and tuned into a hydro turbine of 2.2 maximum capacity. The electrified houses were 110 while the furthest one was 800 meters away of the station. The project was developed by the Micro Hydro centre of Nottingham Trend University while it was funded by the European commission (55). Finally, the monthly fee per households is $1.3 USD for a maximum electricity consumption of 16W.

![Katahmba and Thima pico-hydro turbines](image)
3.4 Solar Home Systems (SHSs)

Solar home systems are integrated energy systems for off-grid electrification. Typically, they are consisted from the power generation part which is either PV panels or wind turbines, and from the energy storage part which is the battery bank. In addition, they include an inverter that increases the power voltage and a charge controller that protects the batteries from overcharging and deeps discharging.

If the system is on-grid, then it can use the electricity grid in order to charge the battery bank when there are shortages in the power generation, as a result of lack of sunshine or low wind speeds. When the battery bank is fully charged and the power generation part is working and generating power, then the owner can supply the grid with electricity and thus earn money. This scheme is called feed-in-tariff policy according to which, individuals receive a payback capital according to the kilowatt hours of electricity they have provided to the grid.

Solar home systems are a reliable and effective solution for off-grid houses. However, they require a high capital and most of the times they are not affordable by rural families. Therefore, they are not orientated for the economic bottom of the pyramid.

3.5 Solar lanterns and larger solar kits

For the majority of Kenyans, the connection to the grid and installation of SHSs are electrification solutions which either they cannot afford or they do not have physical access. In addition, the development of microgrids takes place in a very low rate as there are few companies in Kenya with such operations.

An affordable and sustainable solution that can provide to the users a number of services is solar lanterns. Solar lanterns are small energy systems that are consisted by a PV panel between 1W to 5W, a battery, LED lamps, power outputs for different appliances and a micro-charge controller. Solar lanterns are compact systems that are distributed as one package and can provide the following services:

- Lighting
- Phone Charging
- Radio
- Fan
- TV

The basic purpose of solar lanterns is to provide to poor households an alternative solution of kerosene lamps which on the one hand cost a significant amount for their budget while also they produce toxic fumes. This results in several advantages such as increased studying time for children and household productive activities, money savings and health improvement.
In addition, most of them include phone charging outputs as they aim to solve the problem of people who do not have access to the grid and have to walk long distances in order to recharge their cell phones. As a result, these two basic appliances are provided by all the solar lanterns that are available on the market. Additional appliances, such as radio, TV and fan are included in larger systems that have bigger PV panel and battery capacities and higher prices.

In Kenya, there are several ways of distribution for solar lanterns. That includes small energy companies and super markets, while there are several NGOs. Solar Aid, NGO is the larger distributor of solar lanterns in Sub-Saharan Africa as until today they have distributed more than 1,350,000 energy systems.

### 3.5.1 PAYG and solar lanterns

Similarly to microgrids, three distributors in Kenya, Solar Aid, Bboxx and M-KOPA have been applying the PAYG scheme on compact solar systems. Even if the respective systems are a very cheap alternative to kerosene lamps, PAYG allows customers to save money or to have access to solar lanterns even if they cannot afford the initial capital they require.

### 3.5.2 Lighting Africa

Lighting Africa is an initiative launched by the World Bank and the International Finance Corporation in 2007, that focuses mainly on Sub-Saharan Africa and aims give the choice of more affordable, healthier and cleaner lighting solutions in comparison to kerosene lamps.

A major past problem of solar lighting market in Africa is the significant number of low quality products that were malfunctioning after a short period of usage (56). This resulted in a crisis of the market as customers tended not to trust them and returned to conventional ways of lighting. However, Lighting Africa has introduced qualitative tests for solar lanterns in order to assess their performance and guarantee their proper function.

Furthermore, the initiative publishes several studies that concern off-grid electrification and supports with financial products the manufacturers, importers and distributors as lack of capital is an obstacle that hampers the distribution of solar lanterns. Finally, Lighting Africa organizes educational activities for the consumers and distributors that target to inform them on alternative and quality technologies to kerosene lamps and to support small businesses and small entrepreneurs (57).
3.6 Financing and ownership schemes of energy systems in Kenya

At the moment in Kenya exist several financial and owner schemes of microgrids that involve different stakeholders, such as the state, private investors and consumers and they make the development of projects and rural electrification possible. The most common schemes are the following:

1. Pay As You Go (PAYG) – M-PESA
2. Shares
3. Direct payment
4. Government support

3.6.1 Pay As You Go (PAYG) – M-PESA

M-PESA is an innovative global idea that was developed and first applied to Kenya. M-PESA that is derived from the letter M for mobile and PESA for the Swahili word for payment, is a way of banking, money transfer and payment that uses mobile phones as the means of transaction. Originally, this scheme was launched in the Kenyan market by Safaricom, the state-owned and largest telecommunications operator in the country, in 2007. Later, it was expanded to other countries, such as Afghanistan, India, Romania and South Africa. According to Safaricom site (58), these are the services that M-PESA scheme provides:

1. Person to person money transfer
2. Airtime purchases
3. Bill payments
4. Money withdraws and deposit
5. Microloans (M-Shwari)
6. Goods and services purchases (Lipa na M-PESA)
7. International money transfers

Nevertheless, many of the services that M-PESA can provide require the involvement of a Safaricom agent. All across Kenya, there are kiosks operated by agents who help the M-PESA users for the respective transactions or they sell M-PESA credits, sim-cards and mobile phone accesories. As a result, M-PESA has created thousands of jobs in the country as the agents work as small entrepreneurs and run their kiosks as a micro-finance business.
3.6.2 M-PESA for energy access

The ability to pay for services with M-PESA in Kenya has provided the ability for the people to buy through their mobile phones, energy as a service. More specifically, the M-PESA scheme for energy works under the pay-as-you-go (PAYG) approach, where consumers pay through their mobile phones for the respective amount of energy they use. Until now, customers that use M-PESA can either pay for electricity from microgrids, solar lanterns and larger solar home systems, or for biogas.

That scheme has introduced a new era for increasing energy access in rural areas. Companies provide the energy system such as a microgrid or a biogas digester and they charge a small connection fee from the customers. After that, customers pay for the respective use of electricity or biogas they consume, while also they energy supply is cut off they do not cover their payment responsibilities. Under that scheme, individuals or communities can have access to power generation and distribution units that they could not otherwise afford, while companies decrease the investment risk as on the one hand they do not have any direct transactions with the customers and on the other hand they have much more surety for the payment of the bills.
4 Techno-economic comparative study: Methodology and aspects

4.1 Introduction

In this chapter, the methodology of the techno-economic comparative study included in this MSc thesis is analyzed. The purpose of this techno-economic analysis was to design renewable energy microgrids for five rural communities and to compare them with the existing available and most efficient solutions for rural electrification in Kenya. One of the most important parameters of this study is the examination of real and existing solutions that can be found nowadays in Kenya and they are directly implementable. Thus, results of that study address to public and private stakeholders that are involved in rural electrification in the country, and aim on the one hand to provide an implementable and detailed techno-economic study for five microgrid projects and on the other hand to show the optimal ways of increasing energy access in Kenya.

In order to conduct the research, a field trip in Kenya was done between May and July 2014, for collecting data through a market research, interviewing public and private stakeholders for investigating the different aspects of rural electrification and finding the most accessible and implementable solutions for increasing access to electricity. According to these data, microgrids were designed for five rural communities, the techno-economic analysis was performed, a number of systems that were found to be the best electrification ways were compared and optimal solutions were proposed for rural electrification.

4.2 General methodology

The extension of the national grid requires high capital and it can take years in order to succeed the completion of a project while large solar home systems (SHSs) are not affordable by the majority of rural households. Therefore, during the field trip in Kenya, there were identified two main ways of increasing energy access in Kenya. The first one is solar lamps and solar kits while the second one is renewable energy microgrids.

Solar lamps and kits were identified as a solution that requires very small capital while the distribution of them, mainly by Solar Aid in Kenya, is can be done quickly and efficiently. On the other hand, renewable energy microgrids where found to be an affordable and feasible solution for two reasons. The first one is the increased potential of renewable energy in Kenya, which means that a renewable energy microgrid requires relatively small installed capacity in order to cover the energy needs of a rural community, it requires no expensive fuel such as diesel in order to operate and does not contribute to the climate change as there are zero emissions of polluting gasses. On the other hand, remote renewable energy microgrids bypass the need and high cost of national grid extension; therefore require a much lower capital.
The comparison of the included energy systems was done for five rural communities in Kenya. These were selected according to the climate data of the areas they belong, their population size and their distance from a climate station. The scope was to examine the effect of solar irradiation, wind speed and population of the community on the size and required capital of the microgrids, while also to be able to generalize the results for communities with similar climate and size characteristics.

In order to compare these energy systems and find the optimal solution for rural households, firstly, precise technical and financial data had to be received. Solar lamps and kits have a certain way of function which means their performance is defined and there is no further need of investigation. However, that does not happen to microgrids as they are not fixed systems. The size and performance of renewable energy microgrids are related on the climate data of the area they are built, on the power load they have to cover and the technologies and models of components that are used.

According to that, the definition of the most cost-effective renewable energy microgrid for each community was essential. In order to find the optimal solution for each community, HOMER Energy software was used. Also, for each community, two optimal microgrids were defined, which corresponded to Tier 1 and Tier 2 energy access. Energy access is described extensively in the next paragraphs.

The optimization for each community and tier was done through the following way. All the technical and economic data that were received from the participating companies in the research were used as inputs in HOMER Energy. These data were the available equipment of each company, such as solar panels, wind turbines, batteries and inverters, while also the respective prices. Moreover, climate and power load were also inputs in HOMER Energy.

For every single community and tier of energy access, seven optimization procedures were done, one for each company. This happened in order to optimize the size, sources of electricity and cost of the microgrid that every company can offer for every region and tier, and finally to conclude which company has the most cost-effective energy system in order to increase energy access for each community.

The total cost of the optimal microgrid was annualized and divided by the number of houses in the respective communities. By this was, the annual amount of money that every household would have to pay in order to have connection to the microgrid was known. Also, the cost of solar lamps and kits was annualized. Finally the annual costs of the microgrid per household, of solar lamps and of larger solar kits were compared and the optimal solution was found on how to achieve energy access of Tier 1 and Tier 2 in each of the five communities.

### 4.3 Definition of energy access

A key issue of the techno-economic analysis is the definition of energy access, as the comparison of energy systems has to be done in the same basis. More specifically, in order to be able to compare the different energy technologies, they must satisfy the same energy services, such as lighting, phone charging, refrigeration etc.
For example, a solar lantern with a PV panel of 5W cannot be evaluated under the same criteria with a 2 kW diesel generator. The reason is that the two systems can cover a totally different spectrum of applications. The solar lantern is able supply a household with 4 hours of lighting and phone charging while the diesel generator can support the household with unlimited electricity and provide energy for additional applications except lighting and phone charging, such as refrigeration, TV, electric stove etc. Of course, the solar lantern is affordable by a rural household while the diesel generator has an unreachable cost, but the second one can cover many more applications in comparison to the first one.

So, it is not meaningful to extract results by the comparison of energy systems that do not satisfy the same energy services. Therefore, the techno-economic comparison between, solar lanterns, microgrids and larger solar home kits takes place under the condition they satisfy the same energy services.

### 4.3.1 SE4ALL framework and energy access

In general, there is not a strict definition of energy access while it is usually interpreted as the access of a household to electricity. However, as it is explained before, there can be different levels of energy access. When the SE4ALL – UN global tracking framework was launched in 2013 (59), a new multi-level scheme was proposed in order to measure energy access, both for electricity and cooking. According to the framework, five tiers of access to electricity for households were introduced, based on two ways of distinction. The first one is according to a number of attributes such as peak available capacity, duration, evening supply, affordability, legality and quality while the second one is set on the available energy services (59):

<table>
<thead>
<tr>
<th>Attributes</th>
<th>Tier 0</th>
<th>Tier 1</th>
<th>Tier 2</th>
<th>Tier 3</th>
<th>Tier 4</th>
<th>Tier 5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Power (up to Watts)</td>
<td>-</td>
<td>1</td>
<td>50</td>
<td>200</td>
<td>2,000</td>
<td>Unlimited</td>
</tr>
<tr>
<td>Duration (hrs)</td>
<td>-</td>
<td>4</td>
<td>4</td>
<td>8</td>
<td>16</td>
<td>22</td>
</tr>
<tr>
<td>Evening supply</td>
<td>-</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>4</td>
<td>4</td>
</tr>
<tr>
<td>Affordability</td>
<td>-</td>
<td>-</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>Legality</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>Quality</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
</tbody>
</table>

Table 6: Tiers of energy access as defined in SE4ALL framework (59)

<table>
<thead>
<tr>
<th>Tier 0</th>
<th>Tier 1</th>
<th>Tier 2</th>
<th>Tier 3</th>
<th>Tier 4</th>
<th>Tier 5</th>
</tr>
</thead>
<tbody>
<tr>
<td>-</td>
<td>Task lighting AND phone charging</td>
<td>General lighting AND phone charging AND any low-power appliances</td>
<td>Tier 2 AND any medium-power appliances</td>
<td>Tier 3 AND any high-power appliances</td>
<td></td>
</tr>
</tbody>
</table>

Table 7: Tiers of energy access by electrical services (59)
4.3.2 Tiers of energy access in the techno-economic study

The SE4ALL framework methodology was the basis of the techno-economic study. The included energy systems should have the ability to provide equivalent energy services in order to be comparable; therefore an altered aspect of the SE4ALL Tier 1 and Tier 2 was used. Furthermore, it is important to clarify that the definition of tiers in this thesis has been strictly done in terms of available energy services and not in terms of installed capacity. The decision of limiting the thesis to the first two tiers was shaped by two correlated factors.

The first was the ability of people to pay for the examined systems, as the subject of this study is households that belong to the bottom of the economic pyramid. That means the proposed solutions have to be affordable by rural Kenyan families. Also, as it is easily understood, systems that correspond to the lower tiers have much lower cost in comparison to systems that correspond to higher tiers. After the market research that was performed during the field trip in Kenya, the identified energy systems that could be financially supported by rural households can respectively cover energy services that correspond to Tier 1 and Tier 2.

The second factor was the perspective on the methodology for defining energy access. More specifically, goal of the study is not to achieve a minimum installed power capacity per household but to examine how to increase the access of rural families to appliances such as lighting, phone charging, radio and ventilation fan. As it is shown in the socio-economic study of the thesis, most of these appliances can improve drastically the quality of life for people without electricity, as they impact on health, education, income, social and productive activities. Therefore, there are not equivalent to the developed world standards but they can decrease energy poverty and change peoples’ lives.

The reason of proposing a slightly different aspect of Tier 1 and Tier 2 in comparison to the description of SE4ALL is that the included energy systems of the study can provide similar services but these cannot be absolutely matched with the respective services in the first two tiers of the framework. Nevertheless, the decision for Tier 2 was based on an energy management perspective, as people many times do not use the available systems efficiently.

4.3.3 Tier 1

In Tier 1 of the techno-economic study two simple but fundamental for development appliances are included; task lighting and phone charging. In the previous chapter of socio-economic impact, it has been shown the difference of this energy access can bring in people’s lives.

This tier is identical in terms of energy services with Tier 1 of SE4ALL framework, with the exception that the second one proposes a radio as an alternative service to phone charging. Task lighting has been defined as the availability of one or two LED lamps with total luminous flux per household between 75 and 256 lumens. The total time duration of services was set at 4 hours while all the systems are both legal and have been certified under quality control methods Lighting Africa (46).

In the comparative analysis for Tier 1 energy access, there are five technologies include:
<table>
<thead>
<tr>
<th>Energy System</th>
<th>Manufacturer</th>
<th>Distributor</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sun King Mobile</td>
<td>Greenlight Planet</td>
<td>Solar Aid/Sunny Money</td>
</tr>
<tr>
<td>Sun King Pro 2</td>
<td>Greenlight Planet</td>
<td>Solar Aid/Sunny Money</td>
</tr>
<tr>
<td>S300</td>
<td>d.light</td>
<td>Solar Aid/Sunny Money</td>
</tr>
<tr>
<td>BB7 Kit</td>
<td>BBOXX</td>
<td>Abundant Power Solutions</td>
</tr>
<tr>
<td>Sun King Mobile</td>
<td>Greenlight Planet</td>
<td>Solar Aid/Sunny Money</td>
</tr>
<tr>
<td>Microgird</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

Table 8 Energy systems included in the Tier 1 analysis

4.3.3.1 Sun King Mobile

Solar King Mobile is the smaller of the two solar lamps that are manufactured by Greenlight Planet, in Tier 1 techno-economic comparison. It is equipped with a 1.5W PV polycrystalline panel and a 3.3V Lithium Ferro-Phosphate (LFP) battery of 1.5Ah nominal capacity and 5 years lifespan (60). In addition, it has the LED lamp of 83 lm, one phone charging USB cable and a micro-controller for more efficient utilization of the battery. It is distributed by Solar Aid, NGO and the cost of the solar lamp is $28.90 USD.

![Figure 38 Sun King Mobile](image)

4.3.3.2 Sun King Pro 2

It is the largest product of Greenlight Planet which is also available by Solar Aid, NGO in Kenya. With better performance than Sun King Mobile, this lamp has a 3.3W polycrystalline panel and a 3.3V Lithium Ferro-Phosphate (LFP) battery of 3.3Ah nominal capacity and 5 years lifespan (60). Furthermore the LED lamp has a luminous flux of 165lm, two USB phone chargers for phone and a battery micro-controller. The retail price is $42.46 USD.
4.3.3.3 S300

S300 is manufactured by d.light and has a lifespan of 5 years. It is the last product of Solar Aid, included in Tier 1 study. This solar lamp has a monocrystalline PV panel of 1.6W and only one LED lamp with luminous flux of 110lm. Its battery has a capacity of 1.8Ah and it can provide lighting at a bright mode for 4 hours while at saver mode the duration can be up to 20 hours. Nevertheless, the system has phone charging cabling. The retail price is $35.39 USD.

4.3.3.4 BB7 Solar Kit

This is a larger solar kit that is distributed in Kenya by BBOXX. The system has a PV polycrystalline panel with capacity of 15W and a 12V sealed acid battery with 7Ah capacity of 5 years lifetime (61). The accessories of the kit are two 2W LED lamps with maximum luminous flux 128 lm per unit and a phone charging cable. BB7 was proposed as the Tier 1 solution by the online Solar Usage Estimator (62) of the company. The input parameters in the online calculator were 4 hours of lighting and 4 hours of phone charging.

In order a customer to buy one BB7 solar kit, first they have to pay an initial connection fee of $21.23 USD and then they pay a monthly fee of $11.2 USD for one year. The customers pay through M-PESA and if they do not cover the monthly fee, then the systems stops to function.
4.3.4 Tier 2

The second tier of the techno-economic study examines a scenario of higher energy access in comparison to Tier 1. This includes general lighting, phone charging, table fan and radio.

Tier 2 of the study is defined differently in comparison to Tier 2 of SE4ALL framework as in the analysis of the thesis, the proposed television has been replaced to a radio. This has been done because all the larger available systems in Kenya that can be affordable by rural households, they do not have the battery capacity to support a television and other more basic appliances such as lighting and phone charging. In addition, a previous socio-economic research on rural electrification (32) has shown that families which own a television powered by a small solar system, many times make a mismanagement of the availably energy and they prefer to watch TV programs instead of use other energy services such as improved lighting for their children’s studying.

General lighting has been set to include three or four LED lamps. This can be corresponded to 8W of total installed LED lamps capacity or luminous flux higher than 300lm per household. In addition, the energy services are set to be available for 4 hours per day while all the systems are both legal and have been certified under quality control methods Lighting Africa (46).

The included technologies and systems of the study, for energy access of Tier 2 level are the following:

<table>
<thead>
<tr>
<th>Energy System</th>
<th>Manufacturer</th>
<th>Distributor</th>
</tr>
</thead>
<tbody>
<tr>
<td>Barefoot Connect 600</td>
<td>Barefoot Power</td>
<td>Solar Aid/Sunny Money</td>
</tr>
<tr>
<td>BB7 Kit</td>
<td>BBOXX</td>
<td>Abundant Power Solutions</td>
</tr>
<tr>
<td>Microgird</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

Table 9 Energy systems included in the Tier 2 analysis
4.3.4.1  Barefoot Connect 600

This is the largest solar system distributed by Solar Aid/Sunny Money in Kenya. It is equipped with a polycrystalline PV panel of maximum output 6.6W and a sealed lead acid battery of 4Ah capacity and five years lifespan (63). Furthermore, the kit has 4 LED lamps of 300lm luminous flux, two USB ports for phone charging cable while also connectivity for other Barefoot Power products such as radio, television and table fan. Barefoot is distributed in Kenya by Solar Aid, NGO only after order. The retail price of the solar kit is $141.54 USD.

![Figure 42 Barefoot 600 and connectible appliances](image)

4.3.4.2  BB17 Kit

BB17 Kit is the proposed energy system for Tier 2 by the Solar Usage Estimator (62) of the BBOXX. The polycrystalline solar panel of the kit has maximum output of 5W while the sealed lead acid battery capacity is 17Ah of 5 years lifespan (61). There two LED bulbs of 2W and one LED tube of 6W. The total luminous flux of the lamps is 367. Moreover, the system has a USB multiple charger and power output for radio, television, table fan and other BBOXX products.

Abundant Power Solutions distributes the solar kit in Kenya, firstly with an initial fee of $44.82 USD and then the customer pays a monthly fee of 25.95 USD for one year. The monthly payment takes place under the PAYG scheme and M-PESA.

![Figure 43 BB17 and connectible appliances](image)
4.3.5 M-KOPA

M-KOPA is an innovative energy company in Kenya that distributes a solar kit which included four LED lamps, phone charging and radio. The innovation of M-KOPA lays on the fact that payments take place under the PAYG scheme and M-PESA. Initially, the customer pays a connection fee of $35.39 USD and for one year they pay every day $0.47 USD. When one year of successful payments is completed, then the customer owns the product outright (64). Nevertheless, the product has four years of lifespan (64).

This solar system was not able to be categorized neither in Tier 1 nor Tier 2 energy access. However, since it is a product with high recognition and distribution, it was included in the comparative analysis of all regions and tier.

![M-KOPA Solar kit](Figure 44 M-KOPA Solar kit)

4.4 Techno-economic data collection and synopsis

As said before, the collection of data for the techno-economic study was done in the field trip to Kenya between May and July 2014. During that period, visits and interviews the most active and reliable energy companies in Kenya were performed. Each company that agreed to participate in the research provided for the research purposes the detailed list of equipment they use for smaller or large renewable energy systems and the respective prices of each component.

The selection of the companies for the study was done under certain criteria. First of all, the goal was to include project developers that have done several projects in the past, so they are not just simple retailers with questioning reliability. Furthermore, the purpose of the research was also to assess companies that are characterized by innovation such as the PAYG scheme as a way of payment and the manufacturing wind turbines instead of importing them. The final list of companies included in the research is the following:
In the techno-economic analysis and results, these companies are referred as company 1, company 2 etc. while this numbering does not correspond to the alphabetic order presented above. This happens as some of the representatives that were met in Kenya asked for confidentiality in information that concern economic issues. Nevertheless, three of the above companies are the main energy technology distributors in the country, holding the vast part of the market. Therefore, it can be considered that the results are solid and represent the actual energy market in Kenya. In total, the following number of different models and brands were compared in order to find the optimal microgrid in each community:

<table>
<thead>
<tr>
<th>Technical part</th>
<th>Models included</th>
</tr>
</thead>
<tbody>
<tr>
<td>PV panels</td>
<td>42</td>
</tr>
<tr>
<td>Wind turbines</td>
<td>10</td>
</tr>
<tr>
<td>Batteries</td>
<td>49</td>
</tr>
<tr>
<td>Inverters</td>
<td>73</td>
</tr>
<tr>
<td>Charge controllers</td>
<td>19</td>
</tr>
</tbody>
</table>

Table 10 Number of models by technical component included in the study

### 4.5 Modeling of microgrids

#### 4.5.1 Costs and currency overall parameters

Most of the prices of technical components that were received during the field trip in Kenya were in Kenyan shilling currency. However, since the US dollar is the most common currency of transaction, all the costs were turned to that. In order to have a more representative rate, the mean value of exchange between the Kenyan shilling and US dollar for the last five years, between September 2009 and September 2014 was used. This value was found to be 84.781 Kenyan shillings for 1 US dollar. In synopsis, these are the costs included in the designing of the seven microgrids for each community and tier of access to energy:

- Initial cost of components:
  1. Wind turbines
  2. PV panels
  3. Inverter
  4. Charge controller
  5. Batteries
  6. Mounting
  7. Wiring
• Replacement cost of components
• Labour cost and company profit
• Transmission grid cost
• O&M cost

4.5.2 HOMER Energy software

The Hybrid Optimization Modelling (HOMER) software (22) is a computer model for designing, modelling and optimizing microgrids. Originally developed by the National Renewable Energy Laboratory (NREL), HOMER energy has the ability to simulate a variety of conventional and renewable energy technologies and to evaluate the technical and economic feasibility of them.

HOMER Energy is the tool that is used in the techno-economic analysis in order to simulate and optimize the renewable energy microgrid of each case study region. The software is widely accepted by the energy community as the most precise and reliable model of microgrid optimization, therefore it was chosen to support the study.

![Figure 45 Main configuration screen on HOMER Energy](image)

The inputs of the modelling procedure regarding a renewable energy microgrid are climate data such as average monthly solar irradiation and wind speeds, electricity load, and technical and economic characteristics of the power generation and energy storage equipment. Thus, HOMER Energy can simulate PV panels, wind turbines, batteries and inverters.

Despite that, it has several limitations such as disability of simulation for charge controllers and transmission losses, wrong calculation of the real lifespan of batteries according to their usage and lack of external costs such as wiring and mounting of systems. Therefore, HOMER Energy simulations were the core of optimization for the proposed microgrids but additional calculations were done in order to include the parameters which the software could not assess.
4.5.3 Project and simulations lifetime

The total lifespan of the simulated projects in HOMER Energy was set to be 15 years. The reason for that choice is that, both SE4ALL framework and the Kenyan development plant VISION 2030, aim that until 2030 all citizens in the country will have access to electricity. Therefore, the purpose was to propose community owned and funded energy systems that would be able to cover their energy for the next 15 years without the need of external public or private capital. Of course, there are numerous choices for the management of the proposed microgrid for after 2030 such their enrolling to the national energy system or their continuation as community owned energy systems, if VISION has failed to electrify rural communities.

4.5.4 Battery bank

The battery banks were set to have 24V as nominal voltage. That was done in order to avoid as much the power losses in the strings. In addition, since HOMER Energy misses to calculate correctly the proper lifetime of a battery according to its usage, the lifespan of all the 49 batteries was set to be 5 years. Even if this assumption is a bit optimistic, it is possible to achieve that under the correct maintenance such as proper cleaning, avoiding of misusage and placement of the battery bank in cool and shadowy places.

4.5.5 Charge controller

As HOMER Energy does not allow the modeling and calculations on charge controllers, this component that is an essential part of a renewable energy system as it protect the batteries from overcharging and deep discharging, it was sized and proposed individually for each microgrid. In order to do that, the specification sheet of each charge controller was used. According to that, there is a limit for each charge controller in relation to the installed power capacity of the PV array and the respective array voltage. For example, FLEXmax 80 of Outback can support PV systems of installed capacity up to 4000W if the nominal voltage of the array is 48VDC. Moreover, certain charge controllers can support hybrid wind/solar energy systems, while others cannot. Thus, this parameter was also taken under consideration.

4.5.6 Power load per household

In order to design a microgrid in HOMER Energy, there must be a power load to be covered, according to which the optimal solution is generated. This load included all the appliances such as lighting, phone charging, radios and table fans. In order to define the power load, the respective power consumption of each electrical appliance should be known. Thus, these data were defined according to the respective sources as (65) (66):
### Electric appliance | Power consumption (Watts)
---|---
LED lamp | 2
Phone charging | 7.5
Radio | 5
Table fan | 17

| Table 11 Power consumption by electrical appliance |

Therefore, in Tier 1 energy access which includes one LED lamp and phone charging, the power load was 7.5W for each household while for Tier 2 which included four LED lamps, phone charging, a radio and a table fan the respective power load per household was 37.5W. For both tiers, the electric services were set to be available for 4 hours, between 19:00 and 23:00.

#### 4.5.7 Total community power load demand

A general assumption in order to calculate the power load of each community was to simply multiple the defined power load per household with the number of houses in each community. However, this assumption neglects the electricity transmission losses which, in large systems can have a significant impact on the microgrid’s function. Therefore, in order to calculate the power load for each community, firstly the $P_{optimal}$ was calculated, after the power transmission losses and finally the $P_{real}$ were defined by the following method:

#### 4.5.7.1 Ideal load

The ideal electricity load $P_{ideal}$ is the total load of the community that should be covered. $P_{ideal}$ does not include any losses, therefore it is calculated by the following equation 1:

\[
P_{ideal} = \text{Number of Households} \times \text{Total electricity consumption per household} \quad \{1\}
\]

#### 4.5.7.2 Power losses

The wire that is used for the modelling is 00 (2/0) AWG, with diameter of 9.266 mm and specific resistance of 0.2557 (Ω/km). First is calculated the current of the electricity line $I$ through equation 2. Equation 2 includes the constant 0.8 as the electricity load corresponds to inductive loads such as table fan, radio and phone charging and resistive loads such as lamps. So equation 2 is:

\[
P_{ideal} = V \times I \times 0.8 =>
\]

\[
I = \frac{P_{ideal}}{V \times 0.8} \quad \{2\}
\]

Where, $V$ is the voltage of electricity in the line, equal to 230 V

$P_{ideal}$ is the electricity load that should be covered, without including the power losses of the line

After electric resistance $R_{total}$ of line is calculated by equation 3:
\[ R_{total} = R_{specific} \times Length \quad \{3\} \]

Where,

\( R_{specific} \) is the specific resistance of the cable

\( Length \) is the total length of the cable.

Finally the power losses are calculated by equation 4:

\[ P_{losses} = I^2 \times R_{total} \quad \{4\} \]

\( I \) is the calculated current of the electricity line

\( R_{total} \) is the total electrical resistance of the cable

### 4.5.7.3 Real load

Since there are certain transmission losses in power, this amount should be taken under consideration in order to guarantee the correct function and reliability of the energy system. Therefore, the total electricity load \( P_{real} \) that should be covered in each community is calculated by equation 5:

\[ P_{real} = P_{ideal} + P_{losses} \]

Where,

\( P_{ideal} \) is the electricity load that should be covered, without including the power losses of the line

\( P_{losses} \) is the power losses caused by the resistance of the transmission cable

### 4.5.7.4 Voltage drop

Last but not least, except the power losses in the transmission cable, the system suffers from voltage drop. However, since for the respective lengths of cables and currents these losses were negligible, they were not included in the research.

### 4.5.8 Mounting and wiring costs

Mounting and wiring in microgrids can have a significant cost on the total system budget and should be taken under consideration. The cost for these two parameters depends on the number of PV panels and wind turbines that are installed. As far as the wiring each company has their own price per meter, while also the need for the total length of cables was attributed through the visits and interviews with companies. As far as the mounting is concerned, most of the companies use to cooperate with an external metallurgic workshop in order to build the supporting construction of PV panels or wind turbines. As a conclusion, the cost of wiring and mounting was embodied to the respective cost of PV panels and wind turbines, in order to be taken under consideration at the modeling and optimization in HOMER Energy software.
4.5.9 O&M, labor and electricity transmission line costs

O&M and labor fixed costs were included, as details on that values for each company were received during the interviews and visits. As far as the electricity transmission line is concerned, a cable of AWG 00(2/0) model is proposed to be used. The average cost of the specific cable was found to be $2.59 USD per kilometer.

4.5.10 Comparative analysis results and conclusions

As explained before, for each community and each tier of access to energy, seven microgrids were designed. These microgrids corresponded to the optimal and most cost effective solution that each of the seven participating companies can propose. According to these results, the most affordable one was selected for comparison to solar lamps and solar kits. The comparison between the optimal microgrid of each region and tier and solar lanterns and kits was done in annual base. In other words, the annual cost per household for each energy system was defined and finally they were compared under the same time base. Nevertheless, in the comparison, there is a reference in the annual expenditures on kerosene per household in order to show the how many things can be achieved if that was orientated to other services than lamp fuel.
5 Techno-economic comparative study: Results and conclusions

5.1 Introduction

In this chapter, the results of the techno-economic comparative study are presented. Firstly, there is a short explanation of key parameters. After that, the five case study regions are analyzed. More specifically, the analysis of each region is divided in two parts that correspond to Tier 1 and Tier 2 of energy access respectively. Every part starts with the presentation of the case study region and the power load calculations. In continuity, the analysis of HOMER Energy results follows. That includes in the beginning the optimization results for each of the seven participating companies. Then the technical analysis of the most cost-effective microgrid for the respective region and tier of energy access is done.

In continuity, the included energy systems in this MSc thesis; microgrids, solar lanterns, larger solar kits and kerosene lamps are compared under the perspective of satisfying Tier 1 and Tier 2 energy access in each community. Finally, the chapter closes with the extension of comparison between microgrids, solar lamps and solar kits by the evaluation of their performance in certain factors that affect the sustainable implementation of renewable energy projects in Africa.

5.1.1 Explanation of optimization results

In this section a brief explanation of key technical and financial parameters that are included in the analysis is done.

**Optimal microgrid:** It is the most cost-effective microgrid solution among the seven microgrids that were designed for each tier and community and under the specific optimization procedure and criteria that were used. It should be clarified that the optimal microgrid does not correspond to the general optimal solution that could be achieved but to the optimal solution between the microgrids designed under this MSc thesis.

**Annual cost per household:** It is the total amount of money that each household should pay every year in order to have access to electricity.

**Total capital:** It is the total capital that would be needed in order to build, operate and maintain a microgrid. In total capital, the following costs of components and parameters are included:

- Initial cost of components:
  8. Wind turbines
  9. PV panels
  10. Inverter
  11. Charge controller
  12. Batteries
13. Mounting
14. Wiring
- Replacement cost of components
- Labour cost and company profit
- Electricity transmission grid cost
- O&M cost

**Initial capital:** It is the capital required in order to start up and build a microgrid, including all the costs of components, electricity transmission line, wiring and mounting but excluding labor and replacement of components costs.

**Excess electricity:** It is the dumbed and unutilized electricity by wind turbines and PV panels that keep harvesting wind or solar energy, when the battery bank is fully charged and charging has stopped.

**Unmet electric load:** It is the uncovered load that the system failed to satisfy as a result of power generation shortages or malfunctions.

**Capacity shortage:** It is a shortfall that occurs between the required operating capacity and the actual amount of operating capacity the system can provide (67).

**PV or wind capacity factor:** It is the average power output of the PV array or wind turbines (in kW) divided by its rated power (67).

**PV or wind penetration:** It is the average power output of the PV array divided by the average primary load (67).

### 5.2 Region 1 – Marsabit community

Marsabit County is located in the northern part of Kenya, on the east of Lake Turkana. Capital of the county is Marsabit town and largest city is Moyale. The region was chosen to be a case study as it is characterized by very high wind speeds and therefore there is great wind power exploitation potential. More specifically, the annual average wind speed is 9.4 m/s while also, there is high solar irradiation too, with annual average at 6.06 kWh/m²/d (68).

#### 5.2.1 Marsabit community and proposed electricity transmission line

The Marsabit community (2°20N, 38° 1E) was selected in order to represent villages and small towns Northern Kenya, which are exposed to high wind speeds of the wider area east of Lake Turkana. There were counted 115 households in the settlement, which classifies it as small to medium size that is very common in the country. Moreover, the weather station from which the climate data of the modelling in HOMER Energy were taken is 3.55 km far from the community.

Since the community is developed among a main road, the proposed transmission line is proposed to be placed there. The total length of the transmission line was measured through Google Earth and was found 1km. In the following picture, the transmission line in yellow colour can be seen:
5.2.2 Tier 1 – Marsabit community

5.2.2.1 Ideal load, power losses and real load

There are 115 houses in the community. Therefore, the ideal load for Tier 1 in Marsabit community is calculated by equation 1 as:

\[ P_{\text{ideal}} = 1092.5 \, W \]

The power losses caused by the electric resistance of the electricity transmission cable are calculated by equation 2, equation 3 and equation 4 as:

\[ P_{\text{losses}} = 18.03 \, W \]

Finally, the real total electricity load that would have the Marsabit community for Tier 1 energy access after considering the power losses is calculated by equation 5 as:

\[ P_{\text{real}} = P_{\text{ideal}} + P_{\text{losses}} \Rightarrow \\
P_{\text{real}} = 1092.5 + 18.03 = 1110.53 \, W \]
5.2.2.2 Optimization results

5.2.2.2.1 General results
As Marsabit is an area with very high wind, a renewable energy microgrid in would be depended on wind power. More specifically, wind power would be the dominant source of energy as in five out of seven proposed microgrids, wind turbines would hold the highest fraction of energy output. Wind turbines would produce 50% to 84% of the total power generated during the lifetime of the project.

<table>
<thead>
<tr>
<th></th>
<th>Total capital (USD)</th>
<th>Total (kWatt)</th>
<th>Solar (kWatt)</th>
<th>Wind (kWatt)</th>
<th>Solar output fraction (%)</th>
<th>Wind output fraction (%)</th>
<th>Inverter (kWatt)</th>
<th>Batteries (kWh)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Company 6</td>
<td>20,316.60</td>
<td>1.28</td>
<td>0.48</td>
<td>0.8</td>
<td>16</td>
<td>84</td>
<td>2.6</td>
<td>10.8</td>
</tr>
<tr>
<td>Company 1</td>
<td>20,385.50</td>
<td>1.7</td>
<td>1.7</td>
<td>N/A</td>
<td>100</td>
<td>N/A</td>
<td>1.25</td>
<td>20.2</td>
</tr>
<tr>
<td>Company 2</td>
<td>21,792.84</td>
<td>1</td>
<td>0</td>
<td>1</td>
<td>0</td>
<td>100</td>
<td>1.5</td>
<td>9.6</td>
</tr>
<tr>
<td>Company 7</td>
<td>25,079.80</td>
<td>1.94</td>
<td>0.94</td>
<td>1</td>
<td>28</td>
<td>72</td>
<td>1.6</td>
<td>9.6</td>
</tr>
<tr>
<td>Company 4</td>
<td>27,895.60</td>
<td>1.14</td>
<td>0.74</td>
<td>0.4</td>
<td>50</td>
<td>50</td>
<td>1.4</td>
<td>12.4</td>
</tr>
<tr>
<td>Company 3</td>
<td>31,156.00</td>
<td>1.15</td>
<td>0.75</td>
<td>0.4</td>
<td>50</td>
<td>50</td>
<td>1.2</td>
<td>14.4</td>
</tr>
<tr>
<td>Company 5</td>
<td>34,530.67</td>
<td>1.52</td>
<td>1.52</td>
<td>N/A</td>
<td>100</td>
<td>N/A</td>
<td>1.6</td>
<td>24</td>
</tr>
</tbody>
</table>

Table 12 Optimal microgrid per company, Marsabit - Tier 1

5.2.2.2.2 Cost analysis
The optimization in HOMER Energy and economic analysis showed that Company 6 can propose the most cost effective solution for Tier 1 energy access in Marsabit community. Company 6 offers the lowest cost solution for a Tier 1 microgrid, however, the annual cost per household between the optimal choice and the rest ones varies from $0.04 USD to $8.24 USD. Therefore, it can be said that the microgrid solution offered by other project developers than company 6 can be feasible and financially accessible for rural communities in Kenya. In the next table there can be seen the most important financial parameters according to each company:

<table>
<thead>
<tr>
<th></th>
<th>Total capital (USD)</th>
<th>Initial capital (USD)</th>
<th>Annual cost per household (USD)</th>
<th>PV (USD)</th>
<th>Wind (USD)</th>
<th>Batteries (USD)</th>
<th>Inverter (USD)</th>
<th>Charge Controller (USD)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Company 6</td>
<td>20,316</td>
<td>11,636</td>
<td>11.78</td>
<td>873</td>
<td>2,123</td>
<td>4,344</td>
<td>1,409</td>
<td>603</td>
</tr>
<tr>
<td>Company 1</td>
<td>20,385</td>
<td>10,793</td>
<td>11.82</td>
<td>2,717</td>
<td>-</td>
<td>5,688</td>
<td>436</td>
<td>564</td>
</tr>
<tr>
<td>Company 2</td>
<td>21,792</td>
<td>11,755</td>
<td>12.63</td>
<td>-</td>
<td>3,780</td>
<td>5,868</td>
<td>297</td>
<td>542</td>
</tr>
<tr>
<td>Company 7</td>
<td>25,079</td>
<td>14,772</td>
<td>14.54</td>
<td>2,801</td>
<td>2,943</td>
<td>5,136</td>
<td>1,533</td>
<td>603</td>
</tr>
<tr>
<td>Company 4</td>
<td>27,895</td>
<td>14,002</td>
<td>16.17</td>
<td>2,282</td>
<td>3,384</td>
<td>6,360</td>
<td>472</td>
<td>564</td>
</tr>
<tr>
<td>Company 3</td>
<td>31,156</td>
<td>15,103</td>
<td>18.06</td>
<td>2,157</td>
<td>1,886</td>
<td>11,880</td>
<td>1,356</td>
<td>564</td>
</tr>
<tr>
<td>Company 5</td>
<td>34,530</td>
<td>15,305</td>
<td>20.02</td>
<td>3,849</td>
<td>-</td>
<td>15,240</td>
<td>961</td>
<td>235</td>
</tr>
</tbody>
</table>

Table 13 Costs of microgrid per company, Marsabit - Tier 148

In the microgrid of company 6, the highest cost during the lifetime of the project is the battery bank. As the batteries will have to change every five years, then they raise the required capital as they are an expensive component. Wind turbine has the higher cost than the PV array, as a very small number of panels is proposed.
5.2.2.3 Optimal microgrid characteristics

5.2.2.3.1 System layout

<table>
<thead>
<tr>
<th></th>
<th>Model</th>
<th>Number of parts</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wind turbine</td>
<td>Hugh Piggott 800Watt</td>
<td>1</td>
</tr>
<tr>
<td>PV panels</td>
<td>Canadian Solar 240 Watt</td>
<td>2</td>
</tr>
<tr>
<td>Inverter</td>
<td>Victron multiplus 1600</td>
<td>1</td>
</tr>
<tr>
<td>Charge controller</td>
<td>Morning Star TS-MPPT-45</td>
<td>1</td>
</tr>
<tr>
<td>Batteries</td>
<td>Trojan T-105</td>
<td>8</td>
</tr>
</tbody>
</table>

Table 14 Optimal microgrid system layout, Marsabit - Tier 1

5.2.2.3.2 Electricity

In the following graph it can be seen that wind power is the main source of energy. This is a result of combination between the high wind speeds in the area and the ability of company 6 to build their own Hugh Piggott model of 800 Watt rated power. Their wind turbine is characterized by reliability while the fact that is not imported but it is constructed in Kenya makes it competitive as it has significantly low production cost. Therefore, the microgrid of company 6 would be relied basically on wind power while solar power would act as supplementary. The electricity output by the source of energy would be the following:
In total, 5,358 kWh would be produced every year. 84% of the annual energy is produced by wind turbines while 16% is generated by PV panels. Excess electricity is 3,370 kWh per year as the wind turbine works in rated power for long terms. This energy surplus could be used for other application, such as water pumping. Also, there is no capacity shortage and unmet electric demand; therefore the energy system would be very reliable and would function without any interruptions.

<table>
<thead>
<tr>
<th>kWh/yr</th>
<th>%</th>
</tr>
</thead>
<tbody>
<tr>
<td>PV array</td>
<td>878</td>
</tr>
<tr>
<td>Wind turbine</td>
<td>4,480</td>
</tr>
<tr>
<td>Total</td>
<td>5,358</td>
</tr>
<tr>
<td>Excess electricity</td>
<td>3,370</td>
</tr>
<tr>
<td>Unmet electric load</td>
<td>0.68</td>
</tr>
<tr>
<td>Capacity shortage</td>
<td>0.808</td>
</tr>
</tbody>
</table>

Table 15 Electricity parameters, Marsabit - Tier 1

5.2.2.3.3 Power generation

In the energy system, one Hugh Piggott wind turbine of 800Watt is proposed. In addition, two Canadian Solar panels of 240 Watts rated power and 24 V would be installed in order to provide supplementary charging to the batteries during wind shortages. More details on the power output by component can be seen in the following table:

<table>
<thead>
<tr>
<th></th>
<th>Wind turbine</th>
<th>PV panels</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rated capacity</td>
<td>0.800 kW</td>
<td>0.48 kW</td>
</tr>
<tr>
<td>Mean output</td>
<td>0.51 kW</td>
<td>0.1 kW</td>
</tr>
<tr>
<td>Mean yearly output</td>
<td>n/a</td>
<td>2.41 kWh/d</td>
</tr>
<tr>
<td>Capacity factor</td>
<td>63.9 %</td>
<td>20.9 %</td>
</tr>
<tr>
<td>Total production</td>
<td>4,480 kWh/yr</td>
<td>878 kWh/yr</td>
</tr>
</tbody>
</table>

Table 16 Power generation, Marsabit - Tier 1

5.2.2.3.3.1 Wind turbine

In the following graph it can be observed why wind power can play an important role for electrification in Marsabit area. During the whole year, the wind turbine can work at rated speed for many hours. The total hours of operation were 8,972 hr/yr while the wind penetration was 276%.
5.2.2.3.3.2 PV panel
The PV panels have their maximum output during the solar noun. As it can be seen in the following

diagram, the power generation starts around 6:00 o’clock in the morning and finishes around 18:00.

This is explained by the fact that Marsabit is 2.32 degrees north of the equator; therefore the
duration of the day is almost equal at 12 hours during the whole year. Medium solar irradiation
results in very short periods of rated power function. The total hours of operation were 4,425 hr/yr
while the PV penetration was 54.2%.

5.2.2.3.4 Battery bank
The model of battery that is used for energy storage is the Trojan T-105. This battery has nominal
voltage 6V, nominal capacity 225 Ah and lifetime throughput 884 kWh. More details on the battery
bank can be found in the following table:

<table>
<thead>
<tr>
<th>String size</th>
<th>4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Strings in parallel</td>
<td>2</td>
</tr>
<tr>
<td>Batteries</td>
<td>8</td>
</tr>
<tr>
<td>Bus voltage (V)</td>
<td>24</td>
</tr>
<tr>
<td>Nominal capacity</td>
<td>10.8 kWh</td>
</tr>
<tr>
<td>Usable nominal capacity</td>
<td>7.56 kWh</td>
</tr>
<tr>
<td>Autonomy</td>
<td>40.9 hr</td>
</tr>
<tr>
<td>Lifetime throughput</td>
<td>7,068 kWh</td>
</tr>
</tbody>
</table>

Table 17 Battery bank, Marsabit - Tier 1
5.2.3 Tier 2 – Marsabit community

5.2.3.1 Ideal load, power losses and real load

There are 115 houses in the community. Therefore, the ideal load for Tier 2 in Marsabit community is calculated by equation 1 as:

\[ P_{\text{ideal}} = 4312.5 \, W \]

The power losses caused by the electric resistance of the electricity transmission cable are calculated by equation 2, equation 3 and equation 4 as:

\[ P_{\text{losses}} = 280.92 \, W \]

Finally, the real total electricity load that would have the Marsabit community for Tier 2 energy access after considering the power losses is calculated by equation 5 as:

\[ P_{\text{real}} = P_{\text{ideal}} + P_{\text{losses}} \Rightarrow \]
\[ P_{\text{real}} = 4593.42 \, W \]

![Graph of Hourly Load](image)

**Figure 53** Power load on HOMER Energy, Marsabit - Tier 2

5.2.3.2 Optimization results

5.2.3.2.1 General results

As it is expected, wind power has the most significant role in the rural electrification of Marsabit community. More specifically, the penetration of wind power in the total energy generated can reach from 43% to 98% while as in Tier 1 analysis, in most of the microgrids solar power has a supplementary role for the periods that wind speed gets in lower levels.

As in Tier 1, the element that makes the microgrid of company 6 the optimal is the Hugh Piggott wind turbine of 800Watt that manufactured locally by the company, which results to a very reliable and low cost system for harvesting wind power.
## 5.2.3.2.2 Cost analysis

In contradiction to the cost analysis and results of Tier 1, there is a significant difference between the economic parameters among microgrids of different companies. It is obvious that, as much as the capacity of a system grows, the respective initial and total capital needed gets higher.

In other words, the implementation of a microgrid project varies significantly between the considered companies as the people of the community would have to pay more than the double amount of money every year if the system was built by company 5, in comparison to the amount they would pay for a microgrid build by company 6. Also, the annual cost per household between the optimal solution and the rest lays from $4.91 to $32.11 USD. In the next table, the most important financial parameters of each microgrid are summarized:

<table>
<thead>
<tr>
<th>Company</th>
<th>Total capital (USD)</th>
<th>Initial capital (USD)</th>
<th>Annual cost per household (USD)</th>
<th>PV (USD)</th>
<th>Wind (USD)</th>
<th>Batteries (USD)</th>
<th>Inverter (USD)</th>
<th>Charge Controller (USD)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Company 6</td>
<td>53,383</td>
<td>28,384</td>
<td>30.95</td>
<td>3,940</td>
<td>6,369</td>
<td>17,376</td>
<td>5,897</td>
<td>1,206</td>
</tr>
<tr>
<td>Company 1</td>
<td>61,860</td>
<td>33,217</td>
<td>35.86</td>
<td>13,136</td>
<td>-</td>
<td>19,908</td>
<td>6,279</td>
<td>1,986</td>
</tr>
<tr>
<td>Company 2</td>
<td>64,733</td>
<td>32,595</td>
<td>37.53</td>
<td>441</td>
<td>15,12</td>
<td>24,156</td>
<td>2,357</td>
<td>1,443</td>
</tr>
<tr>
<td>Company 7</td>
<td>66,933</td>
<td>33,271</td>
<td>38.80</td>
<td>7,448</td>
<td>5,886</td>
<td>25,680</td>
<td>5,727</td>
<td>470</td>
</tr>
<tr>
<td>Company 4</td>
<td>70,481</td>
<td>29,360</td>
<td>40.86</td>
<td>2,001</td>
<td>3,772</td>
<td>35,640</td>
<td>4,835</td>
<td>1,692</td>
</tr>
<tr>
<td>Company 3</td>
<td>82,764</td>
<td>39,673</td>
<td>47.98</td>
<td>9,130</td>
<td>10,15</td>
<td>34,344</td>
<td>2,477</td>
<td>1,286</td>
</tr>
<tr>
<td>Company 5</td>
<td>108,786</td>
<td>43,978</td>
<td>63.06</td>
<td>16,642</td>
<td>-</td>
<td>57,912</td>
<td>2,147</td>
<td>705</td>
</tr>
</tbody>
</table>

The main cost of the optimal solution is the batteries. That happens since an increased load has to be satisfied; therefore a large battery bank is required for the energy storage.
5.2.3.3 Optimal microgrid characteristics

5.2.3.3.1 System layout

<table>
<thead>
<tr>
<th></th>
<th>Model</th>
<th>Number of parts</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wind turbine</td>
<td>Hugh Piggott 800Watt</td>
<td>3</td>
</tr>
<tr>
<td>PV panels</td>
<td>Canadian Solar 240 Watt</td>
<td>9</td>
</tr>
<tr>
<td>Inverter</td>
<td>Vlincron Quattro 8000</td>
<td>1</td>
</tr>
<tr>
<td>Charge controller</td>
<td>Morning Star TS-MPPT-45</td>
<td>2</td>
</tr>
<tr>
<td>Batteries</td>
<td>Trojan T-105</td>
<td>32</td>
</tr>
</tbody>
</table>

Table 20 Optimal microgrid system layout, Marsabit - Tier 2

5.2.3.3.2 Electricity

In the following graph, the total power output that is generated by each technology each month is projected. It can be seen that the Hugh Piggott wind turbine is responsible for the greatest part and PV panels play a complementary role:

In total, 15,908 kWh would be produced every year. 75% of the annual energy is produced by wind turbines while 25% is generated by PV panels. Excess electricity is 7,490 kWh per year. This amount is exploitable and could be used for other appliances such as water pumping or street lighting. There is
almost no capacity shortage and unmet electric demand as the respective values count for the 0.1% of the load was unnerved; therefore the energy system would be very reliable and functioning without any interruptions.

<table>
<thead>
<tr>
<th></th>
<th>kWh/yr</th>
<th>%</th>
</tr>
</thead>
<tbody>
<tr>
<td>PV array</td>
<td>3,952</td>
<td>25</td>
</tr>
<tr>
<td>Wind turbine</td>
<td>11,956</td>
<td>75</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>15,908</strong></td>
<td><strong>100</strong></td>
</tr>
<tr>
<td>Excess electricity</td>
<td>7,490</td>
<td>47.1</td>
</tr>
<tr>
<td>Unmet electric load</td>
<td>4</td>
<td>0.1</td>
</tr>
<tr>
<td>Capacity shortage</td>
<td>6</td>
<td>0.1</td>
</tr>
</tbody>
</table>

Table 21 Electricity parameters, Marsabit - Tier 2

5.2.3.3.3 Power generation

In the energy system, three Hugh Piggott wind turbines of 800Watt are proposed. In addition, nine Canadian Solar panels of 240 Watts rated power and 24 V would be installed in order to provide supplementary charging to the batteries during the periods that wind speeds are lower. More details on the power output by component can be seen in the following table:

<table>
<thead>
<tr>
<th></th>
<th>Wind turbine</th>
<th>PV panels</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rated capacity</td>
<td>2.4 kW</td>
<td>2.16 kW</td>
</tr>
<tr>
<td>Mean output</td>
<td>1.36 kW</td>
<td>0.45 kW</td>
</tr>
<tr>
<td>Mean yearly output</td>
<td>n/a</td>
<td>10.8 kWh/d</td>
</tr>
<tr>
<td>Capacity factor</td>
<td>56.9 %</td>
<td>20.9 %</td>
</tr>
<tr>
<td><strong>Total production</strong></td>
<td><strong>11,956 kWh/yr</strong></td>
<td><strong>3,952 kWh/yr</strong></td>
</tr>
</tbody>
</table>

Table 22 Power generation, Marsabit - Tier 2

5.2.3.3.1 Wind turbine

The wind turbines work most of the time close to rated power. As it can be seen in the next graph, this takes places in a very frequent level, which also explains the high amount of excess electricity. In addition, the ability of multiple wind turbines to work almost at rated power shows the potential of exploitation of wind energy in Marsabit region, for smaller or larger renewable energy systems. The total hours of operation were 8,072 hr/yr and the wind penetration 178%.
5.2.3.3.3.2 PV panel
The PV panels have their maximum output during the solar noon while the power generation lasts approximately 12 hours every day, as the area is close to the equator. It should be mentioned that Marasabit has a respectable amount of solar irradiation; therefore, there is a good potential of solar energy exploitation. Total hours of operation were 4,425 hr/yr and PV penetration 58.8%.

![Figure 57 PV array output, Marsabit - Tier 2](image)

5.2.3.3.4 Battery bank
The model of battery that is used for energy storage is the Trojan T-105. This battery has nominal voltage 6V, nominal capacity 225 Ah and lifetime throughput 884 kWh. More details on the battery bank can be found in the following table:

<table>
<thead>
<tr>
<th>String size</th>
<th>4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Strings in parallel</td>
<td>2</td>
</tr>
<tr>
<td>Batteries</td>
<td>32</td>
</tr>
<tr>
<td>Bus voltage (V)</td>
<td>24</td>
</tr>
<tr>
<td>Nominal capacity</td>
<td>43.3 kWh</td>
</tr>
<tr>
<td>Usable nominal capacity</td>
<td>30.2 kWh</td>
</tr>
<tr>
<td>Autonomy</td>
<td>39.4 hr</td>
</tr>
<tr>
<td>Lifetime throughput</td>
<td>28,273 kWh</td>
</tr>
</tbody>
</table>

Table 23 Battery bank, Marsabit - Tier 2

5.3 Region 2 – Malindi community
Malindi is a coastal area in Kilifi county and capital of the county is Kilifi town. As the region is close to the Indian Ocean shore, it has a good potential of wind exploitation. Except Marsabit region that has extreme wind speeds and is the only in Kenya, there are several others, especially in the coastal part of the country that have mean wind speeds of 4 m/s. The region was chosen as it represents all the areas in Kenya that are characterized by average wind speeds of approximately 4 m/s which is the lower speed limit that makes this source of energy exploitable, while at the same time, average solar irradiation of 5.42 kWh/m²/d means there is good potential for solar energy systems.
5.3.1 Malindi community and proposed electricity transmission line

The Malindi community that was chosen for the modeling of microgrid has coordinates (3°15S, 40°2E) and is located 6.5 far from the weather station from which the climate data were received. In addition, there are 183 households in the settlement which makes it a small typical rural Kenyan community.

The electricity transmission line is proposed to partially to be placed among the road and partially at the edge of the community. This design aims on the one hand to serve the houses that are placed close to the main road and on the other hand not affect any settlements inside the community. In addition, as the area is woody, a transmission line that intersects the community would be more difficult to be raised. The proposed line can be seen in the next picture as a yellow line:

![Figure 58 Malindi community](image)

5.3.2 Tier 1 – Malindi community

5.3.2.1 Ideal load, power losses and real load

There are 183 houses in the community. Therefore, the optimal load for Tier 1 in Malindi community is calculated by equation 1 as:

\[ P_{\text{ideal}} = 1738.5 \, W \]

The power losses caused by the electric resistance of the electricity transmission cable are calculated by equation 2, equation 3 and equation 4 as:

\[ P_{\text{losses}} = 45.65 \, W \]

Finally, the real total electricity load that would have the Malindi community for Tier 1 energy access after considering the power losses is calculated by equation 5 as:

\[ P_{\text{real}} = P_{\text{ideal}} + P_{\text{losses}} \Rightarrow \]

\[ P_{\text{real}} = 1784.15 \, W \]
5.3.2.2 Optimization results

5.3.2.2.1 General results

In Malindi community, solar irradiation is the main source of electricity generation. The majority of proposed microgrids uses PV panels while the existence of relatively high wind speeds makes the use of wind turbines as a supplementary source of energy, a feasible choice.

Company 6 has again, as in Marsabit community the most cost effective microgrid, while this is the result of the Hugh Piggott wind turbine of 800Watt that is manufactured by the company, which results to a very reliable and low cost system for harvesting wind power. In addition, in this result have contributed the lower prices of their PV panels in combination to the batteries they distribute.

![Daily Profile](image)

Figure 59 Power load in HOMER Energy, Malindi - Tier 1

<table>
<thead>
<tr>
<th>Company</th>
<th>Total capital (USD)</th>
<th>Total (kWatt)</th>
<th>Solar (kWatt)</th>
<th>Wind (kWatt)</th>
<th>Solar output fraction (%)</th>
<th>Wind output fraction (%)</th>
<th>Inverter (kWatt)</th>
<th>Batteries (kWh)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Company 6</td>
<td>34,109</td>
<td>3.44</td>
<td>2.64</td>
<td>0.8</td>
<td>85</td>
<td>15</td>
<td>2.6</td>
<td>27</td>
</tr>
<tr>
<td>Company 1</td>
<td>35,771</td>
<td>6.24</td>
<td>6.24</td>
<td>0</td>
<td>100</td>
<td>N/A</td>
<td>2.4</td>
<td>14.4</td>
</tr>
<tr>
<td>Company 2</td>
<td>37,278</td>
<td>2.28</td>
<td>0.28</td>
<td>2</td>
<td>8</td>
<td>92</td>
<td>2.4</td>
<td>21.6</td>
</tr>
<tr>
<td>Company 7</td>
<td>40,820</td>
<td>4.6</td>
<td>3.6</td>
<td>1</td>
<td>83</td>
<td>17</td>
<td>2.4</td>
<td>27</td>
</tr>
<tr>
<td>Company 4</td>
<td>52,148</td>
<td>4.7</td>
<td>3.7</td>
<td>1</td>
<td>100</td>
<td>0</td>
<td>2.5</td>
<td>32.1</td>
</tr>
<tr>
<td>Company 3</td>
<td>60,205</td>
<td>3.85</td>
<td>2.85</td>
<td>1</td>
<td>76</td>
<td>24</td>
<td>2.4</td>
<td>28.8</td>
</tr>
<tr>
<td>Company 5</td>
<td>62,384</td>
<td>4.92</td>
<td>4.92</td>
<td>0</td>
<td>100</td>
<td>N/A</td>
<td>2.4</td>
<td>43.2</td>
</tr>
</tbody>
</table>

Table 24 Optimal microgrid per company, Malindi - Tier 1

5.3.2.2.2 Cost analysis

As said before, the optimization showed that company 6 can provide the most low-cost microgrid for Tier 1 energy access in the Malindi community. As before, there are other companies that have competitive systems as company 1 and company 2. In addition, company 2 has the lowest initial cost but the total cost of the project would be $5167 USD than company 6, which is the result of the cost of battery replacement. Nevertheless, all microgrids would have lower cost per household in comparison to the $126 USD that are spent for kerosene every year by each family on average. In the next table, the most important financial parameters of each microgrid are summarized:
As the main source of energy is PV panels in company’s 6 microgrid, the PV array has a high cost. As expected, the batteries contribute to the total capital too as not only they are expensive but also they have to be changed every five years.

![Company 6 cost of components](image)

**Figure 60 Cost of components in optimal microgrid, Malindi - Tier 1**

### 5.3.2.3 Optimal microgrid characteristics

#### 5.3.2.3.1 System layout

<table>
<thead>
<tr>
<th>Model</th>
<th>Number of parts</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wind turbine</td>
<td>Hugh Piggott 800Watt</td>
</tr>
<tr>
<td>PV panels</td>
<td>Canadian Solar 240 Watt</td>
</tr>
<tr>
<td>Inverter</td>
<td>Magnum RD2624E</td>
</tr>
<tr>
<td>Charge controller</td>
<td>Morning Star TS-MPPT-60</td>
</tr>
<tr>
<td>Batteries</td>
<td>Trojan T-105</td>
</tr>
</tbody>
</table>

**Table 26 Optimal microgrid system layout, Malindi - Tier 1**

#### 5.3.2.3.2 Electricity

In the following graph, the total power output that is generated by each technology each month is projected. Most of the electricity is generated by the PV panes while a supplementary role plays the Hugh Piggott wind turbine.
In total, 5,565 kWh would be produced every year. 85% of the annual energy is produced by PV panels while 15% is generated by the wind turbine. Excess electricity is 3,235 kWh per year. This amount is enough in order to be distributed in other appliances such as hot water, water pumping and street lighting. There is almost no capacity shortage and unmet electric demand as the respective values count are less than 1 kWh per year; therefore the energy system would be very reliable and functioning without any interruptions.

<table>
<thead>
<tr>
<th>kWh/yr</th>
<th>%</th>
</tr>
</thead>
<tbody>
<tr>
<td>PV array</td>
<td>5,565</td>
</tr>
<tr>
<td>Wind turbine</td>
<td>976</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>6,541</strong></td>
</tr>
<tr>
<td>Excess electricity</td>
<td>3,235</td>
</tr>
<tr>
<td>Unmet electric load</td>
<td>0.656</td>
</tr>
<tr>
<td>Capacity shortage</td>
<td>0.856</td>
</tr>
</tbody>
</table>

Table 27 Electricity parameters, Malindi - Tier 1

### 5.3.2.3.3 Power generation

Most of the power generated comes from the PV panels of the system, while the wind turbine aims to harvest the existing wind potential. More information on the power generation parameters can be found in the next table:

<table>
<thead>
<tr>
<th>Wind turbine</th>
<th>PV panels</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rated capacity</td>
<td>0.8 kW</td>
</tr>
<tr>
<td>Mean output</td>
<td>0.11 kW</td>
</tr>
<tr>
<td>Mean yearly output</td>
<td>n/a</td>
</tr>
<tr>
<td>Capacity factor</td>
<td>13.9 %</td>
</tr>
<tr>
<td><strong>Total production</strong></td>
<td>976 kWh/yr</td>
</tr>
</tbody>
</table>

Table 28 Power generation, Malindi - Tier 1

#### 5.3.2.3.3.1 Wind turbine

The proposed wind turbine is one Hugh Piggott model that is manufactured by company 6 in Kenya which results to the cost of it to be significantly low. Wind penetration which is the average power output of the wind turbine divided by the average primary load is 38.2%. Furthermore, the wind turbine barely works at rated power while during there are many shortage periods or periods that wind speed equals to the start up speed of the wind turbine, therefore, the power generation remains at low levels. Wind penetration was found 38.2%.
5.3.2.3.3.2 PV panels
In total, 16 Canadian Solar of 240 Watt of rated power and 24 V nominal voltage would be installed.
PV penetration which is the average power output of the PV turbine divided by the average primary load is 218%. Moreover, the solar system harvests energy for 12 hours per day on average as the community is close to the equator. What is interesting it that, there are certain periods such as during mid-May that the PV does not generate any energy. At the same periods, the wind turbine as it can be seen before, work on average in medium or rated speed. That shortage in PV power generation could explain the need of a hybrid system in comparison to an only-solar microgrid.

5.3.2.3.4 Battery bank
The model of battery that is used for energy storage is the Trojan T-105. This battery has nominal voltage 6V, nominal capacity 225 Ah and lifetime throughput 884 kWh. More details on the battery bank can be found in the following table:

<table>
<thead>
<tr>
<th>String size</th>
<th>4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Strings in parallel</td>
<td>4</td>
</tr>
<tr>
<td>Batteries</td>
<td>16</td>
</tr>
<tr>
<td>Bus voltage (V)</td>
<td>24</td>
</tr>
<tr>
<td>Nominal capacity</td>
<td>21.6 kWh</td>
</tr>
<tr>
<td>Usable nominal capacity</td>
<td>15.1 kWh</td>
</tr>
<tr>
<td>Autonomy</td>
<td>51.8 hr</td>
</tr>
<tr>
<td>Lifetime throughput</td>
<td>14,137 kWh</td>
</tr>
</tbody>
</table>

Table 29 Battery bank, Malindi - Tier 1
5.3.3 Tier 2 – Malindi community

5.3.3.1 Ideal load, power losses and real load

There are 183 houses in the community. Therefore, the optimal load for Tier 2 in Malindi community is calculated by equation 1 as:

\[ P_{\text{ideal}} = 6862.5 \text{ W} \]

The power losses caused by the electric resistance of the electricity transmission cable are calculated by equation 2, equation 3 and equation 4 as:

\[ P_{\text{losses}} = 711.36 \text{ W} \]

Finally, the real total electricity load that would have the Malindi community for Tier 2 energy access after considering the power losses is calculated by equation 5 as:

\[ P_{\text{real}} = P_{\text{ideal}} + P_{\text{losses}} \Rightarrow P_{\text{real}} = 7573.86 \text{ W} \]

![Figure 64 Power load in HOMER Energy, Malindi - Tier 2](image)

5.3.3.2 Optimization results

5.3.3.2.1 General results

As in Tier 1, the results for Tier 2 show that solar panels generate most of the electricity for all the designed microgrids and wind turbines play a supplementary role, except the proposed microgrid of company 2. Also, the systems get proportionally larger in comparison to Tier 1 for Malindi's more appliances have to be covered.

<table>
<thead>
<tr>
<th>Company 6</th>
<th>Total capital (USD)</th>
<th>Total (kWatt)</th>
<th>Solar (kWatt)</th>
<th>Wind (kWatt)</th>
<th>Solar output fraction (%)</th>
<th>Wind output fraction (%)</th>
<th>Inverter (kWatt)</th>
<th>Batteries (kWh)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Company 1</td>
<td>112,983</td>
<td>14.48</td>
<td>11.28</td>
<td>3.2</td>
<td>82</td>
<td>18</td>
<td>10</td>
<td>103</td>
</tr>
<tr>
<td>Company 2</td>
<td>122,128</td>
<td>18</td>
<td>18</td>
<td>N/A</td>
<td>100</td>
<td>N/A</td>
<td>8</td>
<td>166</td>
</tr>
<tr>
<td>Company 7</td>
<td>126,152</td>
<td>9.8</td>
<td>3.8</td>
<td>6</td>
<td>25</td>
<td>75</td>
<td>N/A</td>
<td>8</td>
</tr>
<tr>
<td>Company 3</td>
<td>151,676</td>
<td>15.85</td>
<td>11.85</td>
<td>4</td>
<td>81</td>
<td>19</td>
<td>10</td>
<td>108</td>
</tr>
<tr>
<td>Company 4</td>
<td>174,915</td>
<td>14.43</td>
<td>14.43</td>
<td>0</td>
<td>100</td>
<td>0</td>
<td>10.5</td>
<td>148</td>
</tr>
<tr>
<td>Company 5</td>
<td>182,460</td>
<td>11</td>
<td>2</td>
<td>84</td>
<td>16</td>
<td>10</td>
<td>10</td>
<td>163</td>
</tr>
</tbody>
</table>

| Company 6 | 240,921              | 15.91         | 15.91        | N/A         | 100                      | N/A                     | 6               | 187            |

Table 30 Optimal microgrid per company, Malindi - Tier 2
5.3.3.2 Cost analysis

The most cost effective microgrid would be built again by company 6. Furthermore, a key point in the outcomes of optimization is that residents of Malindi community could have access to energy of Tier 2 level with less capital they spend for kerosene on average. So, for that community it is also proved all microgrid would cost less per household in comparison to lamp fuel.

<table>
<thead>
<tr>
<th>Company</th>
<th>Total capital (USD)</th>
<th>Initial capital (USD)</th>
<th>Annual cost per household (USD)</th>
<th>PV (USD)</th>
<th>Wind (USD)</th>
<th>Batteries (USD)</th>
<th>Inverter (USD)</th>
<th>Charge Controllers</th>
</tr>
</thead>
<tbody>
<tr>
<td>Company 6</td>
<td>112,983</td>
<td>28,384</td>
<td>41.16</td>
<td>20,521</td>
<td>8,492</td>
<td>41,268</td>
<td>6,568</td>
<td>3,028</td>
</tr>
<tr>
<td>Company 1</td>
<td>122,128</td>
<td>33,217</td>
<td>44.49</td>
<td>28,914</td>
<td>-</td>
<td>46,926</td>
<td>6,993</td>
<td>4,836</td>
</tr>
<tr>
<td>Company 2</td>
<td>126,152</td>
<td>32,595</td>
<td>45.96</td>
<td>4,725</td>
<td>22,680</td>
<td>54,900</td>
<td>5,573</td>
<td>2,886</td>
</tr>
<tr>
<td>Company 7</td>
<td>151,676</td>
<td>33,271</td>
<td>55.26</td>
<td>34,564</td>
<td>11,772</td>
<td>49,800</td>
<td>10,233</td>
<td>2,418</td>
</tr>
<tr>
<td>Company 4</td>
<td>174,915</td>
<td>29,360</td>
<td>63.72</td>
<td>44,507</td>
<td>-</td>
<td>76,320</td>
<td>3,303</td>
<td>4,144</td>
</tr>
<tr>
<td>Company 3</td>
<td>182,460</td>
<td>39,673</td>
<td>66.47</td>
<td>2,501</td>
<td>11,005</td>
<td>111,510</td>
<td>6,806</td>
<td>2,256</td>
</tr>
<tr>
<td>Company 5</td>
<td>240,921</td>
<td>43,978</td>
<td>87.77</td>
<td>28,831</td>
<td>-</td>
<td>182,880</td>
<td>3,845</td>
<td>1,175</td>
</tr>
</tbody>
</table>

Table 31 Costs of microgrid per company, Malindi - Tier 2

As the biggest part of electricity in generated by the PV array, this part of the system has higher cost in comparison to the wind turbines. Batteries count for the largest part of the total capital while inverters and charge controllers cost a very small amount of money in comparison to other parts.

![Figure 65 Cost of components in optimal microgrid, Malindi - Tier 2](image-url)
5.3.3.3 Optimal microgrid characteristics

5.3.3.3.1 System layout

<table>
<thead>
<tr>
<th></th>
<th>Model</th>
<th>Number of parts</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wind turbine</td>
<td>Hugh Piggott 800Watt</td>
<td>4</td>
</tr>
<tr>
<td>PV panels</td>
<td>Canadian Solar 240 Watt</td>
<td>47</td>
</tr>
<tr>
<td>Inverter</td>
<td>Victron Quattro 10000</td>
<td>1</td>
</tr>
<tr>
<td>Charge controller</td>
<td>Morning Star TS-MPPT-60</td>
<td>5</td>
</tr>
<tr>
<td>Batteries</td>
<td>Trojan T-105</td>
<td>76</td>
</tr>
</tbody>
</table>

Table 32 Optimal microgrid system layout, Malindi - Tier 2

5.3.3.3.2 Electricity

In the following graph, it can be observed that most of the electricity is generated by PV panels, while the wind turbines harvest the available wind energy of the area but contribute much lower to the total outcome of the system:

![Monthly Average Electric Production](image)

In total 17,808 kWh would be produced every year. 82% of the annual energy is produced by PV panels while 18% is generated by wind turbines. Excess electricity is 7,391 kWh per year. Even it is a smaller percentage to the overall load in comparison to Tier 1 for the same region, this energy could be used in other appliances such as irrigation. There is almost no capacity shortage and unmet electric demand as the respective values count for the 0.1% of the load was unnerved; therefore the energy system would be very reliable and functioning without any interruptions.

<table>
<thead>
<tr>
<th></th>
<th>kWh/yr</th>
<th>%</th>
</tr>
</thead>
<tbody>
<tr>
<td>PV array</td>
<td>17,808</td>
<td>82</td>
</tr>
<tr>
<td>Wind turbine</td>
<td>3,893</td>
<td>18</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>21,701</strong></td>
<td><strong>100</strong></td>
</tr>
<tr>
<td>Excess electricity</td>
<td>7,391</td>
<td>34.1</td>
</tr>
<tr>
<td>Unmet electric load</td>
<td>9.31</td>
<td>0.1</td>
</tr>
<tr>
<td>Capacity shortage</td>
<td>10.9</td>
<td>0.1</td>
</tr>
</tbody>
</table>

Table 33 Electricity parameters, Malindi - Tier 2
5.3.3.3 Power generation

In the energy system, four Hugh Piggott wind turbines of 800Watt are proposed. In addition, forty seven Canadian Solar panels of 240 Watts rated power and 24 V would be installed in order to provide. More details on the power output by component can be seen in the following table:

<table>
<thead>
<tr>
<th></th>
<th>Wind turbines</th>
<th>PV panels</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rated capacity</td>
<td>3.20 kW</td>
<td>11.3 kW</td>
</tr>
<tr>
<td>Mean output</td>
<td>0.44 kW</td>
<td>2.0 kW</td>
</tr>
<tr>
<td>Mean yearly output</td>
<td>n/a</td>
<td>48.8 kWh/d</td>
</tr>
<tr>
<td>Capacity factor</td>
<td>13.9 %</td>
<td>18.0 %</td>
</tr>
<tr>
<td>Total production</td>
<td>3,893 kWh/yr</td>
<td>17,808 kWh/yr</td>
</tr>
</tbody>
</table>

Table 34 Power generation, Malindi - Tier 2

5.3.3.3.1 Wind turbine

The wind turbines do not function close to rated power most of the time as there are many periods of shortages too. The reason is that the wind speeds in the area are sufficient to make the wind turbines rotate but they are low enough in order to make them generate electricity in small quantities. Wind penetration is 35.2% and the total hours of operation 5,552 hr/yr.

![Wind turbine output](image1)

Figure 67 Wind turbine output, Malindi - Tier 2

5.3.3.3.2 PV panel

The PV panels have their maximum output during the solar noun while the power generation lasts approximately 12 hours every day, as the area is close to the equator. In addition, there are periods between January to March and September to December that the PV array reaches the rated power. This is explained by the fact that between April and July is the rainy season in Kenya, and therefore there is increased cloudiness resulting in lower levels of irradiation. The solar power penetration is 161% while the total annual hours of operation are 4,390 hr/yr.

![PV output](image2)

Figure 68 PV array output, Malindi - Tier 2
5.3.3.4 Battery bank

The model of battery that is used for energy storage is the Trojan T-105. This battery has nominal voltage 6V, nominal capacity 225 Ah and lifetime throughput 884 kWh. More details on the battery bank can be found in the following table:

<table>
<thead>
<tr>
<th>String size</th>
<th>4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Strings in parallel</td>
<td>19</td>
</tr>
<tr>
<td>Batteries</td>
<td>76</td>
</tr>
<tr>
<td>Bus voltage (V)</td>
<td>24</td>
</tr>
<tr>
<td>Nominal capacity</td>
<td>103 kWh</td>
</tr>
<tr>
<td>Usable nominal capacity</td>
<td>78.1 kWh</td>
</tr>
<tr>
<td>Autonomy</td>
<td>56.9 hr</td>
</tr>
<tr>
<td>Lifetime throughput</td>
<td>67,149 kWh</td>
</tr>
</tbody>
</table>

Table 35 Battery bank, Malindi - Tier 2

5.4 Region 3 – Nadapal community

Nadapal community is placed 10 km far from Lodwar, which is the capital of Turkana County. The area is characterized by highly exploitable solar irradiation of 6.57 kWh/m²/d in average and medium wind speeds of 3.7 m/s in average that can be used as a source of power generation. Therefore, the region was chosen in order to study the performance and parameters of a renewable energy microgrid in an area with very high solar irradiation and medium wind speeds.

5.4.1 Nadapal community and proposed electricity transmission line

The community which is relatively close to the capital of the county, Lodwar has no access to electricity. Its geographical coordinates are 3°4’N, 35°30’E. Also, the number of households measured is 377, which makes it a medium size rural community.

The proposed transmission line for electricity is set on the northern road that exists in the community, while there is one main junction that reaches the further households. The total length of the line is 1 km. The line can be seen in the next picture in yellow color:
5.4.2 Tier 1 – Nadapal community

5.4.2.1 Ideal load, power losses and real load

There are 377 houses in the community. Therefore, the optimal load for Tier 1 in Nadapal community is calculated by equation 1 as:

\[ P_{\text{ideal}} = 3581.5 \text{ W} \]

The power losses caused by the electric resistance of the electricity transmission cable are calculated by equation 2, equation 3 and equation 4 as:

\[ P_{\text{losses}} = 193.76 \text{ W} \]

Finally, the real total electricity load that would have the Nadapal community for Tier 1 energy access after considering the power losses is calculated by equation 5 as:

\[ P_{\text{real}} = P_{\text{ideal}} + P_{\text{losses}} \Rightarrow \]
\[ P_{\text{real}} = 3775.25 \text{ W} \]

![Figure 70 Power load, Nadapal - Tier 1](image)

5.4.2.2 Optimization results

5.4.2.2.1 General results

In the following table it can be seen that the majority of the proposed microgrids, solar power prevails. It is obvious that the relatively good wind speed that in Malindi had a supplementary role, do not take any part in the power generation in six out of seven proposals. This happens as Nadapal is located to an area with high solar irradiation, and as a result this fact makes solar energy a more feasible choice in comparison to wind power.

<table>
<thead>
<tr>
<th>Company</th>
<th>Total capital (USD)</th>
<th>Total (kWatt)</th>
<th>Solar (kWatt)</th>
<th>Wind (kWatt)</th>
<th>Solar output fraction (%)</th>
<th>Wind output fraction (%)</th>
<th>Inverter (kWatt)</th>
<th>Batteries (kWh)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Company 1</td>
<td>49,483</td>
<td>5.04</td>
<td>5.04</td>
<td>0</td>
<td>100</td>
<td>N/A</td>
<td>8</td>
<td>65.5</td>
</tr>
<tr>
<td>Company 6</td>
<td>52,925</td>
<td>4.32</td>
<td>4.32</td>
<td>0</td>
<td>100</td>
<td>0</td>
<td>5</td>
<td>54</td>
</tr>
<tr>
<td>Company 7</td>
<td>69,561</td>
<td>5.405</td>
<td>5.405</td>
<td>0</td>
<td>100</td>
<td>0</td>
<td>5</td>
<td>75.6</td>
</tr>
<tr>
<td>Company 2</td>
<td>69,611</td>
<td>4.08</td>
<td>3.08</td>
<td>1</td>
<td>75</td>
<td>25</td>
<td>5</td>
<td>57.6</td>
</tr>
<tr>
<td>Company 4</td>
<td>69,655</td>
<td>3.885</td>
<td>3.885</td>
<td>0</td>
<td>100</td>
<td>0</td>
<td>7</td>
<td>61.8</td>
</tr>
<tr>
<td>Company 3</td>
<td>95,996</td>
<td>8.25</td>
<td>8.25</td>
<td>0</td>
<td>100</td>
<td>0</td>
<td>6</td>
<td>38.4</td>
</tr>
<tr>
<td>Company 5</td>
<td>101,044</td>
<td>4.32</td>
<td>4.32</td>
<td>0</td>
<td>100</td>
<td>N/A</td>
<td>6</td>
<td>90.2</td>
</tr>
</tbody>
</table>

Table 36 Optimal microgrid per company, Nadapal - Tier 1
5.4.2.2 Cost analysis

The optimization in HOMER Energy and economic analysis showed that Company 1 can build the microgrid that requires the lowest capital. In addition, it can be seen in the following table that the required capital that would be needed by each household is significantly lower to the average expenditures on kerosene fuel which are rated to $126 USD per year. The advantage of company 6 which is their Hugh Piggott wind turbine, would not lay any role for electrification in Nadapal as solar irradiation is more efficient in order to cover the energy needs of the community.

<table>
<thead>
<tr>
<th>Company</th>
<th>Total capital (USD)</th>
<th>Initial capital (USD)</th>
<th>Annual cost per household (USD)</th>
<th>PV (USD)</th>
<th>Wind (USD)</th>
<th>Batteries (USD)</th>
<th>Inverter (USD)</th>
<th>Charge Controllers</th>
</tr>
</thead>
<tbody>
<tr>
<td>Company 1</td>
<td>49,483</td>
<td>24,644</td>
<td>8.75</td>
<td>8,126</td>
<td>-</td>
<td>18,486</td>
<td>3,564</td>
<td>1,612</td>
</tr>
<tr>
<td>Company 6</td>
<td>52,925</td>
<td>25,136</td>
<td>9.36</td>
<td>7,854</td>
<td>-</td>
<td>21,720</td>
<td>3,348</td>
<td>1,514</td>
</tr>
<tr>
<td>Company 7</td>
<td>69,561</td>
<td>35,813</td>
<td>12.30</td>
<td>16,121</td>
<td>-</td>
<td>24,900</td>
<td>4,600</td>
<td>1,612</td>
</tr>
<tr>
<td>Company 2</td>
<td>69,611</td>
<td>27,978</td>
<td>12.31</td>
<td>5,140</td>
<td>3,780</td>
<td>30,744</td>
<td>2,187</td>
<td>1,443</td>
</tr>
<tr>
<td>Company 4</td>
<td>69,655</td>
<td>31,285</td>
<td>12.32</td>
<td>11,992</td>
<td>-</td>
<td>31,800</td>
<td>2,477</td>
<td>1,036</td>
</tr>
<tr>
<td>Company 3</td>
<td>95,996</td>
<td>56,633</td>
<td>16.98</td>
<td>28,400</td>
<td>49,036</td>
<td>35,640</td>
<td>6,783</td>
<td>1,692</td>
</tr>
<tr>
<td>Company 5</td>
<td>101,044</td>
<td>38,022</td>
<td>17.87</td>
<td>10,921</td>
<td>-</td>
<td>57,912</td>
<td>2,147</td>
<td>470</td>
</tr>
</tbody>
</table>

Table 37 Costs of microgrid per company, Nadapa - Tier 1

Cost of PV array in the optimal solution is kept relatively low. That happens because a smaller number of PV panels would need in order to harvest solar energy and generate electricity. The battery bank is responsible for the biggest part of the total capital, while the inverter and the charge controller have the lowest cost.

![Company 1 cost of components](image)

Figure 71 Cost of components in optimal microgrid, Nadapal - Tier 1
5.4.2.3 Optimal microgrid characteristics

5.4.2.3.1 System layout

<table>
<thead>
<tr>
<th></th>
<th>Model</th>
<th>Number of parts</th>
</tr>
</thead>
<tbody>
<tr>
<td>PV panels</td>
<td>Canadian Solar 240 Watt</td>
<td>21</td>
</tr>
<tr>
<td>Inverter</td>
<td>Multi 5000</td>
<td>1</td>
</tr>
<tr>
<td>Charge controller</td>
<td>Morning Star TS-MPPT-60</td>
<td>2</td>
</tr>
<tr>
<td>Batteries</td>
<td>DEKA 8G4D gel</td>
<td>26</td>
</tr>
</tbody>
</table>

Table 38 Optimal microgrid system layout, Nadapal - Tier 1

5.4.2.3.2 Electricity

Company 1 has the affordable energy system. The microgrid would be based completely on solar energy as the solar irradiation of the region is high. In total, 9,674 kWh would be produced every year. Excess electricity is 2,044 kWh per year. This energy could be used for irrigation, especially in a dry area as Nadapal. There is minor capacity shortage and unmet electric demand which is neglectable; therefore the energy system would be very reliable and would function without any interruptions.

![Figure 72 Monthly average electric production, Nadapal - Tier 1](image)

<table>
<thead>
<tr>
<th></th>
<th>kWh/yr</th>
<th>%</th>
</tr>
</thead>
<tbody>
<tr>
<td>PV array</td>
<td>9,674</td>
<td>100</td>
</tr>
<tr>
<td>Excess electricity</td>
<td>2,044</td>
<td>21.1</td>
</tr>
<tr>
<td>Unmet electric load</td>
<td>2.30</td>
<td>0.0</td>
</tr>
<tr>
<td>Capacity shortage</td>
<td>2.68</td>
<td>0.0</td>
</tr>
</tbody>
</table>

Table 39 Electricity parameters, Nadapal - Tier 1

5.4.2.3.3 Power generation

In the energy system, twenty one Canadian Solar panels of 240 Watts rated power and 24 V would be installed in order to provide charging to the batteries during wind shortages. More details on the power output by component can be seen in the following table:
5.4.2.3.3.1 PV panel
The PV panels have their maximum output during the solar noun. As it can be seen in the following diagram, the power generation starts around 6:00 o’clock in the morning and finishes around 18:00. This is explained by the fact that Nadapal is 3.04 degrees north of the equator; therefore the duration of the day is almost equal at 12 hours during the whole year. There are no shortages at the electricity generation while the total hours of operation were 4,350 hr/yr and the PV penetration 176%.

![PV Output](image)

**Figure 73 PV array output, Nadapal - Tier 1**

5.4.2.3.4 Battery bank
The model of battery that is used for energy storage is the DEKA 8G4D gel. This battery has nominal voltage 12V, nominal capacity 210 Ah and lifetime throughput 1,426 kWh. More details on the battery bank can be found in the following table:

<table>
<thead>
<tr>
<th>String size</th>
<th>2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Strings in parallel</td>
<td>13</td>
</tr>
<tr>
<td>Batteries</td>
<td>26</td>
</tr>
<tr>
<td>Bus voltage</td>
<td>24 V</td>
</tr>
<tr>
<td>Nominal capacity</td>
<td>65.5 kWh</td>
</tr>
<tr>
<td>Usable nominal capacity</td>
<td>32.8 kWh</td>
</tr>
<tr>
<td>Autonomy</td>
<td>52.1 hr</td>
</tr>
<tr>
<td>Lifetime throughput</td>
<td>37,072 kWh</td>
</tr>
</tbody>
</table>

**Table 41 Battery bank, Nadapal - Tier 1**
5.4.3 Tier 2 – Nadapal community

5.4.3.1 Ideal load, power losses and real load

There are 377 houses in the community. Therefore, the optimal load for Tier 2 in Nadapal community is calculated by equation 1 as:

\[ P_{\text{ideal}} = 14137.5 \, \text{W} \]

The power losses caused by the electric resistance of the electricity transmission cable are calculated by equation 2, equation 3 and equation 4 as:

\[ P_{\text{losses}} = 3019.05 \, \text{W} \]

Finally, the real total electricity load that would have the Nadapal community for Tier 2 energy access after considering the power losses is calculated by equation 5 as:

\[ P_{\text{real}} = P_{\text{ideal}} + P_{\text{losses}} \Rightarrow \]

\[ P_{\text{real}} = 17156.55 \, \text{W} \]

5.4.3.2 Optimization results

5.4.3.2.1 General results

As for Tier 1, in the proposed microgrids for Tier 2 solar energy is dominant in the power generation. Here are the technical parameters of the optimal microgrid per company:

<table>
<thead>
<tr>
<th>Company</th>
<th>Total capital (USD)</th>
<th>Total (kWatt)</th>
<th>Solar (kWatt)</th>
<th>Wind (kWatt)</th>
<th>Solar output fraction (%)</th>
<th>Wind output fraction (%)</th>
<th>Inverter (kWatt)</th>
<th>Batteries (kWh)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Company 6</td>
<td>200,952</td>
<td>21.12</td>
<td>21.12</td>
<td>0</td>
<td>100</td>
<td>0</td>
<td>20</td>
<td>227</td>
</tr>
<tr>
<td>Company 1</td>
<td>261,163</td>
<td>29.04</td>
<td>29.04</td>
<td>0</td>
<td>100</td>
<td>N/A</td>
<td>20</td>
<td>211</td>
</tr>
<tr>
<td>Company 2</td>
<td>282,907</td>
<td>18.32</td>
<td>12.32</td>
<td>6</td>
<td>65</td>
<td>35</td>
<td>22</td>
<td>245</td>
</tr>
<tr>
<td>Company 7</td>
<td>288,175</td>
<td>23.5</td>
<td>23.5</td>
<td>0</td>
<td>100</td>
<td>0</td>
<td>20</td>
<td>248</td>
</tr>
<tr>
<td>Company 4</td>
<td>316,065</td>
<td>37</td>
<td>37</td>
<td>0</td>
<td>100</td>
<td>0</td>
<td>21</td>
<td>192</td>
</tr>
<tr>
<td>Company 3</td>
<td>394,451</td>
<td>33</td>
<td>33</td>
<td>0</td>
<td>100</td>
<td>0</td>
<td>20</td>
<td>192</td>
</tr>
<tr>
<td>Company 5</td>
<td>396,757</td>
<td>19.8</td>
<td>19.8</td>
<td>0</td>
<td>100</td>
<td>N/A</td>
<td>24</td>
<td>384</td>
</tr>
</tbody>
</table>

Table 42 Optimal microgrid per company, Nadapal - Tier 2
5.4.3.2.2 Cost analysis

The optimization in HOMER Energy and economic analysis showed that Company 6 can build the microgrid that requires the lowest capital. What is important to mention here is that for larger system is plays a major role the developer of the microgrid project. More specifically, the total capital difference between company 6 which has the most cost effective system and company 5 which has the least cost effective system, there is a difference of $200,000 USD. As a result the feasibility and affordability of larger microgrids is highly depended on the project developer.

<table>
<thead>
<tr>
<th>Company</th>
<th>Total capital (USD)</th>
<th>Initial capital (USD)</th>
<th>Annual cost per household (USD)</th>
<th>PV (USD)</th>
<th>Wind (USD)</th>
<th>Batteries (USD)</th>
<th>Inverter (USD)</th>
<th>Charge Controllers</th>
</tr>
</thead>
<tbody>
<tr>
<td>Company 1</td>
<td>200,952</td>
<td>92,667</td>
<td>35.54</td>
<td>38,399</td>
<td>-</td>
<td>91,224</td>
<td>9,923</td>
<td>8,757</td>
</tr>
<tr>
<td>Company 6</td>
<td>261,163</td>
<td>113,736</td>
<td>46.18</td>
<td>46,761</td>
<td>-</td>
<td>128,832</td>
<td>10,563</td>
<td>8,288</td>
</tr>
<tr>
<td>Company 7</td>
<td>282,907</td>
<td>119,735</td>
<td>50.03</td>
<td>20,145</td>
<td>22,680</td>
<td>153,720</td>
<td>14,718</td>
<td>5,772</td>
</tr>
<tr>
<td>Company 2</td>
<td>288,175</td>
<td>144,217</td>
<td>50.96</td>
<td>70,035</td>
<td>-</td>
<td>114,540</td>
<td>21,498</td>
<td>9,324</td>
</tr>
<tr>
<td>Company 4</td>
<td>316,065</td>
<td>170,351</td>
<td>55.89</td>
<td>114,120</td>
<td>-</td>
<td>107,520</td>
<td>5,781</td>
<td>9,430</td>
</tr>
<tr>
<td>Company 3</td>
<td>394,451</td>
<td>177,768</td>
<td>69.75</td>
<td>90,123</td>
<td>-</td>
<td>186,840</td>
<td>11,698</td>
<td>8,487</td>
</tr>
<tr>
<td>Company 5</td>
<td>396,757</td>
<td>145,412</td>
<td>70.16</td>
<td>50,066</td>
<td>-</td>
<td>243,840</td>
<td>7,241</td>
<td>1,645</td>
</tr>
</tbody>
</table>

Table 43 Costs of microgrid per company, Nadapal - Tier 2

As in Tier 1, the price of battery bank and PV array is proportional while inverters and charge controllers have a very low impact in the total capital in comparison to the first two components.

![Company 1 cost of components](image_url)
5.4.3.3 Optimal microgrid characteristics

5.4.3.3.1 System layout

<table>
<thead>
<tr>
<th></th>
<th>Model</th>
<th>Number of parts</th>
</tr>
</thead>
<tbody>
<tr>
<td>PV panels</td>
<td>Canadian Solar 240 Watt</td>
<td>88</td>
</tr>
<tr>
<td>Inverter</td>
<td>VICTRON QUATTRO 10000</td>
<td>2</td>
</tr>
<tr>
<td>Charge controller</td>
<td>Outback FM 80 MPPT</td>
<td>9</td>
</tr>
<tr>
<td>Batteries</td>
<td>DEKA 8G4D gel</td>
<td>168</td>
</tr>
</tbody>
</table>

Table 44 Optimal microgrid system layout, Nadapal - Tier 2

5.4.3.3.2 Electricity

Company 6 has the affordable energy system. The microgrid would be based completely on solar energy as the solar irradiation of the region is high. In total, 9,674 kWh would be produced every year. Excess electricity is 7,925 kWh per year while there is minor capacity shortage and unmet electric demand which is neglectable; therefore the energy system would be very reliable and would function without any interruptions.

![Monthly Average Electric Production](image)

Figure 76 Monthly average electric production, Nadapal - Tier 2

<table>
<thead>
<tr>
<th></th>
<th>kWh/yr</th>
<th>%</th>
</tr>
</thead>
<tbody>
<tr>
<td>PV array</td>
<td>40,540</td>
<td>100</td>
</tr>
<tr>
<td>Excess electricity</td>
<td>7,925</td>
<td>19.5</td>
</tr>
<tr>
<td>Unmet electric load</td>
<td>16.8</td>
<td>0.1</td>
</tr>
<tr>
<td>Capacity shortage</td>
<td>21.8</td>
<td>0.1</td>
</tr>
</tbody>
</table>

Table 45 Electricity parameters, Nadapal - Tier 2

5.4.3.3.3 Power generation

In the energy system, 168 Canadian Solar panels of 240 Watts rated power and 24 V would be installed. More details on the power output by component can be seen in the following table:

<table>
<thead>
<tr>
<th></th>
<th>PV panels</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rated capacity</td>
<td>21.1 kW</td>
</tr>
<tr>
<td>Mean output</td>
<td>4.6 kW</td>
</tr>
<tr>
<td>Mean yearly output</td>
<td>111 kWh/d</td>
</tr>
<tr>
<td>Capacity factor</td>
<td>21.9 %</td>
</tr>
<tr>
<td>Total production</td>
<td>40,540 kWh/yr</td>
</tr>
</tbody>
</table>

Table 46 Power generation, Nadapal - Tier 2
5.4.3.3.1 PV panel
The PV panels have their maximum output during the solar noon. As it can be seen in the following diagram, the power generation starts around 6:00 o’clock in the morning and finishes around 18:00. This is explained by the fact that Nadapal is 3.04 degrees north of the equator; therefore the duration of the day is almost equal at 12 hours during the whole year. No shortage is noted in power generation while the hours of operation were 4,350 hr/yr and PV penetration is 223%.

![Figure 77 PV array output, Nadapal - Tier 2](image)

5.4.3.3.4 Battery bank
The model of battery that is used for energy storage is the Trojan T105. This battery has nominal voltage 6V, nominal capacity 225 Ah and lifetime throughput 884 kWh. More details on the battery bank can be found in the following table:

<table>
<thead>
<tr>
<th>String size</th>
<th>4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Strings in parallel</td>
<td>42</td>
</tr>
<tr>
<td>Batteries</td>
<td>168</td>
</tr>
<tr>
<td>Bus voltage</td>
<td>24 V</td>
</tr>
<tr>
<td>Nominal capacity</td>
<td>227 kWh</td>
</tr>
<tr>
<td>Usable nominal capacity</td>
<td>159 kWh</td>
</tr>
<tr>
<td>Autonomy</td>
<td>55.5 hr</td>
</tr>
<tr>
<td>Lifetime throughput</td>
<td>148,434 kWh</td>
</tr>
</tbody>
</table>

Table 47 Battery bank, Nadapal - Tier 2

5.5 Region 4 – Kasuku community
The Kasuku community is located in Nakuru County where capital is the Nakuru town. The county is in central Kenya. There are two reasons why the community was chosen. On the one hand there is high solar irradiation and very low wind speeds which, is a relatively common climate profile found in Kenya and on the other hand, the distribution of houses around the community center would show the impact of distribution losses.

5.5.1 Kasuku community and proposed electricity transmission line
Kasuku is located at 0°7’S, 36°22’E. In addition there are 457 houses included in the analysis; therefore it is a middle sized community. The proposed transmission line for electricity is set to cross...
the community and pass by the edge of its center as the houses are built south of the road. The reason for designing through this way the line is that it was found to be the shortest way in order to provide on the one hand access to electricity as much as many houses in the settlement and on the other hand to decrease the transmission losses. The total length of the line is 2.15 km.

5.5.2 Tier 1 – Kasuku community

5.5.2.1 Ideal load, power losses and real load

There are 457 houses in the community. Therefore, the optimal load for Tier 1 in Kasuku community is calculated by equation 1 as:

$$P_{\text{ideal}} = 4341.5 \text{ W}$$

The power losses caused by the electric resistance of the electricity transmission cable are calculated by equation 2, equation 3 and equation 4 as:

$$P_{\text{losses}} = 612.13 \text{ W}$$

Finally, the real total electricity load that would have the Kasuku community for Tier 1 energy access after considering the power losses is calculated by equation 5 as:

$$P_{\text{real}} = P_{\text{ideal}} + P_{\text{losses}} =>$$

$$P_{\text{real}} = 4953.63 \text{ W}$$
5.5.2.2 Optimization results

5.5.2.2.1 General results

As Kasuku is characterized by high solar irradiation, all the proposed microgrids by each company are totally based on solar energy. In addition, the big size of the system and the need of high storage capacity and large inverters is the outcome that the microgrid serves 457 households.

<table>
<thead>
<tr>
<th>Company</th>
<th>Total capital (USD)</th>
<th>Total (kWatt)</th>
<th>Solar (kWatt)</th>
<th>Wind (kWatt)</th>
<th>Solar output fraction (%)</th>
<th>Wind output fraction (%)</th>
<th>Inverter (kWatt)</th>
<th>Batteries (kWh)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Company 1</td>
<td>74,868</td>
<td>8.64</td>
<td>8.64</td>
<td>0</td>
<td>100</td>
<td>N/A</td>
<td>8</td>
<td>80.6</td>
</tr>
<tr>
<td>Company 6</td>
<td>78,138</td>
<td>6.48</td>
<td>6.48</td>
<td>0</td>
<td>100</td>
<td>0</td>
<td>8</td>
<td>70.2</td>
</tr>
<tr>
<td>Company 7</td>
<td>100,576</td>
<td>7.56</td>
<td>7.56</td>
<td>0</td>
<td>100</td>
<td>0</td>
<td>6</td>
<td>79.2</td>
</tr>
<tr>
<td>Company 2</td>
<td>103,692</td>
<td>8.225</td>
<td>8.225</td>
<td>0</td>
<td>100</td>
<td>0</td>
<td>6</td>
<td>75.6</td>
</tr>
<tr>
<td>Company 4</td>
<td>109,842</td>
<td>5.55</td>
<td>5.55</td>
<td>0</td>
<td>100</td>
<td>0</td>
<td>7</td>
<td>91.2</td>
</tr>
<tr>
<td>Company 3</td>
<td>120,846</td>
<td>9.3</td>
<td>9.3</td>
<td>0</td>
<td>100</td>
<td>0</td>
<td>6</td>
<td>57.6</td>
</tr>
<tr>
<td>Company 5</td>
<td>137,711</td>
<td>5.88</td>
<td>5.88</td>
<td>0</td>
<td>100</td>
<td>N/A</td>
<td>6</td>
<td>120</td>
</tr>
</tbody>
</table>

Table 48 Optimal microgrid per company, Kasuku - Tier 1

5.5.2.2.2 Cost analysis

The optimization in HOMER Energy and economic analysis showed that company 1 can develop the most affordable solar microgrid. Each household would have to pay each year $13.24 USD which is a relatively small amount in comparison to the mean annual household budget. In addition, all the companies could develop a microgrid that would provide energy access of Tier 1 and would cost less per household than the average annual expenditures on kerosene which are measured at $126 USD.

<table>
<thead>
<tr>
<th>Company</th>
<th>Total capital (USD)</th>
<th>Initial capital (USD)</th>
<th>Annual cost per household (USD)</th>
<th>PV (USD)</th>
<th>Batteries (USD)</th>
<th>Inverter (USD)</th>
<th>Charge Controllers</th>
</tr>
</thead>
<tbody>
<tr>
<td>Company 1</td>
<td>74,868</td>
<td>41,327</td>
<td>10.92</td>
<td>13,909</td>
<td>22,752</td>
<td>6,279</td>
<td>2,418</td>
</tr>
<tr>
<td>Company 6</td>
<td>78,138</td>
<td>40,186</td>
<td>11.40</td>
<td>11,794</td>
<td>28,236</td>
<td>5,897</td>
<td>1,946</td>
</tr>
<tr>
<td>Company 7</td>
<td>100,576</td>
<td>44,062</td>
<td>14.67</td>
<td>11,578</td>
<td>34,860</td>
<td>5,727</td>
<td>2,886</td>
</tr>
<tr>
<td>Company 2</td>
<td>103,692</td>
<td>55,427</td>
<td>15.13</td>
<td>24,525</td>
<td>48,312</td>
<td>2,357</td>
<td>2,418</td>
</tr>
<tr>
<td>Company 4</td>
<td>109,842</td>
<td>49,368</td>
<td>16.02</td>
<td>17,118</td>
<td>51,072</td>
<td>2,477</td>
<td>1,612</td>
</tr>
<tr>
<td>Company 3</td>
<td>120,846</td>
<td>60,183</td>
<td>17.63</td>
<td>26,679</td>
<td>47,520</td>
<td>4,835</td>
<td>1,692</td>
</tr>
<tr>
<td>Company 5</td>
<td>137,711</td>
<td>54,031</td>
<td>20.09</td>
<td>14,877</td>
<td>76,200</td>
<td>2,147</td>
<td>470</td>
</tr>
</tbody>
</table>

Table 49 Costs of microgrid per company, Kasuku - Tier 1

As before, the battery bank and PV array are responsible for the biggest part of the total cost. Batteries have to change every five years while PV panels have a lifetime of 25 years and they would not need replacement, which explains the high cost of energy storage.
5.5.2.3  Optimal microgrid characteristics

5.5.2.3.1  System layout

<table>
<thead>
<tr>
<th>Model</th>
<th>Number of parts</th>
</tr>
</thead>
<tbody>
<tr>
<td>PV panels</td>
<td>Canadian Solar 240 Watt</td>
</tr>
<tr>
<td>Inverter</td>
<td>Quattro 8000</td>
</tr>
<tr>
<td>Charge controller</td>
<td>Morning Star TS-MPPT-60</td>
</tr>
<tr>
<td>Batteries</td>
<td>DEKA 8G4D gel</td>
</tr>
</tbody>
</table>

5.5.2.3.2  Electricity

The microgrid would be based completely on solar energy as the solar irradiation of the region is high. In total, 16,241 kWh would be produced every year. Excess electricity is 6,238 kWh per year which means it can be used for other appliances such as irrigation, while there is neglectable capacity shortage and unmet electric demand; therefore the energy system would be very reliable and would function without any interruptions.
### Table 50 Electricity parameters, Kasuku - Tier 1

<table>
<thead>
<tr>
<th></th>
<th>kWh/yr</th>
<th>%</th>
</tr>
</thead>
<tbody>
<tr>
<td>PV array</td>
<td>16,241</td>
<td>100</td>
</tr>
<tr>
<td>Excess electricity</td>
<td>6,238</td>
<td>38.4</td>
</tr>
<tr>
<td>Unmet electric load</td>
<td>4.27</td>
<td>0.1</td>
</tr>
<tr>
<td>Capacity shortage</td>
<td>5.26</td>
<td>0.1</td>
</tr>
</tbody>
</table>

5.5.2.3.3 Power generation

In the energy system, 36 Canadian Solar panels of 240 Watts rated power and 24 V would be installed in order to provide charging to the batteries during wind shortages. More details on the power output by component can be seen in the following table:

<table>
<thead>
<tr>
<th>PV panels</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Rated capacity</td>
<td>8.64 kW</td>
</tr>
<tr>
<td>Mean output</td>
<td>1.85 kW</td>
</tr>
<tr>
<td>Mean yearly output</td>
<td>44.5 kWh/d</td>
</tr>
<tr>
<td>Capacity factor</td>
<td>21.5 %</td>
</tr>
<tr>
<td>Total production</td>
<td>16,421 kWh/yr</td>
</tr>
</tbody>
</table>

Table 51 Power generation, Kasuku - Tier 1

5.5.2.3.3.1 PV panel

The PV panels have their maximum output during the solar noon. As it can be seen in the following diagram, the power generation starts around 6:00 o’clock in the morning and finishes around 18:00. This is explained by the fact that Nadapal is 3.04 degrees north of the equator; therefore the duration of the day is almost equal at 12 hours during the whole year. PV penetration was 225% and the hours of operation 4,381 hr/yr.

![PV array output, Kasuku - Tier 1](image)

5.5.2.3.4 Battery bank

The model of battery that is used for energy storage is the DEKA 8G4D gel. This battery has nominal voltage 12V, nominal capacity 210 Ah and lifetime throughput 1,426 kWh. More details on the battery bank can be found in the following table:
| String size | 2 |
| Strings in parallel | 16 |
| Batteries | 32 |
| Bus voltage | 24 V |
| Nominal capacity | 80.6 kWh |
| Usable nominal capacity | 40.3 kWh |
| Autonomy | 48.9 hr |
| Lifetime throughput | 45,628 kWh |

Table 52 Battery bank, Kasuku - Tier 1

5.5.3 Tier 2 – Kasuku community

5.5.3.1 Ideal load, power losses and real load

There are 457 houses in the community. Therefore, the optimal load for Tier 2 in Kasuku community is calculated by equation 1 as:

$$P_{\text{ideal}} = 17137.5 \text{ W}$$

The power losses caused by the electric resistance of the electricity transmission cable are calculated by equation 2, equation 3 and equation 4 as:

$$P_{\text{losses}} = 9538.02 \text{ W}$$

Finally, the real total electricity load that would have the Kasuku community for Tier 2 energy access after considering the power losses is calculated by equation 5 as:

$$P_{\text{real}} = P_{\text{ideal}} + P_{\text{losses}} \Rightarrow$$

$$P_{\text{real}} = 26675.52 \text{ W}$$

![Figure 84 Power load, Kasuku - Tier 2](image)

5.5.3.2 Optimization results

5.5.3.2.1 General results

The needed microgrid for Tier 2 energy access to Kasuku community is significantly larger than any other community. This is the outcome for the need to satisfy a relatively large community of 457 households while also to transmit electricity in the distant ones which results to high power losses as the voltage used is 230 V. The next table presents analytical the optimal microgrid of each company:
5.5.3.2.2 Cost analysis

In the comparison of the most cost effective microgrid, company 1 is the one that can develop the most affordable for families in Kasuku. The critical point of this cost analysis is that such a large system requires a high initial and total capital. More specifically, company 1 and company 6 could develop the microgrid with $150,000 USD initially. On the other hand, the initial capital can reach up to $343,000 USD.

This means, microgrid developers require having the financial capacity to implement such a project while this can be solved by private or public funding for rural electrification. Also, it is essential to note that for larger projects the initial and total capital has great difference between the companies, while this is trend is not so effective to smaller microgrids.

As before, batteries have the largest cost as on the one hand they are expensive and on the other hand they need replacement every five years. In fact, it is clear here that in microgrids, the battery bank is the weakest point in terms of economics as they soar the total required capital for the development of a project.
5.5.3.3 Optimal microgrid characteristics

5.5.3.3.1 System layout

<table>
<thead>
<tr>
<th>Model</th>
<th>Number of parts</th>
</tr>
</thead>
<tbody>
<tr>
<td>PV panels</td>
<td>185</td>
</tr>
<tr>
<td>Inverter</td>
<td>3</td>
</tr>
<tr>
<td>Charge controller</td>
<td>12</td>
</tr>
<tr>
<td>Batteries</td>
<td>176</td>
</tr>
</tbody>
</table>

Table 55 Optimal microgrid system layout, Kasuku - Tier 2

5.5.3.3.2 Electricity

The microgrid would be based completely on solar. During December and January the system generates the highest amount of electricity while between April and July there is the lowest production, as during these months it is the rainy season in Kenya, which means increased cloudiness. In total, 83,461 kWh would be produced every year. Excess electricity is 29,417 kWh per year while there is capacity shortage and unmet electric demand count for 0.1% of the total electric load; therefore the energy system would be very reliable and would function without any interruptions.
### 5.5.3.3.3  Power generation

In the energy system, 185 Canadian Solar panels of 240 Watts rated power and 24 V would be installed. More details on the power output by component can be seen in the following table:

<table>
<thead>
<tr>
<th></th>
<th>kWh/yr</th>
<th>%</th>
</tr>
</thead>
<tbody>
<tr>
<td>PV array</td>
<td>83,461</td>
<td>100</td>
</tr>
<tr>
<td>Excess electricity</td>
<td>29,417</td>
<td>35.2</td>
</tr>
<tr>
<td>Unmet electric load</td>
<td>32.6</td>
<td>0.1</td>
</tr>
<tr>
<td>Capacity shortage</td>
<td>38.0</td>
<td>0.1</td>
</tr>
</tbody>
</table>

Table 56 Electricity parameters, Kasuku - Tier 2

#### 5.5.3.3.3.1 PV panel

The following graph confirms that during the rainy season there is the lowest electricity generation by the PV array while between January to March and September to December, the system reaches its rated power. Also, Kasuku is on the equator which means that electricity generation from PV panels last for 12 hours per day during the whole year. PV penetration is 214 % and total hours of operation 4,381 hr/yr.

#### 5.5.3.3.4 Battery bank

The model of battery that is used for energy storage is the DEKA 8G4D gel. This battery has nominal voltage 12V, nominal capacity 210 Ah and lifetime throughput 1,426 kWh. More details on the battery bank can be found in the following table:
<table>
<thead>
<tr>
<th>String size</th>
<th>2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Strings in parallel</td>
<td>88</td>
</tr>
<tr>
<td>Batteries</td>
<td>176</td>
</tr>
<tr>
<td>Bus voltage</td>
<td>24  V</td>
</tr>
<tr>
<td>Nominal capacity</td>
<td>444 kWh</td>
</tr>
<tr>
<td>Usable nominal capacity</td>
<td>444 kWh</td>
</tr>
<tr>
<td>Autonomy</td>
<td>49.7 hr</td>
</tr>
<tr>
<td>Lifetime throughput</td>
<td>250, 952 kWh</td>
</tr>
</tbody>
</table>

Table S8 Battery bank, Kasuku - Tier 2

### 5.6 Region 5 - Mbodoni community

Mbodoni community is located in Kitui County. Capital of the county is Kitui county while the climate data where received from the closest weather station in Mwingi which is 7.78 km far from Mbodoni. The community was chosen as its climate data can represent the biggest part of Kenya. More specifically, solar irradiation and wind speeds in Mwingi and Mbodoni are close to the average values found among the whole country. Solar irradiation has a mean value of 5.69 kWh/m²/d while wind speed has a mean value of 3.5 m/s.

#### 5.6.1 The community and proposed electricity transmission line

Mbodoni is located at central Kenya with coordinates 0°58'S, 37°59'E which means it almost lays on the equator. In the community, 69 households were measured which makes Mbodnoni a small one. However, it has the typical size of unelectrified communities that can be found among Kenya.

The electricity transmission line is set to pass by the main road in order to connect to the microgrid the houses among it. In addition, a shorter line that is connected as a junction to the northern part of the main line serves the houses that are built on the east of the main road. The total length of the line is 260 m. It can be seen as a yellow red line in the next picture:
5.6.1.1 Ideal load, power losses and real load

There are 69 houses in the community. Therefore, the optimal load for Tier 1 in Mbodoni community is calculated by equation 1 as:

\[ P_{\text{ideal}} = 655.5 \, W \]

The power losses caused by the electric resistance of the electricity transmission cable are calculated by equation 2, equation 3 and equation 4 as:

\[ P_{\text{losses}} = 1.69 \, W \]

Finally, the real total electricity load that would have the Mbodoni community for Tier 1 energy access after considering the power losses is calculated by equation 5 as:

\[ P_{\text{real}} = P_{\text{ideal}} + P_{\text{losses}} \Rightarrow \\
\[ P_{\text{real}} = 657.19 \, W \]
5.6.1.2 Optimization results

5.6.1.2.1 General results
Except company 2, solar energy is dominant in the optimal microgrid proposed by each developer according to the HOMER Energy optimization results. In addition, a very small system is the most cost effective and is proposed by company 1. Therefore, it can be extracted the results that most of the communities in Kenya that have climate profile similar to the average values of Mbodoni would require a microgrid based on solar energy.

<table>
<thead>
<tr>
<th>Company</th>
<th>Total capital (USD)</th>
<th>Total (kWatt)</th>
<th>Solar (kWatt)</th>
<th>Wind (kWatt)</th>
<th>Solar output fraction (%)</th>
<th>Wind output fraction (%)</th>
<th>Inverter (kWatt)</th>
<th>Batteries (kWh)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Company 1</td>
<td>13,051</td>
<td>1.44</td>
<td>1.44</td>
<td>0</td>
<td>100</td>
<td>N/A</td>
<td>0.75</td>
<td>80.6</td>
</tr>
<tr>
<td>Company 6</td>
<td>13,621</td>
<td>1.44</td>
<td>1.44</td>
<td>0</td>
<td>100</td>
<td>0</td>
<td>0.8</td>
<td>10.8</td>
</tr>
<tr>
<td>Company 2</td>
<td>14,754</td>
<td>1</td>
<td>0</td>
<td>1</td>
<td>0</td>
<td>100</td>
<td>1</td>
<td>7.2</td>
</tr>
<tr>
<td>Company 4</td>
<td>18,046</td>
<td>1.295</td>
<td>1.295</td>
<td>0</td>
<td>100</td>
<td>0</td>
<td>1.4</td>
<td>12.4</td>
</tr>
<tr>
<td>Company 7</td>
<td>18,892</td>
<td>2.88</td>
<td>1.88</td>
<td>1</td>
<td>100</td>
<td>0</td>
<td>0.8</td>
<td>10.8</td>
</tr>
<tr>
<td>Company 5</td>
<td>20,767</td>
<td>1.56</td>
<td>1.56</td>
<td>0</td>
<td>100</td>
<td>N/A</td>
<td>6</td>
<td>14.4</td>
</tr>
<tr>
<td>Company 3</td>
<td>23,992</td>
<td>1.05</td>
<td>1.05</td>
<td>0</td>
<td>100</td>
<td>0</td>
<td>0.8</td>
<td>14.4</td>
</tr>
</tbody>
</table>

Table 59 Optimal microgrid per company, Mbodoni - Tier 1

5.6.1.2.2 Cost analysis
Small communities like Mbodoni would require microgrids with very low initial capital. More specifically, both the initial and total required capital correspond to the financial capacity of energy companies in Kenya, therefore no external funding would be needed. Moreover, the microgrid with the lowest cost would be developed by company 1. The next table analysis the key financial parameters of each microgrid.

<table>
<thead>
<tr>
<th>Company</th>
<th>Total capital (USD)</th>
<th>Initial capital (USD)</th>
<th>Annual cost per household (USD)</th>
<th>PV (USD)</th>
<th>Wind</th>
<th>Batteries (USD)</th>
<th>Inverter (USD)</th>
<th>Charge Controllers</th>
</tr>
</thead>
<tbody>
<tr>
<td>Company 1</td>
<td>13,051</td>
<td>6,099</td>
<td>12.61</td>
<td>2,317</td>
<td>-</td>
<td>4,266</td>
<td>371</td>
<td>643</td>
</tr>
<tr>
<td>Company 6</td>
<td>13,621</td>
<td>6,485</td>
<td>13.16</td>
<td>2,618</td>
<td>-</td>
<td>4,344</td>
<td>470</td>
<td>643</td>
</tr>
<tr>
<td>Company 7</td>
<td>14,754</td>
<td>7,323</td>
<td>14.26</td>
<td>3,780</td>
<td>-</td>
<td>4,392</td>
<td>191</td>
<td>643</td>
</tr>
<tr>
<td>Company 2</td>
<td>18,046</td>
<td>8,545</td>
<td>17.44</td>
<td>4,004</td>
<td>-</td>
<td>6,360</td>
<td>472</td>
<td>643</td>
</tr>
<tr>
<td>Company 4</td>
<td>18,892</td>
<td>10,116</td>
<td>18.25</td>
<td>5,603</td>
<td>-</td>
<td>4,980</td>
<td>578</td>
<td>643</td>
</tr>
<tr>
<td>Company 3</td>
<td>20,767</td>
<td>8,752</td>
<td>20.07</td>
<td>3,954</td>
<td>-</td>
<td>9,144</td>
<td>169</td>
<td>643</td>
</tr>
<tr>
<td>Company 5</td>
<td>23,992</td>
<td>9,439</td>
<td>23.18</td>
<td>3,018</td>
<td>-</td>
<td>11,880</td>
<td>472</td>
<td>643</td>
</tr>
</tbody>
</table>

Table 60 Costs of microgrid per company, Mbodoni - Tier 1

Proportionally, the battery bank is responsible for the largest part of the capital, while the PV array would cost almost half the value of the batteries. As before, the inverter and charge controller play a very small role in the total capital.
5.6.1.3 Optimal microgrid characteristics

5.6.1.3.1 System layout

<table>
<thead>
<tr>
<th></th>
<th>Model</th>
<th>Number of parts</th>
</tr>
</thead>
<tbody>
<tr>
<td>PV panels</td>
<td>Canadian Solar 240 Watt</td>
<td>6</td>
</tr>
<tr>
<td>Inverter</td>
<td>APSX 750F</td>
<td>1</td>
</tr>
<tr>
<td>Charge controller</td>
<td>Morning Star TS-MPPT-45</td>
<td>1</td>
</tr>
<tr>
<td>Batteries</td>
<td>DEKA 8G4D gel</td>
<td>6</td>
</tr>
</tbody>
</table>

Table 61 Optimal microgrid system layout, Mbodoni - Tier 1

5.6.1.3.2 Electricity

The microgrid would be based completely on solar energy as the solar irradiation of the region is high. In total, 2,388 kWh would be produced every year. During February it is noted the highest electricity production while the lowest is in June and July. Excess electricity is 1,054 kWh per year. This amount of energy is highly exploitable and could be used either for irrigation or for other important energy services or appliances. There is neglectable capacity shortage and unmet electric demand; therefore the energy system would be very reliable and would function without any interruptions.
### Power generation

In the energy system, 8 Canadian Solar panels of 240 Watts rated power and 24 V would be installed in order to provide charging to the batteries during wind shortages. More details on the power output by component can be seen in the following table:

<table>
<thead>
<tr>
<th></th>
<th>kWh/yr</th>
<th>%</th>
</tr>
</thead>
<tbody>
<tr>
<td>PV array</td>
<td>2,388</td>
<td>100</td>
</tr>
<tr>
<td>Excess electricity</td>
<td>1,054</td>
<td>44.1</td>
</tr>
<tr>
<td>Unmet electric load</td>
<td>0.541</td>
<td>0.1</td>
</tr>
<tr>
<td>Capacity shortage</td>
<td>0.607</td>
<td>0.1</td>
</tr>
</tbody>
</table>

Table 62 Electricity parameters, Mbodoni - Tier 1

#### 5.6.1.3.3 PV panel

The PV panels have their maximum output during the solar noon and it is measured at 1.39 kW. As it can be seen in the following diagram, the power generation starts around 6:00 o’clock in the morning and finishes around 18:00. This is explained by the fact that Mbodoni is 0.38 degrees north of the equator; therefore the duration of the day is almost equal at 12 hours during the whole year. PV penetration is 248 % and total hours of operation are 4,369 hr/yr.

![Figure 92 PV array output, Mbodoni - Tier 1](image)

#### 5.6.1.3.4 Battery bank

The model of battery that is used for energy storage is the DEKA 8G4D gel. This battery has nominal voltage 12V, nominal capacity 210 Ah and lifetime throughput 1,426 kWh. More details on the battery bank can be found in the following table:
### 5.6.2 Tier 2 – Mbodoni community

#### 5.6.2.1 Ideal load, power losses and real load

There are 69 houses in the community. Therefore, the optimal load for Tier 2 in Mbodoni community is calculated by equation 1 as:

\[ P_{\text{ideal}} = 2587.5 \text{ W} \]

The power losses caused by the electric resistance of the electricity transmission cable are calculated by equation 2, equation 3 and equation 4 as:

\[ P_{\text{losses}} = 26.29 \text{ W} \]

Finally, the real total electricity load that would have the Mbodoni community for Tier 2 energy access after considering the power losses is calculated by equation 5 as:

\[ P_{\text{real}} = P_{\text{ideal}} + P_{\text{losses}} \Rightarrow \]

\[ P_{\text{real}} = 2613.79 \text{ W} \]

#### 5.6.2.2 Optimization results

##### 5.6.2.2.1 General results

As in Tier 1 analysis for Mbodoni, in Tier 2 the majority of microgrids are based on solar irradiation. However, here it can be seen that wind power is used in most of the companies as a supplementary source in order to harvest the potential of medium wind speeds. As 3.5 m/s is considered to be
relatively low for integrated energy systems, it is proved that in microgrids of 4 to 10 kWatt, wind turbines are more feasible to be used in comparison to solar-only systems.

<table>
<thead>
<tr>
<th>Company</th>
<th>Total capital (USD)</th>
<th>Total (kWatt)</th>
<th>Solar (kWatt)</th>
<th>Wind (kWatt)</th>
<th>Solar output fraction (%)</th>
<th>Wind output fraction (%)</th>
<th>Inverter (kWatt)</th>
<th>Batteries (kWh)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Company 6</td>
<td>43,093</td>
<td>5.6</td>
<td>4.8</td>
<td>0.8</td>
<td>93</td>
<td>7</td>
<td>3</td>
<td>37.8</td>
</tr>
<tr>
<td>Company 1</td>
<td>44,294</td>
<td>4.32</td>
<td>4.32</td>
<td>0</td>
<td>100</td>
<td>N/A</td>
<td>3</td>
<td>70.6</td>
</tr>
<tr>
<td>Company 2</td>
<td>46,931</td>
<td>3.68</td>
<td>1.68</td>
<td>2</td>
<td>42</td>
<td>58</td>
<td>3</td>
<td>36</td>
</tr>
<tr>
<td>Company 3</td>
<td>57,145</td>
<td>9.7</td>
<td>9.3</td>
<td>0.4</td>
<td>99</td>
<td>1</td>
<td>3</td>
<td>28.8</td>
</tr>
<tr>
<td>Company 7</td>
<td>60,171</td>
<td>5.65</td>
<td>4.65</td>
<td>1</td>
<td>92</td>
<td>8</td>
<td>3</td>
<td>48.6</td>
</tr>
<tr>
<td>Company 4</td>
<td>61,805</td>
<td>5.55</td>
<td>5.55</td>
<td>0</td>
<td>100</td>
<td>0</td>
<td>3.5</td>
<td>44.5</td>
</tr>
<tr>
<td>Company 5</td>
<td>79,848</td>
<td>5.4</td>
<td>5.4</td>
<td>0</td>
<td>100</td>
<td>N/A</td>
<td>4</td>
<td>62.4</td>
</tr>
</tbody>
</table>

Table 65 Optimal microgrid per company, Mbodoni - Tier 2

5.6.2.2 Cost analysis

In the comparison of the most cost effective microgrid, company 1 is the one that can develop the most affordable for families in Kasuku. The critical point of this cost analysis is that such a large system requires a high initial and total capital. More specifically, company 1 and company 6 could develop the microgrid with $150,000 USD initially. On the other hand, the initial capital can reach up to $343,000 USD. This means, microgrid developers require having the financial capacity to implement such a project while this can be solved by private or public funding for rural electrification. Also, it is essential to note that for larger projects the initial and total capital has great difference between the companies, while this trend is not so effective to smaller microgrids.

<table>
<thead>
<tr>
<th>Company</th>
<th>Total capital (USD)</th>
<th>Initial capital (USD)</th>
<th>Annual cost per household (USD)</th>
<th>PV (USD)</th>
<th>Wind (USD)</th>
<th>Batteries (USD)</th>
<th>Inverter (USD)</th>
<th>Charge Controllers</th>
</tr>
</thead>
<tbody>
<tr>
<td>Company 6</td>
<td>43,093</td>
<td>21,898</td>
<td>41.64</td>
<td>8,727</td>
<td>2,123</td>
<td>15,204</td>
<td>2,080</td>
<td>2,572</td>
</tr>
<tr>
<td>Company 1</td>
<td>44,294</td>
<td>19,704</td>
<td>42.80</td>
<td>6,936</td>
<td>-</td>
<td>19,908</td>
<td>2,214</td>
<td>2,572</td>
</tr>
<tr>
<td>Company 2</td>
<td>46,931</td>
<td>20,364</td>
<td>45.34</td>
<td>2,570</td>
<td>7,561</td>
<td>21,960</td>
<td>924</td>
<td>643</td>
</tr>
<tr>
<td>Company 3</td>
<td>57,145</td>
<td>27,021</td>
<td>55.21</td>
<td>2,585</td>
<td>1,886</td>
<td>23,760</td>
<td>2,996</td>
<td>10,288</td>
</tr>
<tr>
<td>Company 7</td>
<td>60,171</td>
<td>30,249</td>
<td>58.14</td>
<td>13,571</td>
<td>2,943</td>
<td>22,410</td>
<td>2,347</td>
<td>2,572</td>
</tr>
<tr>
<td>Company 4</td>
<td>61,805</td>
<td>30,319</td>
<td>59.72</td>
<td>17,118</td>
<td>-</td>
<td>22,896</td>
<td>1,651</td>
<td>2,572</td>
</tr>
<tr>
<td>Company 5</td>
<td>79,848</td>
<td>32,514</td>
<td>77.15</td>
<td>13,619</td>
<td>-</td>
<td>39,624</td>
<td>1,769</td>
<td>2,572</td>
</tr>
</tbody>
</table>

Table 66 Costs of microgrid per company, Mbodoni - Tier 2

Again, battery bank has proportionally the highest cost. In addition, the energy system is mainly based on solar energy, therefore, the PV array costs more than the wind turbine. Finally, the inverter and charge controller do not have comparatively a high cost.
5.6.2.3 Optimal microgrid characteristics

5.6.2.3.1 System layout

<table>
<thead>
<tr>
<th>Model</th>
<th>Number of parts</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wind turbine</td>
<td>Hugh Piggott model</td>
</tr>
<tr>
<td>PV panels</td>
<td>Canadian Solar 240 Watt</td>
</tr>
<tr>
<td>Inverter</td>
<td>Quattro 10000</td>
</tr>
<tr>
<td>Charge controller</td>
<td>Morning Star TS-MPPT-60</td>
</tr>
<tr>
<td>Batteries</td>
<td>Trojan T-105</td>
</tr>
</tbody>
</table>

Table 67 Optimal microgrid system layout, Mbodoni - Tier 2

5.6.2.3.2 Electricity

Solar energy produces 93% of the electricity in total while wind turbines produce the remaining 7%. Excess electricity is 3,618 kWh per year while there is capacity shortage and unmet electric demand count for 0.1% of the total electric load; therefore the energy system would be very reliable and would function without any interruptions.
## 5.6.2.3.3 Power Generation

In the energy system, 185 Canadian Solar panels of 240 Watts rated power and 24 V would be installed. More details on the power output by component can be seen in the following table:

<table>
<thead>
<tr>
<th>Component</th>
<th>kWh/yr</th>
<th>%</th>
</tr>
</thead>
<tbody>
<tr>
<td>PV array</td>
<td>7,959</td>
<td>93</td>
</tr>
<tr>
<td>Wind turbine</td>
<td>588</td>
<td>7</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td>8,547</td>
<td>100</td>
</tr>
<tr>
<td>Excess electricity</td>
<td>3,618</td>
<td>42.3</td>
</tr>
<tr>
<td>Unmet electric load</td>
<td>2.57</td>
<td>0.1</td>
</tr>
<tr>
<td>Capacity shortage</td>
<td>3.11</td>
<td>0.1</td>
</tr>
</tbody>
</table>

Table 68: Electricity parameters, Mbodoni - Tier 2

<table>
<thead>
<tr>
<th>Component</th>
<th>Wind turbines</th>
<th>PV panels</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rated capacity</td>
<td>0.800 kW</td>
<td>4.80 kW</td>
</tr>
<tr>
<td>Mean output</td>
<td>0.07 kW</td>
<td>0.91 kW</td>
</tr>
<tr>
<td>Mean yearly output</td>
<td>n/a</td>
<td>21.8 kWh/d</td>
</tr>
<tr>
<td>Capacity factor</td>
<td>8.39 %</td>
<td>18.9 %</td>
</tr>
<tr>
<td><strong>Total production</strong></td>
<td>588 kWh/yr</td>
<td>7,959 kWh/yr</td>
</tr>
</tbody>
</table>

Table 69: Power generation, Mbodoni - Tier 2

### 5.6.2.3.3.1 Wind turbine

The proposed wind turbine of the microgrid is a Hugh Piggott model of 800 Watt rated power. In the following graph it is projected the power generation during the whole year. As it can be observed the medium wind speed are not sufficient to make the turbine work close or half the rated power. Thus it is explained why it has a supplementary and not a major role in the electricity production. Wind penetration was 15.5% and total hours of operation of the turbine were 4,875 hr/yr.

![Wind turbine output](Figure 96 Wind turbine output, Mbodoni - Tier 2)

### 5.6.2.3.3.2 PV panel

The power generation part will have 20 PV Canadian Solar 240 panels. During the noun the panels generate electricity at rated mode, while during the rainy season between April and July there is a lower production as there is increased cloudiness. PV penetration was 210% and total hours of operation of the array were 4,364 hr/yr.
5.6.2.3.4 Energy Storage

The model of battery that is used for energy storage is the Trojan T-105. This battery has nominal voltage 6V, nominal capacity 225 Ah and lifetime throughput 884 kWh. More details on the battery bank can be found in the following table:

| String size | 4 |
| Strings in parallel | 7 |
| Batteries | 28 |
| Bus voltage | 24 V |
| Nominal capacity | 37.8 kWh |
| Usable nominal capacity | 26.5 kWh |
| Autonomy | 61.1 hr |
| Lifetime throughput | 24,739 kWh |

Table 70 Battery bank, Mbodoni - Tier 2

5.7 Comparative analysis of energy systems

5.7.1 Tier 1 energy access

<table>
<thead>
<tr>
<th>Energy system</th>
<th>Distributor</th>
<th>Annual cost per household (USD)</th>
<th>5 year cost per household (USD)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sun king Mobile</td>
<td>Solar Aid/Sunny Money</td>
<td>5.78</td>
<td>28.9</td>
</tr>
<tr>
<td>d.light S300</td>
<td>Solar Aid/Sunny Money</td>
<td>7.08</td>
<td>35.39</td>
</tr>
<tr>
<td>Sun king Pro 2</td>
<td>Solar Aid/Sunny Money</td>
<td>8.49</td>
<td>42.46</td>
</tr>
<tr>
<td>Microgrid - Nadapal</td>
<td>Company 1</td>
<td>8.75</td>
<td>43.75</td>
</tr>
<tr>
<td>Microgrid - Kasuku</td>
<td>Company 1</td>
<td>10.92</td>
<td>54.61</td>
</tr>
<tr>
<td>Microgrid - Marsabit</td>
<td>Company 6</td>
<td>11.76</td>
<td>58.8</td>
</tr>
<tr>
<td>Microgrid - Malindi</td>
<td>Company 6</td>
<td>12.43</td>
<td>62.13</td>
</tr>
<tr>
<td>Microgrid - Mbodoni</td>
<td>Company 1</td>
<td>12.61</td>
<td>63.05</td>
</tr>
<tr>
<td>BB7</td>
<td>Abundant Power Solutions</td>
<td>28.31</td>
<td>141.54</td>
</tr>
<tr>
<td>M-KOPA Solar</td>
<td>M-KOPA</td>
<td>51.9</td>
<td>259.49</td>
</tr>
<tr>
<td>Kerosene</td>
<td>-</td>
<td>126</td>
<td>630</td>
</tr>
</tbody>
</table>

Figure 97 PV array output, Mbodoni - Tier 2
Solar Aid energy systems are the most affordable among the compared ones; however the microgrids are almost identically the same in terms of cost accessibility. Moreover, BB7 is more expensive both by microgrids and solar lanterns, however this can be explained by the fact that it can supply some other small appliances like an extra lamp. M-KOPA, is the most expensive among the renewable energy systems, but it has higher number of appliances like two more lamps and a radio.

As it can be seen in the upper table, kerosene expenditures are significantly higher than any other energy system. As a result, in terms of economic accessibility, it is implementable and directly achievable to eliminate energy poverty and succeed energy access of Tier 1 level for rural families. Those households can save between $74 USD to $120 USD by turning to modern energy systems and services like solar lanterns and microgrids while this spare capital can be used for the improvement of education, health and productive activities like farming. In addition to that, it is proved that the achievement of Tier 1 can happen only based on the economic strength and income of rural families without the need of external support.

### 5.7.2 Tier 2 energy access

<table>
<thead>
<tr>
<th>Energy system</th>
<th>Distributor</th>
<th>Annual cost per household (USD)</th>
<th>5 year cost per household (USD)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Barefoot 600</td>
<td>Solar Aid/Sunny Money</td>
<td>28.31</td>
<td>141.54</td>
</tr>
<tr>
<td>Microgrid Marsabit</td>
<td>Company 6</td>
<td>30.95</td>
<td>154.73</td>
</tr>
<tr>
<td>Microgrid Nadapal</td>
<td>Company 6</td>
<td>35.54</td>
<td>177.68</td>
</tr>
<tr>
<td>Microgrid Malindi</td>
<td>Company 6</td>
<td>41.16</td>
<td>205.8</td>
</tr>
<tr>
<td>Microgrid Mbodoni</td>
<td>Company 1</td>
<td>41.64</td>
<td>208.18</td>
</tr>
<tr>
<td>Microgrid Kasuku</td>
<td>Company 1</td>
<td>44.65</td>
<td>223.23</td>
</tr>
<tr>
<td>M-KOPA Solar</td>
<td>M-KOPA</td>
<td>51.9</td>
<td>259.49</td>
</tr>
<tr>
<td>BB17</td>
<td>Abundant Power Solutions</td>
<td>70.77</td>
<td>353.85</td>
</tr>
<tr>
<td>Kerosene</td>
<td>-</td>
<td>126</td>
<td>630</td>
</tr>
</tbody>
</table>

In the comparative analysis for Tier 2 energy access, it can be extracted the result that Barefoot 600 which is the largest solar kit that is distributed by Solar Aid is the most cost-effective solution. The cost of microgrids per household varies between $31 USD and $44.65 for different areas. The diversity energy potential among the regions is resulted to the respective cost for each family. However, microgrids as a solution are comparable and almost identical in terms of cost with Barefoot 600 as their annual cost per family sis between $2.64 USD and $16.34 USD.

M-KOPA product has higher annual cost than the previous energy systems even if it cannot generate a table fan and the light quality is poorer. Finally, Bb 17 has the highest cost of the compared renewable energy systems but it should be mentioned that it can support further appliances such as a television while Barefoot 600 does not have that capacity.

The most important result of the comparative analysis is the one extracted after comparing the systems to the annual expenditures for kerosene. More specifically, as it is mentioned previously, each household spend $126 USD on kerosene per year. Therefore, it is proved that rural households can abolish kerosene lamps and achieve access to energy at least up to Tier 2, with less money than
they spend on kerosene annually. Thus, it is shown that in terms of economics and costs, not only it is very easy to decrease energy poverty in Kenya, but the capital that could be saved by turning from kerosene to renewable energy can be invested on education, health and other parameters which can improve the quality of rural families and boost their development. Finally, Tier 2 can be financed only and directly by the income of rural households without the need of external sources, but only based on the economic capacity of those families.

5.8 Further comparison of microgrids and solar lamps

In 2011, Marie-Louise Barry et al. (69) published a paper in which thirteen technical, social and economic factors were determined. According to the research, these factors should be taken under consideration for the sustainable selection and implementation of renewable energy projects in Sub-Saharan Africa.

In this section, the comparison between microgrids and solar lamps is extended to these factors. The judgment of performance for the two energy systems in those factors is done under the data and information that were received during the interviews in energy companies and direct observation in Kenya between May and July 2014. It is important to note that the comparison takes place again under the intention of satisfying only Tier 1 and 2. Finally, additional factors are proposed for the integrated comparison of systems.

5.8.1 Technology factors

5.8.1.1 Ease of maintenance and support over the life cycle of the technology

Renewable energy microgrids are large systems that require an annual visit by the developers in order to ensure the correct function of the system. That would include grinding of wind turbines, check on the functionality of different components and further calibrations to the system. On the other hand, solar lamps and larger solar kits are simple systems that do not require any special maintenance except the cleaning of the PV panel which can be done by the owner. Thus, solar lamps and kits have an advantage to that factor.

5.8.1.2 Ease of transfer of knowledge and skills to relevant people in Africa

Operation and maintenance of a microgrid is a simple procedure as it is an automated energy system. Many times, owners are involved in the O&M. However, that requires demonstrations, booklets and other informational material regarding that factor. Solar lamps and kits usually have their own booklet. Through, their operation is a very simple procedure; therefore it is very easy for someone learn operating such a system. So, solar lamps and kits have better performance in that factor.
5.8.2 Site selection factors

5.8.2.1 Local champion to continue after implementation

Local champion is someone that continues to take care and perform simple maintenance after the completion of the project, such as cleaning of PV panels or protecting it from smuggling. A local champion is essential for a microgrid while for a solar lamp this role is undertaken by the owner. Therefore, solar lamps have an advantage on that.

5.8.2.2 Adoption by community

Adoption by the community is a very important factor. If a microgrid is not adapted by the community, there is a danger of abandonment and finally destruction or malfunction of the system. On the other hand, a solar lamp is a more personalized product which is taken care by the owner and as long as it saves them money and provide better living conditions, it can be adapted more easily.

5.8.2.3 Suitable sites ready for pilot studies

For this factor, both microgrids and solar lamps seem to have the same performance. If there is a proved functionality and correct operation of the companies or distributors, then there is no need for pilot studies.

5.8.2.4 Access to suitable sites can be secured

This factor refers to the recognition of the priorities each community has and the special conditions that affect the implementation of each technology. The distribution of solar lamps is the toughest part under this criterion since they are fixed products while the development of microgrids does not only contain the logistics part but also the development and feasibility study.

5.8.3 Economic/financial factors

5.8.3.1 Economic development

In this factor, microgrids have better performance. Development of microgrids can create jobs for local champions, technicians and project developers while the ability to extend the size of the system can provide higher access and allow the operation of tools for small workshops and businesses. In addition, the increased operation hours of systems and savings from kerosene fuel is a common characteristic of microgrids and solar lamps. Nevertheless, the excess of energy that is observed in microgrids can be used on other activities except the included ones of Tier 1 and Tier 2, such as irrigation, farming and machining processes.
5.8.3.2 Availability of finance

As proved before, the annual cost per household for solar lamps and microgrids is almost the same and the difference is neglectable. This factor should concern also the way of payment and not only the actual amount of money that has to be paid per family. Since both microgrids and solar lamps can be funded under PAYG payment scheme and direct payment, there is no meaning of comparison.

5.8.4 Achievability by performing organisation

5.8.4.1 Business management by the performing organization

As the availability of finance, this factor does not correspond directly to the system but to the project development organization. Both solar lamp distributors and microgrid developers with excellent managerial performance were found in Kenya. Notable example is Solar Aid which has achieved to be the biggest rural electrification NGO in Africa as a result of the sustainable project management innovation.

5.8.4.2 Financial capacity

Financial capacity is a very important factor. Microgrid projects as it has been shown in the previous analysis require many times a high initial and total capital. Even if they are affordable for the rural families, many times it is impossible to implement them because of that parameter. In order to solve this problem, the involvement of the state is proposed. The state can act as a warrantor for the project, by funding initially the development of the system. That would serve on the need for short payback periods of the private companies while also, the in the end of the project lifetime, the state would have a net zero capital damage. The role of the warrantor can be played by banks also, but then a rate would need in order to motivate such an investment.

On the other side, solar lamp distributors do not require such an increased financial capacity. The reason is that, if there is a proper planning and management, the company or NGO makes the respective transaction with the customers and producers in a much more direct way and short term period, without involving a project payback period. Therefore, this factor favors solar lamps.

5.8.4.3 Technological capacity

Microgrid developers need be have expertise in renewable energy technologies while solar lamp distributors handle fixed packages without being involved to the product development in most of the times, even if in some cases, NGOs and solar lamp distributors have their own product. So, in this factor, solar lamps have an advantage too.
5.8.5 Newly identified factors

5.8.5.1 Government support

In combination to the financial capacity, it can be seen that governmental support might be important for the development of larger microgrids through funding of projects or providing reduced taxes, while in solar lanterns the distribution is independent to the state help. Therefore, solar lamps have better performance in that factor.

5.8.5.2 Environmental benefits

Microgrids seem to have a better performance under this factor. There are two reasons for that. The first one is that the ability of the system extension can have increased environmental impact. More specifically, in such a case, rural families can turn from charcoal and wood for cooking in more efficient solutions, such as electric stoves. On the other hand, solar lamps and kits can only help to the abolishment of kerosene lamps but cannot be used for cooking or other similar utilities.

The second reason is the management of the systems when they complete their operational lifespan and stop working. There is a high concern for solar lamps that when the system stops functioning after approximately five years, users seem to treat them as common. That enables a danger of environmental pollution, as solar lamps not only can increase the amount of plastic wastes in rural Africa but also the existence of batteries in the garbage can contaminate the soil and water resources.

As a result, there is a need for the development of a sustainable disposal management system solely for solar lanterns and kits. Such a disposal system is under development by Solar Aid in Kenya. On the other side, when the batteries of a microgrid stop operating, there replacement is done by the developing company, thus it is easier to recycle them properly without causing environmental damage.

5.8.6 Proposed factors

5.8.6.1 Ease of distribution

In this factor, solar lamps have a distinct advantage in comparison to microgrids. More specifically, solar lamps are much more easily to be distributed in a community. Organizations such as Solar Aid have a very high capacity and efficiency in supplying a community with the respective products, so the commission and supply of rural families could last for a very short period of few days or few weeks.

On the other hand, the development of a microgrid project can last for a long period. Such a project has many phases, from data collection to designing and implementation. Therefore, it takes a much longer time to electrify a rural community in comparison to distribute solar lamps or kits.
5.8.6.2 Ability of system extension

This last factor corresponds to the ability of the system to support further appliances and to extend the services that it can cover. More specifically, a microgrid that is designed to provide energy access of Tier 1 or Tier 2 level to a community, it can be increased in terms of power generation and energy storage capacity. Thus, even if a microgrid is initially built in order to support a limited number of appliances, it has ability to be developed further and cover the needed energy requirements of appliances such as refrigeration or TV. Moreover, in future, a microgrid can be connected to the national grid and supply it with electricity generated by renewable sources.

On the other hand, solar lamps and solar kits are designed in order to cover a very specific range of appliances while it is impossible to be extended in terms of installed capacity and battery storage as they are fixed products. Therefore, in this factor microgrids have a better performance.

5.9 Conclusions

In this techno-economic analysis, five microgrid were designed and compared with solar lamps and solar kits. The common base of evaluation among the systems was their technical and cost performance in covering similar energy consuming services and appliances and providing to the users increased energy access of Tier 1 and Tier 2 level, as it is defined in the Sustainable Energy for All – UN framework. Five different communities were chosen as case studies. For each community and each tier of energy access, seven microgrids were optimally sized according to the technical and economic data of the seven Kenya energy companies that participated in the research. Finally, for each community and tier, the microgrid with the lowest cost was selected and compared to solar lamps and solar kits, in order to find the overall optimal solution for increasing energy access to the respective case study.

In the analysis, it is shown the important role that renewable energy can play for electrifying rural Kenya. More specifically, the increased potential of solar and wind power decreases the needed size of installed power generation systems, while communities do not need to rely on diesel generators that have high costs and require expensive fuels in order to produce electricity. Moreover, the renewable energy potential of specific regions has been highlighted. Communities in the northern Kenya, at Marsabit County can exploit the available wind speeds. In areas with medium irradiation and wind speeds such as Mbo doni and Malindi communities, wind power can be feasible as a supportive power generation system while the main one is PV panels. In areas with high solar irradiation such as Nadapal and Kasuku solar power is the dominant energy system while it is not feasible even for very cost effective wind turbines to be installed.

For all five communities and tiers of energy access, the lamps of Solar Aid where found to be the most cost effective solution. In addition, the annual cost per household for microgrids was found very accessible as it was slightly higher than the cost of solar lamps. BBOXX and M-KOPA products were more expensive in comparison to Solar Aid lamps and microgrids for all the studied cases.

The most important outcome of the techno-economic study was the cost comparison between all the above mentioned energy systems to the annual household expenditures for kerosene fuel. It is proved that the average cost for kerosene is by far higher than the cost of both microgrids and solar
lamps and kits. As a result, there is solid evidence and proof of the techno-economically feasibility and achievability of abolishing the kerosene lamp in Africa and replacing it with renewable energy systems, providing the poor rural households of Kenya increased energy access and securing them a brighter and more sustainable future without the need of external financial help or resources but only based on their own economic capabilities, under the “from the people for the people” perspective of view.
6 Overall conclusions

In this MSc thesis, the different parameters of rural electrification in Kenya have been examined. This work is divided in two main parts, the socio-economic impact study of abolishing kerosene lamps and a techno-economic comparative study between the different alternatives for rural electrification in Kenya.

In the socio-economic study, it has been showed the importance of improving energy access to rural households. A significant difference has been identified between kerosene lamp and solar lantern users in a variety of socio-economic parameters such as, health education and income. Moreover, it is shown the change that has in rural families’ lives the action of NGOs like Solar Aid and their social-enterprise Sunny Money, which until today has sold more than 1,400,000 in Africa.

The most important effects are the following. As far as the users’ health, this means escape from dangerous and polluting conditions that cause several problems while for education it means among others, better reading conditions and increased hours of children’s studying. In terms of income, people can save money and avoid drudgery of finding fuel, while a significant change was found in social activities and tendencies like immigration and safety.

In the techno-economic impact study, microgrids were designed for five rural communities in Kenya and for two different tiers of energy access, Tier 1 and Tier 2, mainly as described in Sustainable Energy for All framework, but with some adaptations in the included electrical services. The communities were mainly chosen according several criteria. These were the local energy source potential described by solar irradiation and wind speeds, their size and their distance from a climate station. The designing included not only the cost of the energy system but also external costs such as labor, maintenance operations and the distribution system.

The optimal microgrids for each community and tier were compared to a number of alternative solutions for rural electrification that exist nowadays in the Kenya. In the result, it is shown that the solar lamps distributed by Solar Aid/Sunny money are the most cost effective systems while microgrids have been found to be affordable for rural households with a small annual cost difference to solar lamps. Most importantly, it has been shown that solar lamps, larger solar kits, and microgrids have a significantly lower cost in comparison to the annual household expenditures on kerosene fuel. More specifically, if rural communities would turn from kerosene to renewable energy, not only they would improve significantly their living conditions and climb the energy ladder but they would also save a very high capital that can be used on education, health, investment or support of productive activities such as agriculture.

Closing, the work of this MSc thesis addresses to governments, public and private organizations and companies as it tries to highlight the importance and required efforts of increasing energy access and abolishing the kerosene lamp for poor families in Kenya, while also to show a way towards the achievement of energy poverty elimination and the ensuring of a healthier, cleaner and brighter future for rural communities in Africa.
7 Bibliography


59. **Sustainable Energy for All - Global Tracking Framework.** s.l.: Sustainable Energy for All - UN, 2013.


67. HOMER help. **HOMER Energy software.**


8 The socio-economic questionnaire

Part 1 - General questions

1. Date
2. Name
3. Age
4. Gender
5. Profession
6. Location of the House
7. How many rooms does your house have?
8. How many adults and children does your family have? | Adults: | Children: |
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>&lt; 5,000 KSH</td>
<td>5,000 to 10,000 KSH</td>
<td>10,000 to 15,000 KSH</td>
</tr>
</tbody>
</table>
9. How much money does your household earn per month?

Part 2 – Energy Modelling

Lighting

10. Which of the following do you use for lighting?

Other – Please indicate:

If you use a PV-Solar Device, please answer the following:

11. Which of the following PV-Solar Devices do you use? Write the number in the box
12. How long ago did you buy the PV-Solar Device  
13. How often in the week do you use your PV-Solar device for lighting?  
14. How much time per night do you use your PV-Solar device for lighting?  
15. Is your PV-Solar Device still working?  
16. How much happy in general, are you by the PV-Solar Device?  
17. Which of the following devices do you connect to the PV-Solar Device?  

<table>
<thead>
<tr>
<th>Device</th>
<th>Mobile Phone</th>
<th>Fan</th>
<th>TV</th>
<th>Radio</th>
<th>None</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dlight S2</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sun King Pro</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Barefoot 600</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Barefoot 2000</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

If you use Kerosene Lamps, please answer the following:

19. How many kerosene lamps do you have in your house?  
20. Where is the place you find kerosene?  
21. How much time do you have to walk in order to find kerosene?  
22. How often in the week do you use your Kerosene Lamps?  
23. How much time per night do you use your Kerosene Lamps?  
24. How much money do you spend per day/week/month for kerosene?  
25. How frequently do you buy kerosene?  
26. How frequently do you buy new kerosene lamps?  
27. How much money do you pay per kerosene lamp?  
28. How much happy in general are you by the use of kerosene lamps for lighting?  

If you use another source of lighting, please answer the following questions:

29. What is the source of lighting you use?  
30. Where is the place you find fuel?  
31. How much time do you have to walk in order to find fuel or candles etc?  
32. How frequently do you buy fuel or candles etc?
33. How often in the week do you use the lighting source? | Days per week
---|---
34. How much time per night do you use the lighting source? | 
35. How much money do you spend per day/week/month for fuel or candles? | KSH per day/week/month
36. How much happy in general are you by the use that source for lighting? | Very Happy | Happy | Neutral | Sad | Very Sad

**Part 3 – Socio-economic measurements**

**Education - Study behaviour and health issues related**

*If you can read, please answer the following questions*

<table>
<thead>
<tr>
<th>Question</th>
<th>Options</th>
</tr>
</thead>
<tbody>
<tr>
<td>37. Can you read and write?</td>
<td>None, Only read, Read and write</td>
</tr>
<tr>
<td>38. How often do you read during the night?</td>
<td>PV-Solar Device, Kerosene Lamps, Candles, Other</td>
</tr>
<tr>
<td>39. What source of light are do you use in order to read and write at night?</td>
<td>Very Happy, Happy, Neutral, Sad, Very Sad</td>
</tr>
<tr>
<td>40. How much do you like the light source in order to read during the night in?</td>
<td>Very Happy, Happy, Neutral, Sad, Very Sad</td>
</tr>
</tbody>
</table>

*If your children go to school, please answer the following questions:*

<table>
<thead>
<tr>
<th>Question</th>
<th>Options</th>
</tr>
</thead>
<tbody>
<tr>
<td>41. Do the children study during day, night or both?</td>
<td>Day, Night, Both</td>
</tr>
<tr>
<td>42. How much time do the children study for school?</td>
<td>Minutes/Hours</td>
</tr>
<tr>
<td>43. What source of light do your children use in order to study at night?</td>
<td>PV-Solar Device, Kerosene Lamps, Candles, Other</td>
</tr>
<tr>
<td>44. How much happy are your children with the light they use for studying during the night?</td>
<td>Very Happy, Happy, Neutral, Sad, Very Sad</td>
</tr>
<tr>
<td>45. Do your children complain about the quality of lighting when they study for school?</td>
<td>Yes, No</td>
</tr>
<tr>
<td>46. How good are your children’s grades?</td>
<td>Good, Moderate, Bad</td>
</tr>
<tr>
<td>47. Do your children listen to the radio</td>
<td>Yes, No</td>
</tr>
</tbody>
</table>
### Household and Social Activities

<table>
<thead>
<tr>
<th></th>
<th>Question</th>
<th>Yes</th>
<th>No</th>
</tr>
</thead>
<tbody>
<tr>
<td>48</td>
<td>Do you gather and have social activities in your house with family or friends during the night?</td>
<td></td>
<td></td>
</tr>
<tr>
<td>49</td>
<td>Do you feel safe during the night?</td>
<td></td>
<td></td>
</tr>
<tr>
<td>50</td>
<td>Are you thinking of moving to another place in order to have access to electricity?</td>
<td></td>
<td></td>
</tr>
<tr>
<td>51</td>
<td>How many hours do your children stay at home?</td>
<td>Hours</td>
<td></td>
</tr>
<tr>
<td>52</td>
<td>Do you cook during the night?</td>
<td></td>
<td></td>
</tr>
<tr>
<td>53</td>
<td>Do you do domestic work (cleaning etc) in the house during the night?</td>
<td></td>
<td></td>
</tr>
<tr>
<td>54</td>
<td>Do you listen to the radio?</td>
<td></td>
<td></td>
</tr>
<tr>
<td>55</td>
<td>Does anyone in your house have a cell phone?</td>
<td></td>
<td></td>
</tr>
<tr>
<td>56</td>
<td>If yes, how often do you charge it?</td>
<td></td>
<td></td>
</tr>
<tr>
<td>57</td>
<td>If yes, where do you charge it?</td>
<td>At home PV-Solar Device</td>
<td>Neighbour</td>
</tr>
</tbody>
</table>

### Health and Safety Adults

<table>
<thead>
<tr>
<th></th>
<th>Question</th>
<th>Yes</th>
<th>No</th>
</tr>
</thead>
<tbody>
<tr>
<td>58</td>
<td>Do/did you have any breathing problems when you use a kerosene lamp or a candle?</td>
<td></td>
<td></td>
</tr>
<tr>
<td>59</td>
<td>Do/did you feel irritation and/or itching in your eyes when you use a kerosene lamp?</td>
<td></td>
<td></td>
</tr>
<tr>
<td>60</td>
<td>How many times has a kerosene lamp caused a fire in your house?</td>
<td>Times</td>
<td></td>
</tr>
<tr>
<td>61</td>
<td>Have you or other people in your house ever been burnt by a kerosene lamp?</td>
<td></td>
<td></td>
</tr>
<tr>
<td>62</td>
<td>Do you or other people in your house feel heat when you use kerosene lamps?</td>
<td></td>
<td></td>
</tr>
<tr>
<td>63</td>
<td>Does the kerosene lamp produce smoke or dirt?</td>
<td></td>
<td></td>
</tr>
<tr>
<td>64</td>
<td>Do you think you have other health problems by the kerosene lamps? <strong>Indicate problems</strong></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

### Children

<table>
<thead>
<tr>
<th></th>
<th>Question</th>
<th>Yes</th>
<th>No</th>
</tr>
</thead>
<tbody>
<tr>
<td>65</td>
<td>Do your children have any breathing problems when they use a kerosene lamp or a candle? <strong>(for example, when they study)</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>66</td>
<td>Do your children feel irritation or itching in their eyes when they use a kerosene lamp or a candle? <strong>(for example, when they study)</strong></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Income and Small businesses

If you have a business, please answer the following questions:

<table>
<thead>
<tr>
<th></th>
<th></th>
<th>Yes</th>
<th>No</th>
</tr>
</thead>
<tbody>
<tr>
<td>67.</td>
<td>Do you run a business?</td>
<td></td>
<td></td>
</tr>
<tr>
<td>68.</td>
<td>What kind of business do you run?</td>
<td></td>
<td></td>
</tr>
<tr>
<td>69.</td>
<td>Do you run your business during the night?</td>
<td>Yes</td>
<td>No</td>
</tr>
<tr>
<td>70.</td>
<td>What kind of lighting do you use in your business?</td>
<td>PV-Solar Device</td>
<td>Kerosene Lamps</td>
</tr>
</tbody>
</table>

If you used kerosene lamps/candles in your business and now you use PV-Solar Devices

<table>
<thead>
<tr>
<th></th>
<th></th>
<th>Yes</th>
<th>No</th>
</tr>
</thead>
<tbody>
<tr>
<td>71.</td>
<td>Did you use to run your business during the night?</td>
<td></td>
<td></td>
</tr>
<tr>
<td>72.</td>
<td>Have you changed the opening hours of your business?</td>
<td>Yes</td>
<td>No</td>
</tr>
<tr>
<td>73.</td>
<td>Do you have more customers by using the PV-Solar Device?</td>
<td>Yes</td>
<td>No</td>
</tr>
<tr>
<td>74.</td>
<td>Have you seen a difference in your profits after using a PV-Solar Lamp in your business?</td>
<td>Yes</td>
<td>No</td>
</tr>
</tbody>
</table>