Rural Electrification of Uganda

- a Technological and Least-Cost Feasibility Study

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A: Modelling and calculations
B: Data on generation sites
C: Interviews

As rural electrification rates are down to 7 % in Uganda, more than 26 million people do not have access to electricity. There are several issues regarding this, but both human and economic development are proven to be linked with access to electricity.

As Uganda has one of the lowest GDP's in the world, and an urgent need of bringing electricity to those who have none, it becomes important to choose the right way of electrification, both regarding technology and costs. As grid electricity generation is cheaper than off-grid generation, but expensive to extend, it becomes a question of whether or not to extend the grid or install off-grid solutions. This choice is different for all villages as their distance to the grid and consumption differs.

Several technologies are applicable as the most important factor for rural electrification success is not the technical aspect but the human factors behind, such as lack of technical knowledge regarding design, installation, and management – these however being general and do not make any technology more or less feasible. The most feasible are found to be grid extension and solar PV mini-grids. Solar PV mini-grids are modular which makes a large difference as rise in consumption can be more easily met than for the other solutions where it is necessary to change generator unit.

Financially, diesel generator mini-grids are the most feasible off-grid technology. However, as they are only 16 % more feasible than solar PV, which is more technologically feasible, solar PV is chosen as the most feasible off-grid solution. Comparing solar PV and grid costs of electrifying villages through GIS, choosing the least-cost option, it is found that Uganda should be electrified in a 3:1 ratio by grid and off-grid, after a 10 year payback period.

1 Table of Contents

PREFACE

This report is the master thesis of Rasmus Bjergegaard, for the study programme "Sustainable Energy Planning and Management" at Aalborg University, Department of Development and Planning. Written in the timespan from the 2nd of February 2015 to the 6th of August 2015.

The topic was chosen based on an internship in Centre for Research in Energy and Energy Conservation in Uganda, between 1st of August 2014 and 1st of November 2014, where the issue of rural electrification and the consequences of not having it became clear. The relevance is thus high, as millions of people in Uganda do not have access to power, limiting their mobility, education and even length of day, compared to those who have access. With Uganda's GDP being one of the lowest in the world, it makes it that much more important to choose the right solution of electrification, for the different villages, and it is the aim of this thesis to give stakeholders an analytical input, tools and inspiration for further extending access to electricity.

Referencing is done with the Harvard style, where surnames and year of publishing is given in the text. When referring to a section, the source is behind the dot. When referring to a sentence the source is in front of the dot. When referring to a single statement in the middle of the sentence, everything after the reference does not refer back to the reference.

Tables, figures, and others are referred to continuously but separated by chapter. This means that the second figure in chapter 1 is referred to as figure 1.2.

Appendixes are placed after the report, and can be used to look up information for further detail. A CD with Excel models and interview is attached to the project in the back.

Appreciations are given to project supervisor Poul Alberg Østergaard for supervision and support during the project period. Gratitude also goes out to the people who accepted to help with giving interviews, sending other data and answering questions.

1 INTRODUCTION

Developing countries face many difficulties, including a lack of access to basic needs such as to clean water, proper education, sanitation and others. (Globalization101, u.d.) 1.3 billion people worldwide are without access to modern energy services[1] and 3 billion still cook with biomass – the vast majority of these on inefficient and harmful cook stoves or open fires. More than 4 million people (800,000 of these being children (UNDP, 2013)) die annually as a direct consequence of cooking on open fires, due to inhalation of soot particles and poor indoor climate. (WHO, 2014) Studies show that by decreasing the use of biomass by 10 percentage points so does child mortality by 0.7 %. (Yeh, 2004) Other consequences of lack of access are shortened periods of productivity and social interactions due to lack of lighting, insecurity due to lack of street lighting, or limited mobility such as no access to media including internet, phones or TV. (Walsh, 2011)

Some of the negative consequences for the populations of developing nations can be alleviated by access to modern energy services. It is also widely accepted that access to modern energy services is paramount for development – financial as social[2]. Especially within the United Nations (UN), starting with the milestone UN-commissioned publication "Our Common Future" (1987) up till present day energy programmes such as Sustainable Energy for all (SE4ALL)[3], which also focuses on development issues. SE4ALL is thus linked with all the UN Millennium Development Goals (MDGs)[4] as energy access is the cornerstone of all the MDGs (Practical Action, 2014).

"Energy is the golden thread that connects economic growth, increased social equality, and an environment that allows the world to thrive" – quote UN secretary Ban Ki-Moon (UNDP, 2013)

1.1.1 ENERGY ACCESS IN AFRICA

More than 95 % of the people affected by the lack of access to modern energy services live in Sub-Saharan Africa or developing Asia, as well as 84 % of those being rural populations. (UNDP, 2013)

[1] Access to modern energy services is defined by SE4ALL as: *"household access to electricity and clean cooking facilities"* (OECD/IEA, 2010)

[2] It is important to mention however, that although access to electricity is important for economic growth it does not necessarily in itself bring such. (Neelsen & Peters, 2010)

[3] SE4ALL is a United Nations Development Programme (UNDP) energy programme set down in 2011 with a target of achieving its three different energy goals by 2030. The three goals being: *"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"* (UNDP, 2013)

[4] The MDGs are eight global development goals, with specific sub-targets, set down by the UN in 2002 and were set to be reached by 2015. These goals are: *1) "Eradicate extreme poverty and hunger 2) Achieve universal primary education 3) Promote gender equality and empower women 4) Reduce child mortality 5) Improve maternal health 6) Combat HIV/AIDS, malaria and other diseases 7) Ensure environmental sustainability 8) Global partnership for development"* (UN, u.d.)

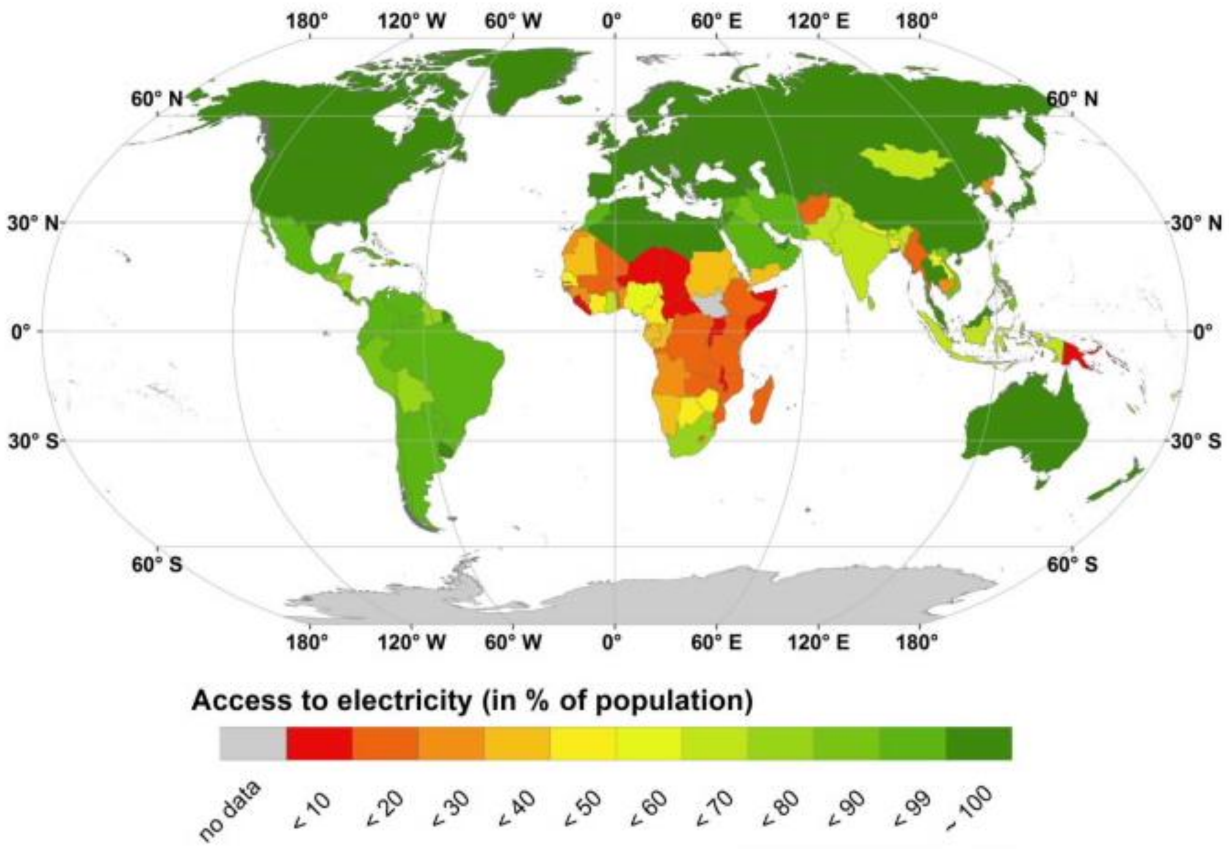

Figure 1.1 (Seguin, 2014): An overview of electricity access in the world, which shows that the majority of people without access to electricity live in Sub-Saharan Africa and developing Asia.

The lowest electrification rate in the world is in Sub-Saharan Africa, where more than 620 million people are without electricity[5], average national electrification rates are at 32 %, rural electrification rates are down to 16 % and 80 % of the population still rely on traditional use of biomass for cooking. (EIA, 2015)

One of the African countries with a low electrification rate is Uganda, with an overall electrification rate of 15 %. The urban electrification rate is 55 % and the rural electrification rate is 7 %. (EIA, 2015)

In 2014 the population was 34.9 million inhabitants with a mix of 18.4 % urban inhabitants, and 81.6 % rural inhabitants. This means that there are 28.4 million rural inhabitants – 26.4 million of these not having access to electricity. (UBOS, 2014)

1.1.2 Off-grid energy solutions

For many years (and still ongoing today) extending electricity grid has been the policy for electrifying rural areas, around the world (incl. Uganda). However, IRENA (2012) questions whether this approach has shown to be cost and technically beneficial compared to off-grid energy solutions that can bring some of the same services as grid extensions to the rural populations. An example of such is the cost of installing a substation for one remote village, which greatly increases the per capita electrification costs (Sovacool & Drupady, 2012). The off-grid solutions are thus seen by some as the future for electrification of developing countries

[5] In this instance electricity access is defined as: household access with a consumption of a minimum of 250 kWh/year for rural households and 500 kWh/year for urban households. (EIA, 2015)

and as such it is expected that by 2030, 60 % of additional electricity generation, compared to today, is generated by off-grid solutions in developing countries. (IRENA, 2012)

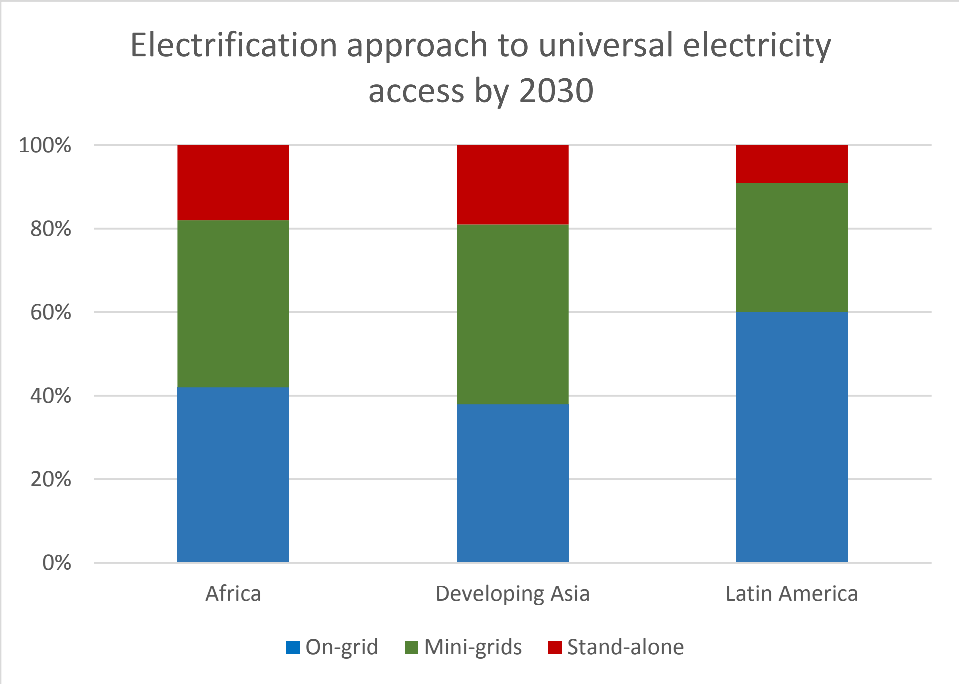

Figure 1.2 (IRENA, 2012): The expected universal access by 2030 electricity mix for the developing world is made up of central on-grid solutions and off-grid off-grid solutions in form of mini-grids and stand-alone systems.

As can be seen from the columns showing the future electricity approach, rural electrification is not a black and white issue, however. As Mahapatra and Dasappa (2012) dictate, there is a financial optimum where different technologies are more beneficial than others, which means that rural electrification is not a question of whether to extend the grid or install off-grid solutions but to decide which technology and approach is most fitting for specific areas and communities. This is because different off-grid solutions as well as grid electricity have different pros and cons, and which solution should be chosen for rural electrification can be locally specific (Kjellström, et al., 2005). Some of the various aspects that play a role in feasibility of solutions is population density, consumption, infrastructure and more (Murphy, et al., 2014).

1.2 Research Question

Sustainable energy is seen as the foundation of development for developing countries, and without it, development, is expected to be difficult. Alongside this there are social and health consequences of lack of access to modern energy services – consequences that can be alleviated through giving access to these services. This is especially an issue for the rural populations of developing nations as their electrification rates are lower than the ones of the urban populations.

Sub-Saharan Africa is the least electrified region in the world, with Uganda having one of the lower rates. In Uganda the overall electrification is 15 % with 7 % for the rural population – less than half the rural and overall electrification rates of average Sub-Saharan Africa – leaving more than 26 million rural people without access to electricity.

For many decades grid extension has been the main tool to solve rural electrification but in recent years there has been a change of mind towards off-grid solutions, as they by some are regarded as being more financially and technologically viable. There is no clear answer however, to which solution should be used for rural electrification of a country as it can be locally specific.

This brings the research question of:

"How can rural Uganda be electrified in the most feasible way?"

In this context "feasible" covers the aspects of being technologically and financially feasible, which gives the following sub-questions:

1. How can rural Uganda be electrified in the most technologically feasible way?
2. How can rural Uganda be electrified in the most financially feasible way?
3. Using answers to sub-questions 1) and 2) which off-grid solution is most feasible overall and which impact does it have on total electrification?

For this report, when mentioning rural electrification of Uganda, a 100 % electrification rate is used. This is according to the SE4ALL goals along with Uganda governmental plans such as the Uganda Rural Electricity Strategy and Plan 2013-2022 of 100 % electrification by 2030 and 2040, respectively. The electrification is thus seen from a point of view of final electrification and not a first step towards it.

1.3 PROJECT STRUCTURE

The three sub-questions of the research question are answered through four areas:

1.3.1 RURAL CONSUMPTION

First off, to create the basis for answering the three sub-questions the rural consumption has to be determined, as it is regarded to be the most important aspect for technologies to handle. This comes with a general overview of Uganda for a better contextual understanding.

1.3.2 TECHNOLOGY CATALOGUE

To answer which technologies are feasible for rural electrification of Uganda a technology catalogue is made to analyse which technologies are applicable as well as their potentials, including resources and ability to meet demand of the rural population.

1.3.3 FINANCIAL LEAST-COST ANALYSIS

Once the technology catalogue has given answer to which technologies are applicable for rural electrification of Uganda, the next step is to analyse which of these technologies are the most financially feasible, using a least-cost analysis. For this two steps are taken:

1. A method of how to compare the different technologies financially is chosen.
2. Calculations based on real numbers from implemented projects are made for comparisons of which are most financially feasible.

As it is a least-cost analysis regarding different technologies for rural electrification of Uganda, current governmental subsidies etc. are not included. Solely the costs of electrifying Uganda is included as well as the parameters that might affect that cost. Neither is it looked at which financial impacts the different technologies have on national or local level, although it is acknowledged that socio economics is also an important factor. The premise behind this is that the lower the cost, the lower the prices are for government to build capacity and consumers to pay for consumed electricity, thus getting the cheapest and presumably fastest electrification to Uganda.

1.3.4 GIS analysis of national electrification

The results of the technology catalogue and the financial least-cost analysis are basis for a discussion of which of the off-grid solutions is the most feasible in general. This solution is then compared to grid extension, which is done by applying the financial findings for the chosen off-grid solution to a GIS with data on distribution lines and population in smaller areas, which are treated as demand nodes[6]. The data on population is used together with the rural consumption found in the first area of "Rural consumption" to calculate a demand node consumption which can be used along with distance to grid to find the financial break-even point of distance and consumption. This determines which electrification solution should be applied, thus giving a GIS map on the most feasible electrification of Uganda.

Although focusing on rural areas, "rural" is an open definition in this report, as it focuses on electrifying demand nodes. However, this is done from data gathered on rural settings, including rural consumption, which is expected to differ from urban consumption.

[6] Villages or small cities are here understood as demand nodes, which are areas with electricity demand based on inhabitants.

This gives a structure as follows:

Chapter 1: Introduction
An introduction to the research topic as well as a research question.

Chapter 2: Methodology
The methods used to answer the research question and sub-questions are given here.

Chapter 3: Rural consumption
A brief overview is given of Uganda for key numbers and a contextual understanding of the issue of rural electrification of the country. The main aspect of the chapter is determining the rural consumption both in peak kW and kWh.

Chapter 4: Technology catalogue
The technology catalogue includes an analysis of which technologies are feasible in Uganda, including the usual technical design and the potential for each renewable energy source, and how they correlate to consumption and needs.

Chapter 5: Financial feasibility of solutions
In this chapter financial feasibility of solutions is uncovered and it is determined which

Chapter 6: National electrification
The findings of chapter 4 and 5 are discussed in this chapter to determine the most feasible solution overall, which can be used along with GIS and consumption data found in chapter 3, to determine the electrification solution for each demand node in Uganda.

Chapter 7: Discussion of results and sensitivity
In this chapter parameters are checked for sensitivity to reconsider the reliability of the findings. And results are discussed.

Chapter 8: Conclusion
A summary of the report and an answer to the research question.

2 METHODOLOGY

In this chapter an overview of methods used to answer the research question are given, including choices regarding the data gathered for the methods.

2.1 DATA GATHERING

The data gathering for the chapters is given below. The data gathering methods for each chapter are chosen based on the solution to solving the problem or sub question of the chapter. It is important to collect data well as no report is stronger than the quality of data it has.

2.1.1 Context of data gathering in Uganda[7]

There are several issues regarding gathering data in Uganda, where the two biggest are the cultural differences between author (personal as well as academic, which gives a different world view) and potential interviewees or research subjects, and the other one is the poor quality of data available (if even). The cultural differences is one part due to lack of natural understanding of Uganda, from not having lived there for years, and one part interviewees not being used to interviews and therefore not understanding or trusting the approach. It is also considered bad taste to say negative things about someone else and it is not unlikely that interviewees will give the answers they expect the interviewer want. If attempted to do surveys or interviews with the approach of the Danish academic background and cultural understanding, it is regarded as most likely that results will be wrong, and therefore such data gathering can be problematic. The poor quality and lack of availability of data comes from not much data being documented in Uganda along with some entities not willing to share their data readily. This creates a situation where some data gathering is left to estimates and improvised procedures that might not be found elsewhere in other studies. Therefore it is often a question of taking the least poor data rather than the best, if anything is even available.

2.1.2 General

Before any analysis is done, an explorative semi-structured interview is done with Benon Bena, manager of off-grid renewable development under Rural Electrification Agency, to understand the issues and context of rural electrification in Uganda. This is deemed a good way to initially get an understanding of the overall problem as well as the underlying issues.

2.1.3 Chapter 3: Rural consumption

For this chapter, it is considered that a literature review is sufficient. Where data is insufficient follow up questions with experts are asked, although through email correspondences, and not as complete interviews. This is done as the empirical data needed for this part are numbers and follow up questions.

Email correspondence: Benon Bena, manager of off-grid renewable development under Rural Electrification Agency. Questions regarding rural consumption.

2.1.4 Chapter 4: Technology catalogue

It is considered that a brief understanding of the electrification solutions is enough to understand whether or not a certain solution could be applied in Uganda, and a literature review supplemented by expert interviews is thus regarded as sufficient. The literature study is to give general insight into technologies and designs of systems, as well as their applicability in rural electrification. The interviews with local experts is to complement with local knowledge and experience with the solutions to see if anything important is neglected in the literature, as well as theoretical studies not always comparing to reality properly. Furthermore interviews are done to follow up on issues found in literature regarding technologies.

Interviews: Mary Suzan Abbo, director of Centre for Research in Energy and Energy Conservation (CREEC), as she has worked several years with implementing several of the solutions and has knowledge of the energy situation in Uganda. A semi structured interview is done in order to get answers to specific questions but also keep it open for the interviewee to give additional information.

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[7] The context of data gathering in Uganda is not from an academic source but comes from own experience during a three months internship at CREEC (1st of August – 1st of November 2014). However, CREEC director Mary Suzan Abbo concurs with the statements.

Opio Innocent Miria, former head of pico hydro power and bio gasification at CREEC, as he has extensive knowledge of gasifiers and the issues they face in Uganda. A semi-structured interview is done as there is knowledge of issues about gasifiers, but not to which extend, thus leaving room for the interviewee to elaborate on certain aspects, as well as follow up questions for these. Further follow up questions are done via email.

2.1.5 Chapter 5: Financial feasibility of solutions

A literature study is done in order to find the best calculation methodology along with which parameters to include in the calculations. The literature looked into is, when possible, about similar projects of rural electrification in developing countries, and preferably about or close to Uganda. Otherwise general financial comparison methodologies for technologies are looked into.

Financial data for the analysis is complicated, as there is no source that can give comparable numbers for the variety of technologies and solutions for Uganda. For the different technologies, where possible, implementers of the technology are asked about costs and data, as data on real implemented projects is more representative of actual costs than a procurement catalogue. Although it is considered that face to face interviews would be best to collect that data, as follow up questions and mutual understanding is regarded is higher, phone calls and emails are made to save time as it is a substantial amount of people that need to be contacted. As it is data about numbers and costs, and not qualitative answers, it is considered an acceptable compromise. For a list of data used here see appendix B.

2.1.6 Chapter 6: National electrification

For this chapter, GIS layers are used with data from Uganda Bureau of Statistics (layer of consumption nodes) as well as Rural Electrification Agency (layer of distribution lines).

2.2 Method of technology catalogue

The technology catalogue is based on literatures studies, expert interviews and modelling of energy systems in Excel.

For some of the technologies data is not available on their technical ability to meet consumption. This is mainly due to the fact that in this report, to compare grid and off-grid solutions in the best possible way, off-grid solutions are supposed to meet the average mature rural consumption at all times, whereas off-grid solutions are normally installed with the purpose of simply bringing electricity to a demand node – not designed to meet a specific consumption (Abbo, 2015). Therefore, for a full understanding and perspective of the solutions, some of them are modelled in Excel as systems to uncover their technical ability to meet demand. For further detail see appendix A.

2.3 Method of financial analysis

The first step of the financial analysis is choosing a method for which to compare the different technologies financially. There are several ways of calculating comparable costs for RE technologies. Some of the studies and methods found for this report are both general and used for the purpose of rural electrification in Africa. Unless otherwise stated the following sources compare technologies on a general basis and not for rural electrification in Africa.

Lund (2014) use an annual costs calculation for each technology, as the sum of an annual discounted per kW cost of installed capacity plus the annual fixed O&M costs.

IRENA (2012) and European Commission (2013) use Levelized Cost of Electricity (LCOE) which calculates a discounted total lifetime cost of cost per kWh of technologies. In their case this includes the sum of the discounted sum of initial investment, O&M, and fuel costs, divided by the discounted sum of electricity generation. Mainali & Silveira (2013) use the same LCOE approach, although they do not discount the total lifetime electricity generation. There are several other studies who use LCOE who, however, have not stated how. These being (World Energy Council, 2013), (Dale, 2013), (Szabó, et al., 2011) and (Murphy, et al., 2014).

Parshall, et al. (2009) use a Net Present Value (NPV) calculation by finding a per unit of installed capacity cost through a project lifetime discounted initial investment plus O&M costs, for electrification of Kenya.

Mahapatra & Dasappa (2012) use life cycle costs (LCC), for electrification of India through a model of their own, which is similar to the LCOE method. Their model use discounted total lifetime costs divided by lifetime generation costs to give a discounted lifetime kWh price:

$$\frac{Initial\ investment + (annual\ O\&M + fuel\ costs + component\ replacement + external\ costs) \cdot PVF}{Lifetime\ generation\ of\ electricity}$$

PVF is Present Value Factor, and external costs are in form of a carbon credit. The above is shown for a off-grid technology, as grid is different in it having both generation costs and extension distance costs.

Nässen, et al. (2002) also use their own LCC model for rural electrification of Northern Ghana. As it is a complex model it is shown more simplistically here:

$$\begin{aligned} &Generation\ costs \cdot number\ of\ households \cdot household\ consumption\ factor \cdot PVF \\ &\quad + [distance\ cost\ of\ MVL + number\ of\ households \cdot (household\ generation\ cost \\ &\quad + household\ connection\ cost)] \cdot (1 + O\&M\ factor \cdot PVF) \end{aligned}$$

MVL is medium voltage lines. The above is shown for grid extension, where the first part is a discounted generation cost and the second part is a discounted extension cost, which gives a specific cost for electrifying a community[8].

As mentioned above, some of the methods used for rural electrification show that there is a difference between grid extension and off-grid solutions as the parameter of cost/distance is added, which is not a parameter in the general calculations. It is regarded that this is because most of the sources are from countries with fully developed grid infrastructure and technologies are expected to feed electricity to a larger grid and are not made for off-grid solutions.

Although using different approaches, the common demeanour of all of the above methods are that they calculate a variation of discounted life cycle costs of the technology, which makes the different technologies comparable as the total costs over their lifetime are compared and, for example, not only their initial investment or their annual O&M costs. In this regard it is also noticed that they have similar parameters, which include:

- Initial investment[9]

[8] The source is also a case study about a region in Northern Ghana, whereas the other sources have a national, continental or global scope.
[9] From here on known as CAPEX, which is the total capital expenditure of developing and constructing a plant (World Energy Council, 2013)

- Operation and maintenance (O&M) costs[10]
- Project or technical lifetime of technology
- Discount rate for a present value

This leads to the conclusion that the specific method of which the above parameters are presented, are not as important as including the right parameters as long as it is done in the same LCC way for all the technologies. This is because it is regarded that as long as the technologies are compared in a LCC manor with the same parameters and approach, the specific approach used should not have a large impact on results of comparison.

There are different ways of applying LCOE models, and they can be more or less complicated, through amount and detail of parameters, thereby analysing costs of technologies more adequately. How complex an LCOE model should be is depending on the data available as insufficient data along with more assumptions in a complex model can result in a less correct analysis, where a less complex model is more transparent for readers and better fit poorer quality data. (IRENA, 2012) The calculations in this report are attempted to be as realistic as possible by including as many real life parameters as can be responsibly done without compromising results with poor data. That means that the model can be complex but where it is considered that the data is of too poor quality, the parameter is neglected. This is shown in the fact that the different technologies are difficult to compare, as many parameters are different, such as availability and operating hours and operating situations (productive use for example) (Mahapatra & Dasappa, 2012). Therefore these parameters have to be taken into consideration and, if possible, monetised in such a way that they can impact the financial analysis and make the solutions more comparable.

With this in mind three of the above methods stand out as less applicable. The first one is the annual costs comparison of Lund (2014), where O&M costs are not discounted – as they are in the other methods. For a full LCC comparison it is regarded that all future costs should be discounted to give an understanding of the present value of future costs. The second is the specific case cost of electrifying an area from Nässen, et al. (2002). It is deemed that this method is better for determining the technology of electrification for a region or smaller area and does not compute with the national focus of this analysis and report. The third is Parshall, et al. (2009), who finds a discounted kW price instead of a discounted kWh price, which is considered to be better fitting of the purpose of the report, as a consumption and distance break-even point has to be found, as mentioned in 1.3 “Project structure”.

It is considered that a lifetime discounted kWh cost is the most fitting comparison basis for this analysis and the focus of the report. As the methods of Mainali & Silveira (2013) and Mahapatra & Dasappa (2012) is almost identical to the IRENA (2012) LCOE method, which gives a kWh output and is also the most widely used method found in the above literature, it is chosen to use this method for the calculation with the approach shown below:

$$LCOE = \frac{\sum_{t=0}^{Lifetime} \frac{CAPEX_t + OPEX_t}{(1 + discount\ rate)^t}}{\sum_{t=0}^{Lifetime} Annual\ electricity\ consumption}$$

Where t is year of calculation. The only difference made is that the above sources use electricity generation, which makes sense if a technology is feeding electricity to a grid, where all kWh generated are consumed.

[10] From here on known as OPEX, which is total operating expenditure covering annual operation and maintenance costs (World Energy Council, 2013). O&M costs can include fixed costs, such as salaries, and variable costs, such as fuel costs.

For an off-grid setting (seen as a secluded island system), generation does not necessarily match consumption, for various reasons. This is an issue when generation is higher than consumption, as it makes cost/kWh lower than it should, which gives a wrongful comparison basis of technologies. A hydro power plant, for example, with continuous generation, having close to zero generation costs, can produce more electricity than is consumed without further costs, thus bringing down LCOE. For systems with batteries, storage losses are not accounted for if only looking at generation. Therefore it should be a consumption price and not a generation one, as it is for grid feeding technologies. Costs of generation are still referred to as generation costs although they are generated for the final consumption.

The difference between Mainali & Silveira (2013) and Mahapatra & Dasappa (2012), and the IRENA (2012) LCOE method is that IRENA also discounts electricity generation. It is chosen not to discount the generation (consumption) as it is understood that only costs should be discounted as electricity generation is in this report, not understood as having a different present or future value. The reason the sums of all years are used and not an equal annual payments calculation is that some technologies have extra component replacement expenditures during their lifetime. These are included in CAPEX, thus CAPEX is not limited to initial investment, as CAPEX of year 1 and forward would otherwise be 0. As this varies from technology to technology it is not shown in the general LCOE equation, but for the specific technology. It is the same for the extra parameters, such as for example external costs, which are expected to be added to the equation as they are discussed later in chapter 4.1.

Grid extension is calculated differently from the other technologies as extending the grid includes covering the distance between current grid and the demand node, which includes an extra cost in form of km price. Therefore distance between grid and demand node is a financial parameter for grid extension that is not found for the off-grid solutions, which only have a kWh price. (Mahapatra & Dasappa, 2012) Since grid extension has the extra dimension of price/distance it has CAPEX and OPEX for both grid extension and generation costs.

LCOE is calculated with specific data for Uganda as generation and installation costs of electricity vary considerably across the world (World Energy Council, 2013), and therefore cannot be directly compared to LCOE, and underlying data, from other sources. In particular, LCOE cannot be compared as the extra parameters determined in this report might not be included in other sources.

The way specific data for Uganda is found is through costs of actual generation sites and projects installed in Uganda. This is expected to give a more realistic cost of technologies than theoretical costs found through procurement catalogues. LCOE is therefore calculated as an average kWh price depending on costs of already installed projects.

Mahapatra and Dasappa (2012) use three different system sizes due to economies of scale. In this analysis however, economies of scale and different system sizes are not taken into consideration. This is because of the choice of using costs of real projects and not expected costs of theoretical projects, to which the same size (i.e. 10 kW, 50 kW, and 100 kW) for all solutions cannot be found. This approach does have the downside of not taking economies of scale into consideration, due to being an average as well. Another aspect is that few off-grid solutions have been installed (Bjergegaard, 2015), making it impossible to find same size for different technologies, and in general making data gathering, difficult.

2.4 GIS METHOD

Using the results of the financial and technological analysis, a discussion and decision is made about the most feasible off-grid solution, which can be compared to grid extension.

2.4.1 ECONOMIC DISTANCE LIMIT

The comparison of grid and off-grid is done using GIS data of distance to grid and consumption on demand nodes, along with the Economic Distance Limit (EDL). The EDL is the financial break-even point between grid extension and the off-grid technologies, where grid extension becomes less feasible (Murphy, et al., 2014). The EDL thus comes under the premise that grid electricity is cheaper per kWh than off-grid solutions, as otherwise all of Uganda should be electrified through the least cost off-grid solution. As EDL is used along with demand node data on distance to grid and consumption, it is not a constant distance from the grid, but instead it is calculated for all demand nodes showing the most feasible electrification form. Below is the calculation of EDL.

$$\frac{Cost}{km_{grid}} \cdot km\ distance + \frac{cost}{kWh_{grid}} \cdot\ kWh\ consumption \leq \frac{cost}{kWh_{offgrid}} \cdot kWh\ consumption = EDL$$

2.4.2 MODIFICATION OF GIS DATA

The GIS data available is a layer of village areas, and not point data. Point data is expected to be more precise than areas since villages are not spread over larger areas and points give a more concrete point of centre for measurement of distance between grid and village.

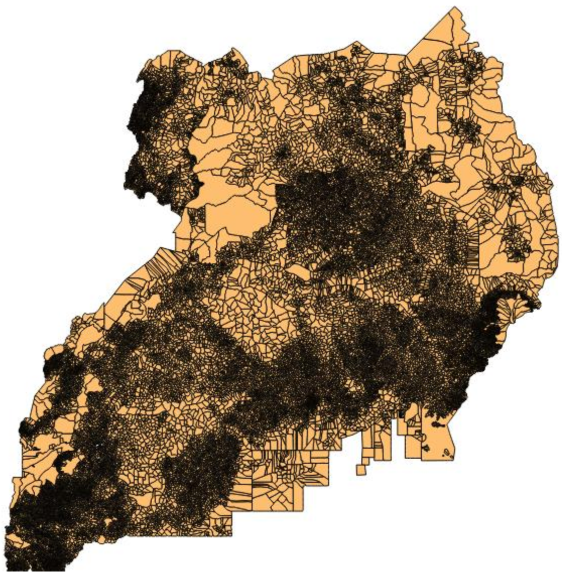


Figure 2.1: GIS map showing a visualisation of village data

The area layer has the issue of having several large areas that are not densely populated enough to be categorised as a village, and it is necessary to remove them. There is no clear approach to this as it is difficult to assess from the data which are villages and which are areas with scattered households. Parshall, et al. (2009) state that in Kenya average demand nodes are 15 km^2, however the limit is set at 25 km^2 (5x5) as areas above this should not be villages and lowering the limit could potentially remove areas which are villages. This gives the following data:

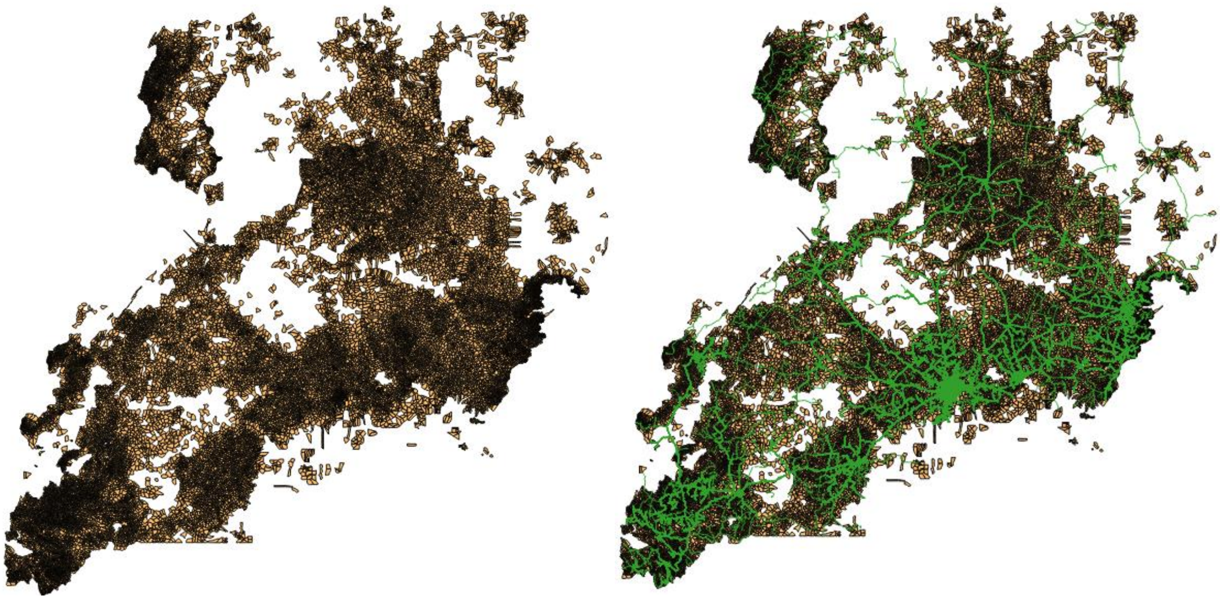


Figure 2.2: The layer after areas higher than 25 km^2 are removed to show expected villages. To the right including layer of grid distribution lines.

Due to the nature of the areas and large quantities of data of the layer, it is difficult to assess if villages are left out of the analysis, but it is considered that removing the larger areas gives a more accurate analysis.

With the new layer the distance between each village area and nearest grid distribution line[11] is calculated, and added as data in the layer. Applying the EDL calculation to the data in the layer (demand node distance to grid and population) along with average rural consumption found in Chapter 3 "Rural Consumption", this gives an overview of most feasible electrification of Uganda.

2.5 PROJECT UNDERSTANDING OF RURAL ELECTRIFICATION

One of the more important aspects of the least cost analysis of rural electrification is the choice of how to deal with how long the electrification is expected to take (time span) and how dynamic the approach of electrification is expected to be within this time span. According to Rural Electrification Strategy and Plan 2013-2022 for Uganda the expected end year of rural electrification is 2040, which gives a time span of 25 years – 15 years for the 2030 end year of universal access from SE4ALL.

It is difficult to make an economic analysis or electrification strategy for an entire country (more than 26 million people) to be given access to electricity as it is something that is expected to happen gradually for the next 15 – 25 years. For example: with a theoretical EDL of more than 5 km of grid compared to cheapest other technology, a here-and-now analysis will show that everything outside of a radius of 5 km from the grid should be electrified through off-grid solutions. However, in reality a village 5 km away from the grid might be electrified through grid extension which means that the grid is then 5 km closer to the surrounding villages that were otherwise outside the EDL of the grid, but might then be inside. See figure 2.3.

[11] Grid distribution layer is from 2013 and therefore not 100 % updated, which should have an impact on the distance from grid to village of some villages.

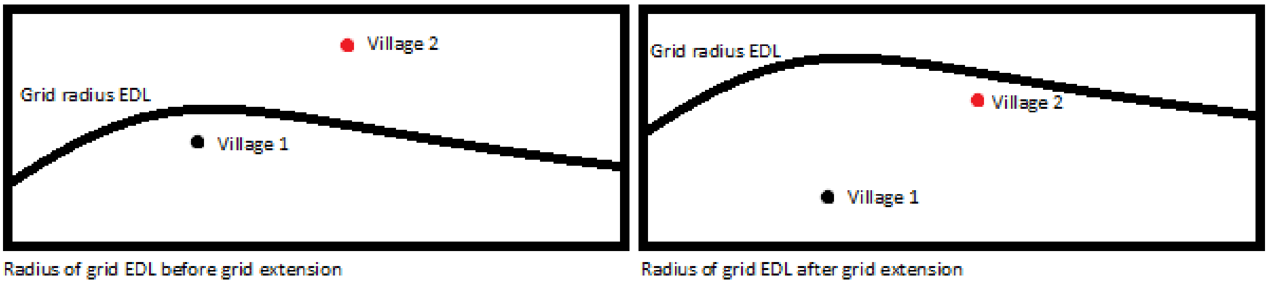


Figure 2.3: Radius of grid EDL before and after grid extension of village 1. In the after scenario Village 2 is now inside the EDL radius, whereas before it was a village with theoretical off-grid power supply.

This means that Village 2 (figure 2.3) is cheaper to electrify through grid extension, after the grid has been extended to Village 1, and other villages further away from Village 2, might then also be within grid EDL and so on, (Bena, 2015) which in time could potentially bring most villages within the EDL of the grid. This is a complex issue and modelling and analyses are difficult to make as dynamic as reality.

One way used to overcome this issue in other studies such as Levin and Thomas (2012) and Parshall et al. (2009) is to use algorithms to calculate minimal grid line extension for maximum connection. One of these algorithms is the Minimum Spanning Tree first used and altered by Czechoslovakian economist Otakar Boruvka to find the optimal economic expansion of grid between cities in the 1920's by finding minimal distance of grid lines (Parshall, et al., 2009).

Though these algorithms the case from figure 2.3 might have been solved more dynamically, and given a more realistic output, this approach is out of the reach of the author and for simplicity reasons are not looked into. For the same reasons of complexity and simplicity it is decided to look at the analysis as though all of Uganda would be electrified at the same time (over-night), thus finding a time consistent EDL and not a dynamic one as mentioned above. This means that the LCOE calculation is done from a 2015 perspective, instead of an approach where future parts of the electrification would have to be calculated from a 2020, 2025, 2030 etc. perspective, thus being discounted from baseline year 2015 and/or having to include future research and development in technologies. Another aspect is the intricate – and presumably uncertain – forecasting of parameters that have an effect on consumption, and thereby EDL. Some of these being future economic development, population growth, and urbanisation and depopulation of rural areas.

2.6 Overview of methods used

In the below is given an overview of all data gathering as well as methods and tools used.

Chapter	**Methods**
1 Introduction	Literature review
2 Method	Literature review
3 Rural consumption	Literature review, email correspondence, Excel consumption modelling
4 Technology catalogue	Literature review, expert interviews, Excel technical system modelling, email correspondence
5 Financial feasibility of solutions	Literature review, LCOE calculations, Excel fuel consumption modelling
6 National electrification	GIS
7 Conclusion	

3 RURAL CONSUMPTION

Before any analysis is done, an overview of Uganda is given to give a contextual understanding of rural electrification in Uganda.

3.1.1 UGANDA OVERVIEW

Uganda is situated in East Africa around Lake Victoria, with the southern part of the country being on or below the equator and the majority of the country being above, thus giving a constant length of day all year round, with no winter or summer. However, there are dry and wet seasons, where amount of precipitation differs and thus also temperatures. (Climatemp, 2015)

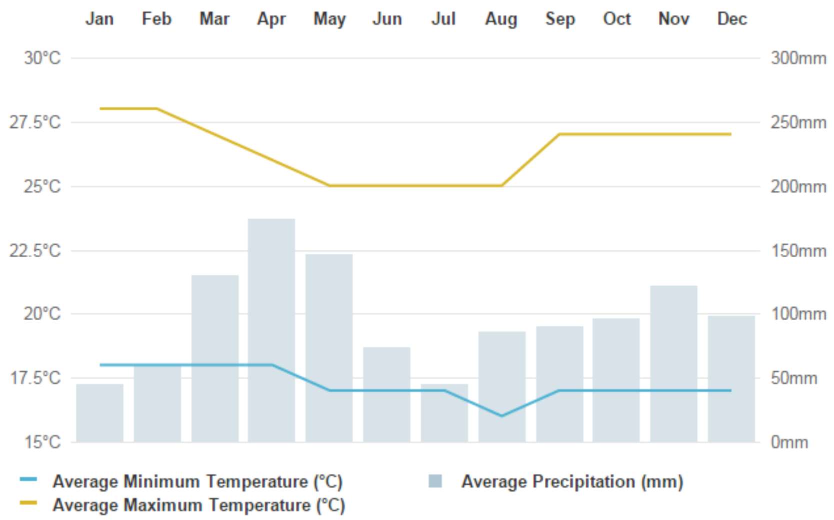


Figure 3.1 (BBC Weather, 2015): Averages of weather conditions in Uganda over the year

The total population of Uganda in 2014 was 34.9 million people. This constitutes 7.4 million households, of 4.7 people/household (4.8 for rural households). (UBOS, 2014)

6 million people live in urban areas, although that also counts towns of less than 5000 inhabitants, (UBOS, 2014) and a clear definition of "urban" is not present.

With an expected annual population growth of 3.03 % (UBOS, 2014) the total population in 2040 will succeed 72 million people – more than double the population of current.

With a 2014 GDP per capita of 1800 USD/capita (CIA, 2014), Uganda is one of the lesser wealthy countries in the world, which is expected to mean less investment possibilities for energy infrastructure.

The current centralised electricity mix in Uganda is constituted of 86.7 % hydro power, 3.4 % biomass and 9.9 % diesel, for thermal power plants. (Ministry of Energy and Mineral Development, 2015)

3.2 RURAL ELECTRICITY CONSUMPTION

The consumption of demand nodes is an important factor, as mentioned earlier 2.3 "Method of financial analysis", as it has an expected impact on which technologies are more feasible depending on generation and installation costs. I.e. high installation costs but low generation costs can be more feasible than low installation costs and high generation costs at a certain consumption.

There are two parts to rural consumption: the overall consumption in kWh and the consumption peaks in kW. The peaks can be found through demand profiles, where systems then can be designed accordingly, and kWh consumption per consumer are found through literature studies and email correspondences with local experts.

Rural electrification can be broken down into three parts: household consumption, public consumption (schools, churches, mosques, etc.), and commercial consumption (agricultural processing, trading centres, etc.). (Nässen, et al., 2002) (Mahapatra & Dasappa, 2012) The three parts have expected different peaks as the nature of electricity use and consumption is different.

3.2.1 MONTHLY CONSUMPTION

It is difficult to estimate rural power consumption, as it is expected to rise gradually as more new consumers grow accustom to having electricity. However, electricity use in rural Uganda is usually restricted to lighting, radio, TV, phone charging and refrigerators, and is unlikely to be used for heating or cooking, which biomass is used for. (Buchholz & Silva, 2010) According to Buchholz and Silva (2010) average rural household consumption varies from 15 kWh/year to 30 kWh/month, (Bena, 2015) states that it is 30 kWh – 50 kWh per month, albeit for the more wealthy, and (Ministry of Energy and Mineral Development, 2009) conclude 50 kWh/month. A field study to a 5 kW solar mini-grid in Kayanja for 120 households show the initial consumption of rural households and a much lower per month consumption, with maximum generation of 6.2 kWh/household/month[12].

Mature consumption is used over initial consumption as it is easier to calculate as well as giving a better picture of how it is in a 100 % electrification scenario, as goes for this report. It is not feasible to copy urban consumption and apply it to rural areas, as the difference in income and thereby disposable income, have an effect on possible consumption. This means that with the same availability of electricity an average rural household would not be able to pay for as much consumption as an average urban household (Ministry of Energy and Mineral Development, 2009). Although different consumption is expected from different classes of wealth, which also differs from region to region, a national average is determined as it is a national analysis.

Through the numbers above and statistics found in (Ministry of Energy and Mineral Development, 2009) average public, commercial and household consumption (per rural capita) are calculated to be:

Type of consumption	**Monthly per capita consumption in kWh**
Public	0.53
Commercial	3.20
Household	8.33
Total	12.07

Table 3.1: Rural electricity consumption (kWh/month/rural capita) broken down.

Public consumption covers education, health centres and water pumping. Commercial consumption covers a variety of commercial activities incl. agro-processing, trading centre shops, bars, video halls and others. Household consumption covers use of average household appliances such as indoor and security lighting, radios, TV's and more. See appendix A for further detail.

[12] Based on modelling of solar generation (mentioned later in appendix A)

3.2.2 Consumption peak

Although a demand profile have not been possible to find for public consumption or general commercial consumption, demand profiles for a village sample as well as a coffee factory (agricultural processing) have been found in Sprei (2002).

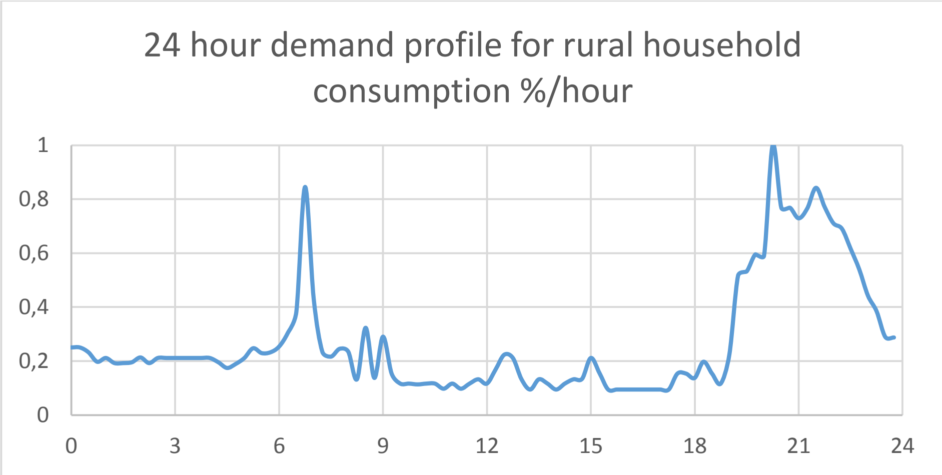


Figure 3.3: The 24 hour demand profile for rural household consumption, which shows a large morning peak, followed by somewhat steady midday consumption and with another large peak in evening time, levelling out again at night.

Figure 3.3 shows that there is a steady consumption at night, which is due to security lighting and some fridges which are turned on 24 hours a day. The large morning peak around 6.30 can be attributed to consumers waking up and getting ready for the day, including using indoor lighting, listening to radio, etc. During the day, where indoor and security lighting is no longer needed, the consumption comes from fridges being turned on in the morning for keeping drinks cold. The largest part of consumption comes when it gets dark around 19 and consumers stop working and have time to watch TV, listen to radios, and need indoor and security lighting. (Sprei, 2002)

The above demand profile is a sample of just five customers in a village with grid access (Sprei, 2002), and is therefore not deemed to be 100 % representative of all villages in Uganda, but it has not been possible to find other sources for rural demand profiles, and it is thus used as such, in lack of better.

As for public consumption, the demand profile is expected to somewhat follow that of household consumption, due to several reasons. The major part of school consumption comes from lighting, as computer services and laboratory facilities can also have a high usage, but are not common in rural settings without electricity. (Ministry of Energy and Mineral Development, 2009) In the same village as the above load profiles the consumption mainly came when it got dark, implying that teachers used it to get ready for the next day's curriculum. (Sprei, 2002) Common rural health centres do not have much electricity consumption, as they do not have much electric equipment (Ministry of Energy and Mineral Development, 2009), therefore mostly lighting is required.

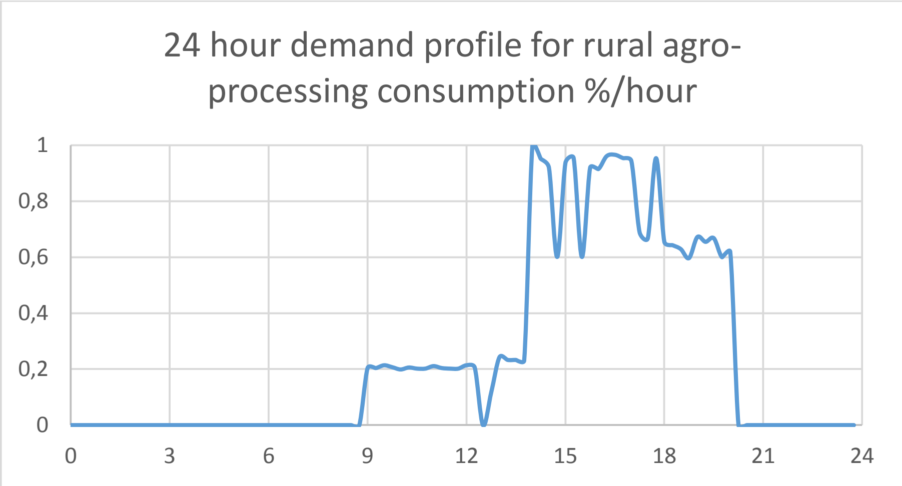


Figure 3.4: The 24 hour demand profile for rural agro-processing shows large peak fluctuations and a consumption of 12 hours of use and 12 hours of no use.

Figure 3.4 shows the demand profile of a coffee factory, with an approximate 12 hours of consumption from 9-20.30, and a dip in consumption around 12.30, which is expected to be due to a lunch break. The difference between the above agricultural processing and household consumption is the more concentrated use of power, and with less steady low load use.

As it is with the household consumption, this sample of a coffee factory is not necessarily to be representative for agro-processing in Uganda, however, in lack of one that is, it is used as such.

From the differences between commercial, household and public consumption as can be seen in table 3.1 (in the section above), a total demand profile is generated. This is done through simple integral calculation of the area under the curves of household and agro-processing profiles for total kWh consumption and making them match the per capita consumption.

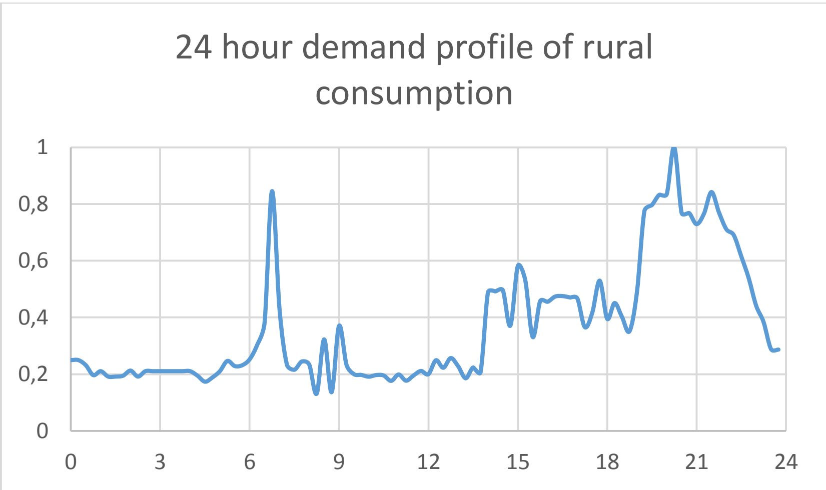


Figure 3.5: 24 hour demand profile for rural Uganda, including household, commercial and public consumption.

Rural consumption is thus determined both in daily peaks and kWh total consumption.

4 Technology catalogue

The first sub-question about feasibility of technologies is answered in this chapter, which gives an overview of the different technologies that have been found for rural electrification in other sources.

Although called technology catalogue, the important part of this chapter is to uncover the systems and solutions, more than it is the technologies themselves, as it is as much the design of the system as it is the technology that defines success of rural electrification. This is especially true for Solar Home Systems (SHS) and grid extension as the technologies do not differ from the ones already mentioned – only the design of the systems. Therefore, unless directly referring to the technology, “technologies” are forth on mentioned as systems or solutions. However, as technology is also about how the technical aspect cope with other societal aspects, these are briefly looked at before analysing the technical aspects of solutions.

The different solutions looked at are:

- Solar PV mini-grid
- Solar Home Systems
- Hydro turbine mini-grid
- Wind turbine mini-grid
- Bio gasifier mini-grid
- Biomass generator mini-grid
- Solar PV-diesel generator hybrid mini-grid
- Grid extension

Except for the solar home system, which is an individual electrification form, all the solutions mentioned in this chapter are expected to supply villages with electricity. This means that all system designs are with the power plant in the centre generating power to be distributed to the connected villagers, which means putting down local electricity grid connecting consumers and plant. Thus all communal solutions are expected to work as mini-grids, except for grid extension.

There are various technologies with RE sources such as solar, wind, water and biomass. The only technology that does not use RE sources are diesel generators, as grid electricity is mainly generated through large hydro power plants.

The overview of different solutions is designed in such a way that first it is explained how the technology and system works, then the potential for the solution in Uganda, price development and a pros and cons list at the end.

The pros and cons are compared to other solutions, and thus only what stands out as either positive or negative in that sense, is noted in the pros and cons list.

4.1.1 Societal aspects of technology

Before analysing the different technologies it is important to notice that most of the known technologies are applicable for rural electrification, although some are better than others. The main issues for success rates of electrification projects regarding technology is the human factors behind it, such as technical expertise (both for design, installation and O&M). All these capacities are lacking in Uganda. It is not limited to manufacturing, it is design, maintenance and even operation – all aspects that have immense importance on implementation feasibility of technologies (Abbo, 2015).

Rural electrification is not a direct path, because of other factors, which are not connected with technology. It should be looked at from a transitional point of view. Quote (Abbo, 2015)

Thus the specifics of the technology is not as important for future rural electrification success as the technical infrastructure and expertise capacity in the country. The issue is enlarged by the maturity for several aspects of capacity of technical expertise being low.

As it is not known how the Government of Uganda would finance off-grid solutions it is difficult to assess the issues regarding it. However, due to reasons of distrust in technologies and lack of disposable income, among others, it is not considered likely, even with the right financial and political framework, that rural inhabitants will invest in large communal off-grid solutions, anywhere in the near future. Along with most Ugandan policies being for open liberal market ideals, it is expected that the off-grid solutions would be through independent contractors and companies. Despite not having the aforementioned barriers, the companies that venture into off-grid solutions still face other barriers. If coming from Europe, North America or Asia, one of them could be not understanding the Uganda context (including bureaucracy and lack of good policy framework) and trying and failing with their solutions by using the same approach as their country and market of origin. Another barrier could be that, at current, lack of aftersales services is a major hindering for the off-grid solutions, as no components or technologies are made in Uganda, waiting time for new components can be months, which means months without electricity. (Bjergegaard, 2015)

It is also worth mentioning that in reality electrification would rarely be limited to one technology, and not necessarily in mini-grid form either. (Abbo, 2015) As it is mentioned above, however, mini-grids are expected to be the most feasible form of village electrification as well as other designs making the analysis otherwise too complex. Therefore all systems are still seen from the point of one technology.

These issues however are systematic for every solution and are seen as general issues regarding implementation, and not specific to each solution, thus not making any of them more or less feasible, compared to each other. Although the above issues are seen as very important for a discussion of feasibility of implementation of the findings of this report, they are not the focus of this report, which focuses on choosing the best available technology based on aspects of technical and economic feasibility.

One aspect of the feasibility of solutions that is specific is the local conditions that apply, (Abbo, 2015) such as solar potential, flow of water for hydro, which biomass is being processed at the location if residues are needed, distance from the nearest diesel station and so on.

4.2 Solar PV

Solar Photovoltaics (PV) are a solar based technology which converts sunlight into electricity.

A solar PV mini-grid system is constructed through several components, including: (Leonics, 2013)

- PV modules: To convert sunlight into DC electricity.
- Inverter: To convert the DC current into AC current, which is the current used for most household appliances.
- Batteries: To store electricity from the PV modules.
- Charge controller: To regulate the amount of electricity going into the batteries to prevent overcharging, as well as controlling batteries do not fully discharge, which protects the battery and prolongs its lifetime.

The PV module converts the energy of the sun to DC current, which then goes to the battery, controlled by the charge controller. When the electricity is needed by the consumer the DC current goes from the battery, through the inverter which changes it into AC current, and to the consumer.

There are various losses in the system, both internally and externally. Batteries alone create a 20 % loss, with dirt on panels, ageing of system and internal losses between components, being other contributing factors. (Wade, 2008)

One of the issues of PV stand-alone systems is that the batteries are expensive and have a low lifetime. (Energyinformative, 2013) The PV modules, however, have a 25 year efficiency lifetime, which means that after 25 years they still work, only the efficiency declines. (Energistyrelsen and Energinet.dk, 2012) Kjellström, et al. (2005) mention the larges issue of solar PV to be that it is not as adequate as other technologies, such as for example diesel generators, for peak consumption – for example productive uses, which means more restrictions for income generating activities. One reason is that PV generation is directly connected to installed capacity, unlike generators where generation can be controlled and is connected with fuel use. This means that for the needed amount of kWh a high peak capacity is not enough, and additional battery storage is also needed, unless peak consumptions are during generation hours. This however has been modelled (see appendix A for explanation of how), and as can be seen in figure 3.1 below. Peak consumption is outside of generation hours, which means a larger battery storage. As mentioned, this makes it a more investment heavy system.

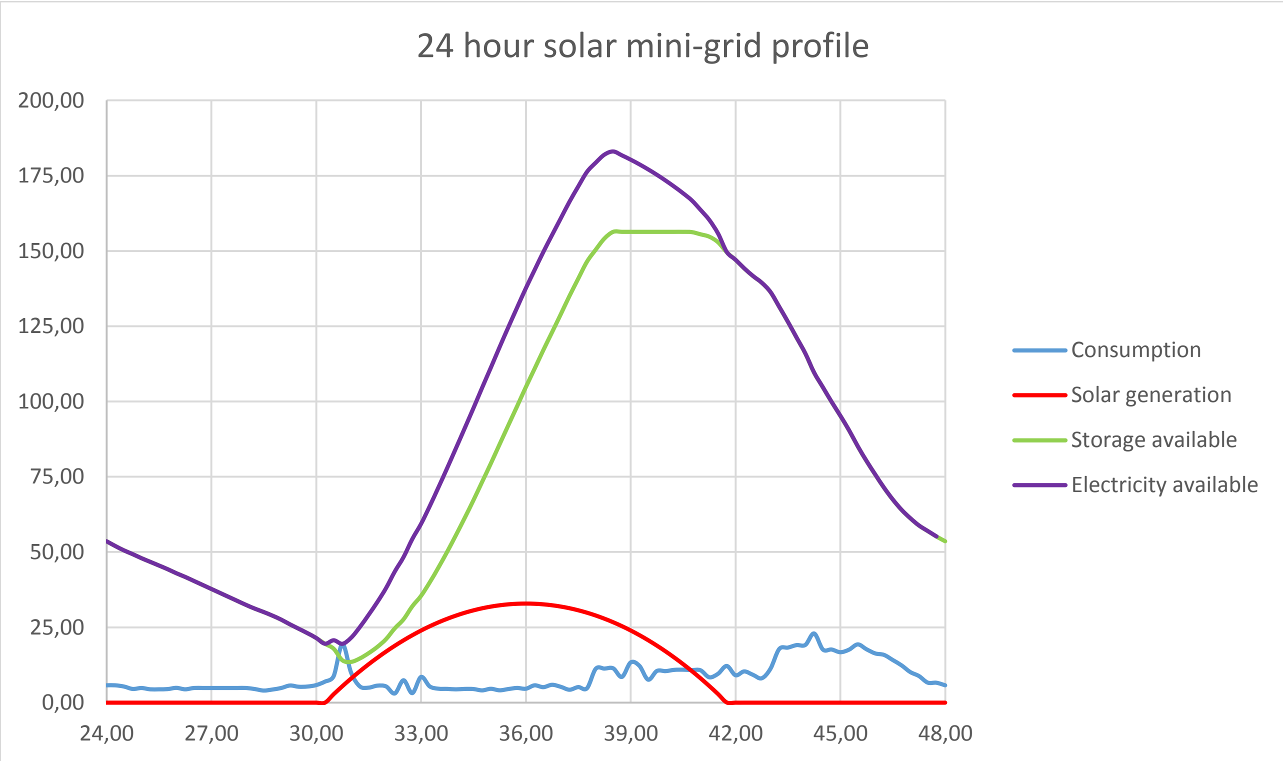


Figure 3.1: Mini-grid profile of a 23 kW peak consumption, showing the high storage capacity necessary to meet demand at all times.

Modelling shows that battery storage capacity needs to be approximately four times larger than installed solar PV capacity in order to meet consumption at all times. For example, to meet demand for a 23 kW peak consumption installed capacity of Solar PV and battery storage needs to be 51 kW and 195.5 kWh respectively. A smaller battery storage is possible, however for 23 kW peak consumption battery storage only goes down 15.5 kWh whereas the installed solar PV capacity goes up by 64 kW, thus increasing NPV with 210,000 Euro[13]. This constellation is therefore not deemed feasible. The model shows that an approximate ratio of 1:4 is needed for capacities of solar PV panels and battery storage.

The reason why the graph does not fit the installed capacities is that the graphs show the generation and storage electricity after losses are accounted for, thus installed solar PV capacity generates electricity at 65.7 %. For further detail of the model see appendix A.

No technical issues have been found regarding using solar PV mini-grids as solution for rural electrification. It is expected that Kjellström, et al. (2005) are referring to the costs of the system rather than technical aspects, when mentioning solar PV as being less feasible than other solutions. These costs being analysed in Chapter 4 “Financial feasibility of solutions”, and the source being 10 years old.

One of the benefits of solar PV, however, is that it is modular, which means that future capacity is easier and cheaper to increase, in comparison with for example generators, as more modules and batteries can be added to the system instead of changing power generator. (Kjellström, et al., 2005)

As mentioned above, the largest part of failing technologies is the human factor behind it, and solar PV is no different. Village Energy (2015) estimate that more than 50 % of solar systems installed in East Africa fail. The reasons for this mainly being: poor quality of products, operating conditions, and user errors. Along with this distributors face the challenges of poor infrastructure when getting to the villages furthest away from the grid (also those needing the off-grid solution the most), after-sale services that are difficult do to aforementioned issue, and consumer trust, which is declining due to the many failing systems. (Village Energy, 2015)

4.2.1 Potential in Uganda

The potential for solar PV in Uganda is large as there is a steady amount of daylight every day and many sun hours. (Mpagi, 2012)

4.2.2 Price development

System prices of residential and commercial PV systems have been declining 6-7 % per annum from 1998 – 2013. Market analysts say the overall systems will continue to be declining, but the module prices will start to stabilise in the near future. (SunShot, 2014)

[13] This NPV calculation is based on data from a 15 kW project used for LCOE in Chapter 5.2 ”LCOE costs of calculation”

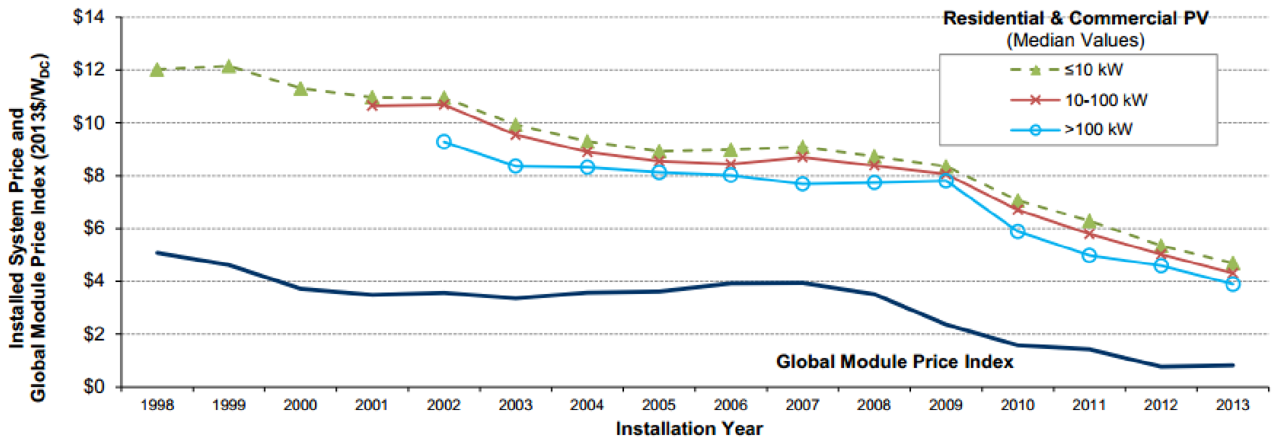


Figure 3.2 (SunShot, 2014)*: A price overview of 15 years from 1998 to 2013 that shows the overall decline of solar PV modules, which is now expect to stabilise.*

Especially batteries, which is one of the more criticised components due to their somewhat frequent replacement and high costs, have seen a steady decline in prices and are expected to decline even further, as much research and development is being done in this area. (Godske & Wittrup, 2015)

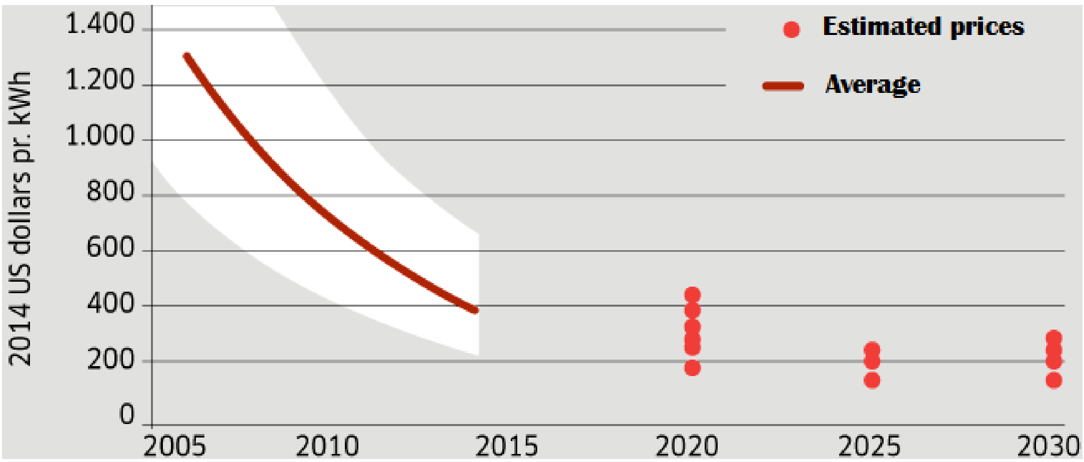


Figure 3.3 (Godske & Wittrup, 2015): Current and expected price trends for battery storage in USD/kWh.

4.2.3 Pros and cons of solution

+	-
Modular and easy to expand capacity	Batteries are expensive and have a low lifetime
Future prices are expected to lower	

4.3 Solar Home System (SHS)

Although using the same technology as solar PV and therefore not a different technology in itself, SHS's are here discussed as an energy solution different from solar PV in form of mini-grids or others, as they are individual solutions, and the other technologies mentioned in this chapter are mainly seen as communal solutions.

The design of the system is the same as the solar PV mini-grid, except for the connection wires, as it is for one household only. The difference between the two systems is mainly due to size and capacity.

Many household items can be powered through SHS's – depending on the capacity installed, however, a single secluded household in Uganda does not have a big electricity need, and can benefit from a small installation.

As such a 30 W_p system can power two lamps for 7 hours, as can be seen in the table below:

Size	**Use**
30 W_p	Two 9 W low-energy lightbulbs for 7 hours
130 W_p	Two 10 W fluorescent tubes as well as radio or small TV
400 W_p	Three 18 W fluorescent tubes as well as radio, small TV, a fan, and a 20 L refrigerator

Table 3.1 (Leonics, 2013)*: An overview of which services can be gained from different capacities of SHS's. This is an overview based on one source only, as storage capacity and solar access can vary, so can services of the SHS's.*

SHS's can be purchased as package solutions which makes them easy to set up and transport. (Power for Africa, 2012)

4.3.1 Potential in Uganda

The potential in Uganda for SHS's is large, as the solar resource is high in Uganda, and the panels do not take up much space.

4.3.2 Price development

It is an individual solution and there is thus no need for a manager of the system, meaning lesser O&M. As mentioned in the above about solar PV the panels have come to a somewhat stable price, whereas batteries might decline further in price.

4.3.3 Pros and cons of solution

+	-
Easy to transport and install	Not feasible for production
Feasible for single secluded households	Not feasible for several households

SHS's do not have a role in the remaining parts as it is not a system solution and therefore not feasible as demand node solutions. It is however mentioned to show a solution for the individual rural households that are not close to a demand node.

4.4 Hydro turbine

Micro-hydro power is a well-known technology in several developing countries and has showed itself to be a successful technology, where the hydro potentials are present. (Kjellström, et al., 2005) Another aspect is that it is not as fluctuating as other RE sources such as wind or solar, making it more predictable and dependable. (Cunningham & Woofenden, 2007)

The main issue, however, is that unlike solar power, for example, micro-hydro potential is locally specific, and several studies have to be done before installing a turbine – some of them with a time limit of up to one year. This is, among others, due to seasonal changes in water flow. Daily and weekly changes are also expected to occur, but can typically be diverted by building a small dam for water storage. (Kjellström, et al., 2005) In Uganda the amount of studies and the time they take to perform and be processed by authorities is long and difficult. (Bjergegaard, 2015)

Figure 3.4: A 200 W hydro turbine system using a storage water dam, installed in Vietnam (Alibaba, 2015)

The hydro system needs several parts for a functional design (Cunningham & Woofenden, 2007):

- Intake: Not necessarily a component, the intake is made to minimise air- and debris levels in the water.
- Turbine: Turns the flow of water into electricity. Since sites specifics are so important for the hydro systems, different designs of turbines are available and one fitting the site specifics can be chosen. One might be better for seasonal changes and another for a steady flow (Abbo, 2015).
- Batteries: A deep cycle battery can be used as backup if the flow of water decreases or it can be used as extra capacity when the electricity is needed. Compared to Solar PV and wind turbines, hydro systems in general are easier on the batteries, thus giving them a longer lifetime and/or giving a possibility of smaller battery capacity.
- Charge controller: A device that controls the charge of the batteries and system in general, so the system does not overload. The excess electricity is transferred by the charge controller to the dump load.
- Dump load: An electrical resistance heater that can convert excess electricity, which cannot be absorbed by the batteries, into heat so that the system does not overload.
- Inverter: Changes the current from DC current to AC current, which is used for most household appliances.

The water runs through the turbine, creating DC electricity, after it has been cleaned by the intake. That DC electricity goes into the batteries, controlled by the charge controller – excess electricity going into the dump load. When the electricity is needed, the DC current goes through the inverter to become AC current, and into the household. (Cunningham & Woofenden, 2007)

An alternative to applying batteries as backup or extra capacity is to install a diesel generator. This is often the cheapest way to optimise micro-hydro systems when the sites specifics are not fully adequate to produce the needed electricity. (Kjellström, et al., 2005)

Two Ugandan hydro projects of 64 kW and 20 kW, respectively, are without battery storage or diesel generators as they run continuously, however, and are not in need of such. (GIZ, 2012) (GIZ, 2012)

4.4.1 Potential in Uganda

There is an estimated 123 MW potential for small scale hydro power plants in Uganda. (Buchholz & Silva, 2010)

4.4.2 Price development

Micro-hydro power, like many RE technologies, has a high initial cost but low O&M costs. (Kjellström, et al., 2005) It is a mature technology as well as already being successfully used and produced in developed and developing nations and it is therefore expected that the price is stable. As several of the components in the hydro system are the same as those used for a solar PV system, it is expected that the overall system price might decrease, as is the case for solar PV (SunShot, 2014).

4.4.3 Pros and cons of solution

+	-
Well known functioning technology	Site specific
No generation costs and somewhat continuous generation	Not modular – increase in capacity means a larger turbine
	Several pre instalment studies needed

4.5 Wind turbine

There is an expected potential of wind power in the north-eastern regions of Karamoja and Mukono districts, but the average wind speeds in Uganda are 3 m/s which makes it an unfeasible solution. Another aspect is that wind speeds in Uganda have been measured only for meteorological usage, so far, which means that wind speeds have been measured at a few meters above ground level instead of the height needed for a turbine, and the uncertainty of the data for the potentials is thus high. (Mpagi, 2012)

Due to this uncertainty, little expected potential and low national experience with the technology it is regarded that wind power is not a feasible solution in Uganda.

4.6 Bio gasifier

Biomass gasifiers is an old technology that dates back to the 1930's. Today the technology is especially used in India for rural electrification of villages not electrified by grid. One of the reasons the technology is so popular in India is that it can produce electricity from locally produced biomass of various sources, including agricultural residue. Not all gasifier designs are compatible with all biomass sources, however, which means that the gasifier might have to be designed for the specific biomass resource locally available. The availability of local fuel means self-reliance for the villages, compared to travelling to cities for diesel or petrol for conventional generators. (Kjellström, et al., 2005)

An example of the usability of bio gasifiers is the Indian village of Hosahalli, where a 20 kW gasifier, running on agricultural residue and harvested biomass, is used for domestic and street lighting, as well as productive use for pumping drinking water and milling flour. The reliability of electricity supply is also better than what the surrounding grid-electrified villages experience[14]. (Kjellström, et al., 2005)

[14] 5 % of downtime for Hosahalli and app. 40 % for surrounding villages. (Kjellström, et al., 2005)

Gasification happens by dry biomass getting partially combusted with air in a reactor under atmospheric pressure, releasing gas. After removing tar and particles, it can then be combusted in a spark or compression ignition engine[15], with minor modification of the fuel system, as fuel. For compression ignition engines it can substitute 80-90 % of diesel, due to a minor injection of diesel per power stroke for ignition of the gas. (Kjellström, et al., 2005)

There are some Indian small-scale wood gasifiers who have already proven themselves robust and functional under similar geographical and meteorological conditions as Uganda, who can produce electricity at 1kWh per 1.5 kg of oven dried wood (0 % moisture content). (Buchholz & Silva, 2010)

Buchholz & Silva (2010) determine that even with conservative assumptions bio fuel for basic rural electricity needs can be produced on 3 % of a hectare per person and thus does not interfere notably with local food production, as residuals can be used or the fuel can be grown in hedges and other areas not fit for farmland. This means that Uganda can be self-reliant and biofuels can be produced locally, which can have a positive impact on local economies. (Buchholz & Silva, 2010)

Unlike solar PV, for example, biogas generators are not modular and a future increase in capacity thus means a new generator or initial oversizing of the system, which complicates financial feasibility of a lifetime project. (Kjellström, et al., 2005)

Depending on design and model of gasifier the moisture content of the biofuel has to be low. There is therefore a processing step before the fuel can be used, which can include drying, sizing and densification. (Kjellström, et al., 2005) This creates higher logistics, than for example buying diesel for a diesel generator, which can also have an impact on the feasibility of growing and harvesting biomass for fuel, as it becomes more complex. (Abbo, 2015) This means either buying processed biomass for fuel or investing in processing equipment, such as cutting machines. To this aspect it is also worth mentioning that the difference between technical levels of gasifiers is large, along with the issues of those. An electronically controlled gasifier will have larger efficiency as it is controlled more by electronics and not an operator, however, so far there have been several issues with these more delicate machines, as they are not fit for the climate and environment of Uganda. The more sturdy gasifiers, such as those mentioned by Buchholz and Silva (2010) from India in the above, can cope with the climate and environment, however as they are not electronic it is up to the skill and knowledge of the operator to get high efficiencies out of the fuel, which is an issue due to low technical capacity in Uganda. (Miria, 2015) The above both lower financial feasibility and regarding the human factor behind the technology expectedly lowers general feasibility of technology.

A technical issue for the gasification is that two gasifiers in Uganda found (10 kW and 32 kW) cannot run for more than one and two 8 hour shifts a day, respectively, and thereby cannot accommodate the 24 hour demand. In general the bigger power plants can run for 24 hours, but the majority of the smaller ones do not cope with 24 hour generation as reactor temperatures become too high. (Miria, 2015) For this reason bio gasification is not found to be a feasible technology for rural electrification of Uganda at its current state. There are hopes however of future research and development making them feasible (Miria, 2015). Another possibility is to add battery storage to the gasifier to accommodate for the remaining hours. This is modelled and details can be found in appendix A.

[15] diesel generator – which is the usual generator type in Uganda

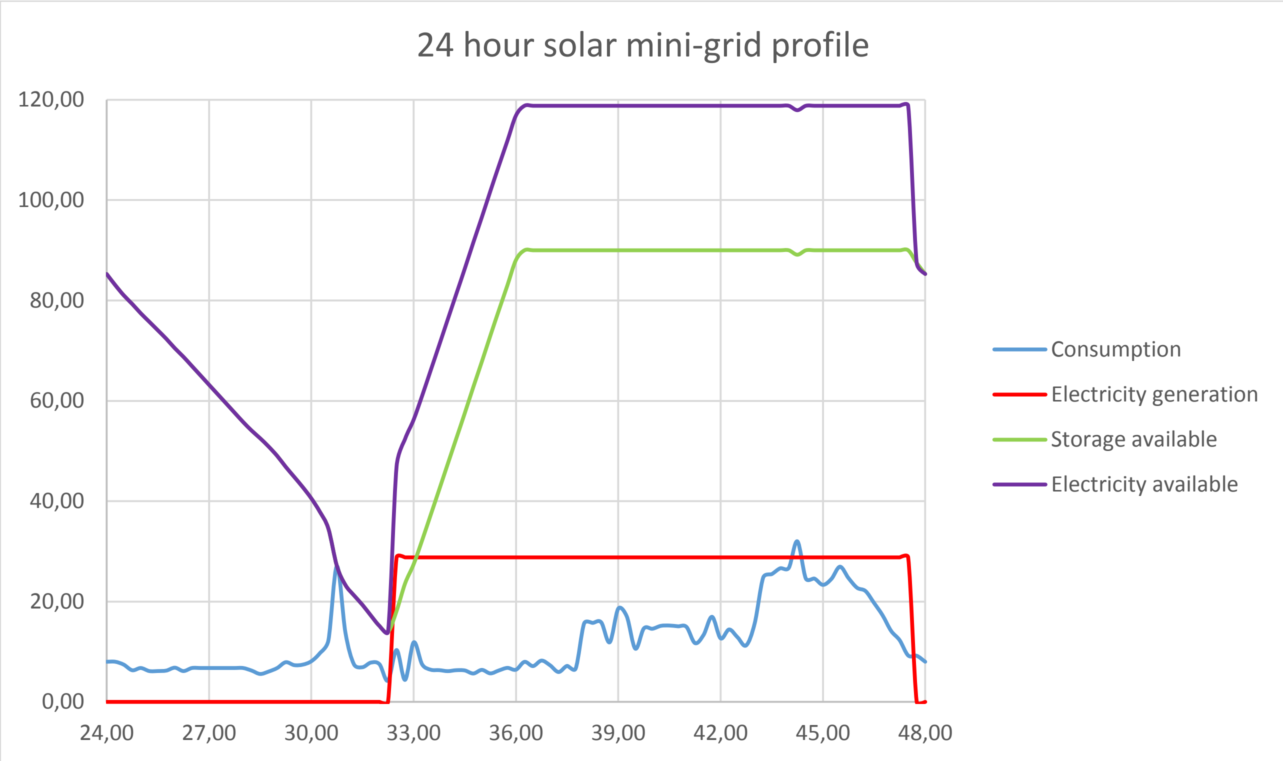


Figure 3.5: Mini-grid profile of 32 kW gasifier with 112.5 kWh battery storage, accommodating a 24 hour 32 kW peak consumption.

Through the model it shows that gasification with battery storage in theory can be technically feasible. The 10 kW gasifier however, cannot accommodate a similar peak consumption, and its maximum feasible consumption is 6.88 kW, with 48 kWh storage. This is mainly due to only being able to run 8 hours. The modelling of the gasifiers is quite theoretical as they are modelled as running almost full capacity for the maximum runtime, and if the issue is overheating, running full capacity continuously could enhance that issue.

4.6.1 Potential in Uganda

In agricultural residues alone there is a potential of more than 2,600 MW electricity, excluding the aforementioned 3 % hectare/person, which means that there is a large potential for bio gasification in Uganda. (Buchholz & Silva, 2010)

4.6.2 Price development

Bio gasifiers use a fuel/kWh which is a factor in price. However, since the fuel can be produced locally and mainly from residuals and non-farmland, there is an expected little or none impact on food prices, which means that prices on fuel should be somewhat steady. (Buchholz & Silva, 2010) Bio gasifiers is a mature technology although more research and development need to be done before they can be implemented without issues in Uganda (Miria, 2015).

4.6.3 Pros and cons of solution

+	-
Fuel can be produced locally	Not modular – increase in capacity means a larger turbine

	Not a mature technology in Uganda either due to lack of development of technology for a Uganda setting, or due to low technical capacity and infrastructure
	Although available, local fuel production can be an issue, among others due to low technical capacity and infrastructure.
	Cannot accommodate a 24 hour demand without battery storage
	Fuel has to be processed, which creates logistical issues

4.7 Biomass generator

Biomass used in a steam power plant is only a more feasible technology than bio gasifiers if above 1 MW, where gasifiers are more feasible below 1 MW. (Kjellström, et al., 2005) Therefore biomass generators are not seen as a feasible off-grid technology for rural electrification, as gasification, using the same fuel, is more feasible, as 1 MW is not considered suitable for village consumption.

4.8 Diesel generator

Diesel generators are already widely used in the developing world and is therefore a mature technology in this context. In India for irrigation pumps alone, an estimated 4 million diesel engines are installed. (Diesel Service and Supply, 2013)

A diesel generator is a diesel engine with an electric generator to create electricity. The engine generates mechanical energy by burning the diesel fuel, which then is turned to electrical energy by an alternator. The remaining components are service components to keep the system running or for user purposes. (Diesel Service and Supply, 2013)

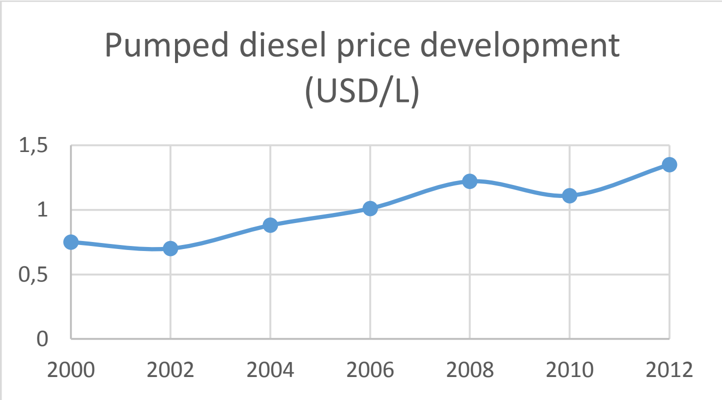
Since diesel generators do not cost much to keep as backup capacity it is often the cheapest and most obvious choice for backup capacity for RE systems, and could be used as such for other technologies mentioned here. (Kjellström, et al., 2005)

4.8.1 Potential in Uganda

The potential in Uganda is only limited to areas without access to diesel, which is considered as being very low or none.

4.8.2 Price development

Diesel generator is the only technology in this catalogue that has a fuel which cannot be produced locally and is affected to a severe extent by international prices. This is shown in the Ugandan diesel price development for the last 15 years:



Figur 3.6 (World Bank, 2015): Historical price development of pumped diesel prices in Uganda from 2000-2012 in US$/L, which shows fluctuating price trends and a raise of almost 100 %.

Another aspect of diesel is the transport costs, which can become high for certain regions. (Kjellström, et al., 2005)

4.8.3 Pros and cons of solution

+	-
Useful for productive use, as generation can fit consumption	High kWh costs due to fuel prices
Well known and used many places in Uganda	Uncertainty of fuel price development
	Dependency on foreign supply of fuel
	Health and climate impacts of burning of fuel

4.9 Grid extension

Grid extension is here understood as extending the national electricity grid to rural villages in order to give them access to modern electricity services, and not as a specific technology.

The distribution grid in Uganda is made up of 33 kV distribution lines connecting power plants with demand nodes, where a substation transforms the 33 kV into lower voltage for the households and smaller 240/440 V lines connect to the households. Which means distribution losses of 21.3 % (Bena, 2015)

The grid offers an unlimited amount of power for the consumer, which none of the other solutions do, as they have to be fitted to their consumption context. The issue regarding the grid, however, is that for various reasons, including old and unreliable power plants and grid infrastructure, it is not reliable and black outs are common, which is not expected to happen as much for off-grid solutions (Murphy, et al., 2014).

4.9.1 Potential in Uganda

The generation mix of grid electricity is 86.7 % large hydro, 3.4 % cogeneration bagasse power plant and 9.9 % thermal diesel power plants, (Ministry of Energy and Mineral Development, 2015) where large hydro has an expected further potential of more than 2,600 MW (Buchholz & Silva, 2010).

4.9.2 Pros and cons of solution

+	-
Unlimited amounts of power	Not always available, and thus not reliable

4.10 CONCLUSION

Several technologies are feasible for rural electrification of Uganda. Although some have different forces and might fit specific purposes better than others, the following solutions are found to be technologically feasible:

- Solar PV mini-grid
- Solar Home Systems[16]
- Hydro turbine mini-grid
- Bio gasifier mini-grid
- Diesel generator mini-grid
- Grid extension

Hydro power is technically feasible and a good solution as it does not necessarily require battery storage of fuel consumption. It is rather site specific however and has a small potential when looking at electrification on a national scale, which means that it alone cannot be used as a technology for rural electrification of all of Uganda.

Gasification has the advantage of consumers being able to produce fuels locally, which means less cost and being self-reliant compared to buying foreign fuels such as diesel for example. Gasification however, face technical implications as they are not able to accommodate 24 hour electricity consumption and need battery storage. Another aspect is that some gasifiers are not designed or built in the right material to withstand the environment of Uganda and are thus not fit for electrification purposes. Especially as there can be a long wait for new components to arrive.

SHS's are the best choice for individual solutions but not for villages and productive uses. They are therefore not compared to the other solutions, which are in mini-grid form, but could be used to bring access to electricity for the secluded rural households.

Diesel generator is a mature technology that has proven itself feasible in Uganda before, which does not need battery storage or similar. The negative aspect is that the burning and dependency of fossil fuels have several negative consequences, such as health impacts on consumers.

Solar PV is a more complicated system than the other mini-grids as it needs battery storage, which needs replacing several times through lifetime of technology. However, as long as the system is designed to accommodate consumption at all times, no technical issues have been found, and the solar resource is strong enough all over Uganda for implementation. The positive that separates solar PV from the other off-grid technologies is that it is modular and thus easy to meet future demand as PV modules and batteries can be added to the system. For the other solutions future consumption means reinvestment in a larger generator to meet demand.

Grid extension is the most used and well known solution in Uganda. It is the most feasible solution in ways of consumption as there is an unlimited amount of electricity available for consumers, although there are current issues with black outs and thus availability and reliability of power, at the same time making it the most unfeasible.

[16] For individual solutions only

One aspect of the above solutions being found feasible is that they are all possible from a technical point of view, however, as mentioned by Bjergegaard (2015), Miria (2015), and Abbo (2015), the largest issue regarding success of these solutions is the human factor behind it, due to among others lack of technical expertise, knowledge, infrastructure, and more. These human factors are general though, and does therefore not limit or exclude any specific technology.

As mentioned the above technologies are all feasible, however the technologies found most feasible are grid, diesel generators and solar PV.

The most technically feasible off-grid solutions are diesel generators and solar PV. From a more broad technology point of view however, solar PV is chosen as the most feasible due to being modular and as the dependency and negative consequences of burning fossil fuels makes diesel generators less attractive.

Grid is the main method of electrification in Uganda and has been so for decades, meaning the human factor behind it is more developed than that of the off-grid solutions, making it the most feasible technology.

5 FINANCIAL FEASIBILITY OF SOLUTIONS

The least-cost analysis answers the second sub-question by giving a LCOE kWh price for the different solutions, which makes them comparable and easy to highlight the most financially feasible one, based on the parameters of the analysis. These parameters are discussed in the first part of the chapter, and in the second part the calculations are presented.

5.1 POTENTIAL PARAMETERS FOR LCOE CALCULATION

Reality is seldom simple and for the analysis to be as realistic as possible, there are several potential parameters that could be included. These are discussed in the following.

5.1.1 CAPEX

CAPEX is the investment costs of the project. This includes replacement of components and is therefore not limited to initial investment.

5.1.2 OPEX

The OPEX for the different solutions can vary depending on their need. For example, solar PV has been found to have between 0.5 % - 1% of capital costs as OPEX in Ghana (Nässen, et al., 2002) where it is around 1.5 % of capital costs in Europe (European Commission, 2013). Other solutions have fuel use and might need more or less maintenance as well as operator skill and supervision, thus different salaries for the manager as well.

All OPEX costs in this analysis are kept as constants because future development and forecasting is deemed too uncertain and complicated to take into consideration. For example raises in operator salary or fuel costs. Sensitivity analyses are made however, to determine the potential impact variables could have.

5.1.3 DISCOUNT RATE

The discount rate is one of the most important parameters from the calculations, as it is a token of how future costs and benefits are valued compared to a current value. It is not technology specific and therefore constant for all technologies throughout the analysis. However, it is not an easy parameter to determine, as it varies from study to study, which is shown in the following:

- The World Bank use a social discount rate, which includes infrastructure and other public projects, between 10 and 12 % for developing nations (The Federal Reserve System, 2014).
- Levin and Thomas (2012) use a discount rate of 15 % for energy projects for the least developed nations.
- IRENA use a 10 % discount rate for their LCOE studies of global RE technologies (IRENA, 2012).
- Nässen et. al (2002) use a discount rate of 8 % for Ghana.
- Mahapatra and Dasappa (2012) use a discount rate of 12 % for India.

The discount rates mentioned above vary between 8-15 % - a 7 % point difference, which can have a big impact on analysis results. It is chosen to use an average discount rate of the above, which is 11 % and sensitivity analyses with lower and higher discount rates are done to test sensitivity.

5.1.4 GEOGRAPHY AND DEMOGRAPHY

Zvoleff et al (2009) state that geography can be an important parameter for the cost of bringing electricity to rural populations. Demography of villages and how the households spread, along with the distance between them, are especially important parameters as they have an effect on internal village grid length and thus investment cost. It is also expected that extending grid over swamp land, through dense forest and over mountains is costlier than extending over barren flat land. These, however, are locally defined parameters that are difficult to analyse on a national level, and therefore are limited from.

5.1.5 Internal village grid and penetration

Both Nässen, et al. (2002) and Parshall, et al. (2009) found that the length of the internal grid in a village connecting the households with the power plant or grid, as well as the percentage of households connected (penetration), have a large influence on costs and feasibility of the systems of the technologies used. However, as the internal low voltage transmission lines are expected to be the same for the village no matter choice of technology (Bena, 2015) (Mahapatra & Dasappa, 2012) this parameter is not taken into consideration as there is no expected difference for the technologies.

Penetration is also a large parameter and should be taken into consideration as it is the percentage of households connected, which affects consumption. This is only for determination of which villages should be electrified through grid or the least cost off-grid solution, due to the fact that demand node consumption, as a determining part of EDL[17], have an effect on feasibility of grid extension, but not LCOE. A study from Ghana found that it might be impossible to get a 100 % penetration in the poorer areas (Nässen, et al., 2002), but with the Uganda Rural Electricity Strategy and Plan 2013-2022 and SE4ALL goals as well as the research question of electrifying all of Uganda, a 100 % penetration has been decided. It has not been possible to find data on the penetration in Uganda. (Bena, 2015) Seeing as penetration is regarded as having a large impact on results as well as 100 % being potentially unattainable, a sensitivity analysis is done to show impacts of a different scenario.

5.1.6 Reliability and availability of electricity

Reliability and availability of power is an important parameter for the consumers, and society in general. A study (Burlando, 2010) on a month long blackout in Zanzibar in Tanzania showed that there was a large drop in household income of those whose work require electricity – with those using electric lights having 40 minutes less work per day and those using power tools with a 35 % drop in orders. The study even showed that children that had been exposed to the black out before birth, had a lower birth weight than the average. Other consequences of black outs can be lack of water pumping or vaccines and medicine deteriorating due to lack of cooling (Nässen, et al., 2002).

Although the case of Zanzibar is an entire month and for urban people who had been used to power, it shows the importance of reliability and availability of power. A field study to a solar mini-grid in Kasese in Western Uganda showed something similar as half the village was cut off from the mini-grid as a voltage line had been cut, and the consumers were upset about the missing power and pushed the manager for it to come back. (Field study to Kasese, 05.04.15)

Reliability and availability and the consequences of the lack of those is an issue that few take into consideration when calculating and modelling for choice of technologies for rural electrification (Murphy, et al., 2014). Mahapatra and Dasappa (2012) use three different hours of availability (6/8/12 hours) for the grid in their calculations regarding comparisons of different technologies for rural electrification, which shows a linear correlation between availability and EDL – thus EDL of 12 hours is twice of 6 hours. This fits the premise that grid electricity is cheaper per kWh, which means consumption has a large impact on EDL. However, these hours are not modelled to be fitting of peak hours of electricity or not, and in that way not fitting reality, where black outs can come and go for hours, which can make the need of the more stable off-grid solutions

[17] Scenarios with low population density along with low consumption favour off-grid solutions over centralised. (Levin & Thomas, 2012)

bigger (Murphy, et al., 2014). Murphy et al. (2014) found that the Uganda grid is down 10.7 times a month for an average of 10.1 hours a time (108 hours/month), giving an availability of 85 % of the time, thus having 15 % down time. It is expected that this differs from region to region, but the grid is in this report treated as the same everywhere for simplicity reasons.

Murphy et al. (2014) state that across Africa, and including Uganda, new electrical connections and capacity cannot follow the rapid population growth, as well as 25 % of installed capacity being vacant due to poor maintenance and aging power plants. They conclude that:

"In effect, the lack of access and reliable access means that in Uganda and much of Africa, it is not a choice between grid extension and DER (distributed energy resources), it is a choice between DER and building a new bulk grid from the bottom up" Quote (Murphy, et al., 2014, p. 2)

It is recognised that poor transmission line infrastructure through the country can have an effect on the new theoretical grid extension, however, the technologies are analysed solely through the view of the LCOE, which already includes lifetime value, and deteriorating existing infrastructure is therefore not taken into consideration.

Although more realistic, modelling and calculating the impact of the unsystematic black outs is beyond this analysis and therefore the 85 % availability is monetised and added to the costs of grid prices, which is done to better compare the grid with the off-grid solutions that are less likely to have black outs (Nässen, et al., 2002). It is problematic to assess the monetary value of electricity downtime as it has a large human impact (Field study to Kasese, 05.04.15) and presumably an impact on local and therefore national economy. It is chosen to look at the costs of the local community through current willingness to invest in back up diesel generator capacity, to which the costs of those can be added to the grid costs. The premise is that the current level of downtime has enough of an economic impact on local people that a certain percentage have invested in backup capacity thus suggesting the financial impact of downtime. This is done through a survey of CREEC staff with field experience (see appendix B). The idea being that with their experience in the field they have an understanding of who and how many in rural electrified areas have invested in backup capacity. Although these are estimates and not concrete surveys of villages, which would be more precise, it is considered acceptable for the purpose of the project, and the time spent on village surveys not efficient compared to the output. Quantification and monetisation of social aspects of downtime has not been as it is deemed too difficult and uncertain.

The output of the survey is that only business owners have backup capacity, as these are bought only when it can pay to have one from a business point of view, i.e. when benefits become higher than costs, and not for convenience. It is expected that no more than 5 % of business owners have invested in backup capacity.

5.1.7 Grid extension and voltage lines

The big difference between grid extension and off-grid solutions is the extra cost from putting down the grid, thus adding a per km price on top of the kWh LCOE price (Mahapatra & Dasappa, 2012). The cost of these include 11 kV and/or 33 kV lines and an 11 kV substation (Mahapatra & Dasappa, 2012) as well as transformers, and poles (Parshall, et al., 2009).

Transmission and distribution losses of grid has an impact on costs of grid generation (Mahapatra & Dasappa, 2012). In Uganda there is a transmission loss of 4 % and a distribution loss of 21.3 % giving a total of 25.3 % grid loss. (Bena, 2015)

5.1.8 Lifetime of project or technology

The lifetime of the LCOE is important as it impacts costs, due to both the discount rate and OPEX costs. For this analysis the issue is whether to choose lifetime of technology or lifetime of project. For example, a solar PV system has an expected lifetime of approximately 25 years, whereas the SE4ALL goal of universal electricity access is 2030, which is a project lifetime of 15 years. Since solar PV has high CAPEX but low OPEX compared to diesel generators which are opposite, solar PV's financial break-even point with diesel generators is dependent on a certain amount of years before the larger OPEX of diesel becomes costlier than the high CAPEX of solar. This means that the more years available up until solar PV's lifetime the better for this technology, compared to diesel generators.

Deciding on a project lifetime or technical lifetime is depending on approach and worldview on electrification of Uganda. If a project lifetime is chosen, the technologies chosen resulting from the analysis will show the cheapest solution to electrifying Uganda within a political end goal, whereas a technical lifetime will show the cheapest way to electrify Uganda in the long term future, not taking political goals into account. The project lifetime would show the cheapest way to electrify Uganda the quickest (within the project period) whereas technical lifetime shows the cheapest possible way to electrify Uganda over time.

Although it is decided to look at the analysis as an overnight project, investment-wise, it is also recognised that the electrification of Uganda will not happen that way, and might take several decades. Therefore it is considered that using technical lifetimes is more appropriate than project lifetime which, however, imply more of an overnight implementation.

5.1.9 Decommission costs and salvage value

Although it is recognised that decommission costs and salvage value can have an effect on the outcome of the analysis and are present in reality, they are not considered in this report, as the insecurity of what these values could be is high. Since the off-grid solutions are currently underutilised it is not expected that there has been much decommissioning or salvaging done, and therefore data on this would be very difficult to find.

5.1.10 Average numbers and baseline year

Although there are different potentials for RE sources in different regions, especially solar, averages for Uganda are used. This is also done as it is a national analysis and the benefit of doing regional analyses is not regarded as being higher than the resources spent on it. It is the same for labour and transportation costs, which are expected to differ from region to region, but are not treated as such, as an average is used.

As data is difficult to find in Uganda, and some of the data found is not from the same years, a baseline year has been decided and data older than that year has been attempted to correspond the baseline year by correcting it, including applying inflation rates. The baseline year for this report is 2015.

5.1.11 Inflation

Due to the unstable inflation rate of the Ugandan Shilling, with current annual inflation of 6.2 %, it is chosen to keep all costs in euros. On the 11th of June 2015 the exchange rate was 1 euro = 3.555,71 Uganda Shillings, which will be used throughout the report. (XE, 2015)

5.2 LCOE costs of solutions

The above was a discussion of which parameters to include in the LCOE calculations. In this part the parameters are implemented in the LCOE calculations and the LCOE values are given.

Unless otherwise stated the data for the different calculations are gathered in appendix B. This is done to minimize the amount of numbers in the chapter for easier overview of how the calculations have been done and the reasoning behind the choices made for them.

All LCOE's are calculated according to the consumption that comes from the equivalent peak consumption of the peak generation. Therefore, the LOCE of a diesel generator, for example, is calculated according to the expected consumption according to the generators peak generation and not the highest possible generation. I.e. a 50 kW peak consumption according to the load profile of 3.2 "Rural electricity consumption" is 440 kWh/day, which is notably less than the total kWh the generator can generate if run 24 hours on full capacity, and thus a different LCOE.

As only few off-grid village size solutions have been installed before, several factors and numbers have not been possible to find. Therefore some of these are based on estimates. Where this is done, it is explained. For example operator salary for diesel generators is not available data, so the one from gasification has been used.

5.2.1 Grid extension

As mentioned earlier, where the other solutions only have LCOE for generation, grid extension also has a lifetime cost for the distance of extending the distribution grid. Therefore the LCOE of generation is first considered here, and then the cost of extending the grid.

Generation costs

Determining the LCOE of generation for grid electricity is difficult as a specific amount of generated kWh cannot be determined along with salaries and reinvestment in power plants. The only option is to make LCOE calculations for an average power plant or make several LCOE calculations for different power plants, thus finding an average LCOE value. This has not been possible to find data for, so the second best option is considered to be to look at the price the transmission company (Uganda Electricity Transmission Company Ltd. (UETCL)) sells the electricity for to the distribution companies. It is considered that that price is, if not close to, then higher than the LCOE of grid generated electricity. This is because it is expected that the power plants generating the electricity and UETCL selling it to be distributed are interested in making profits, which means that the current price of electricity should be above the LCOE, as there would otherwise not be any profits. This also means that various OPEX costs are included in the above price as well as the 4 % transmission loss is accounted for. Not calculating the value is expected to have some implication for the comparison of grid extension against the off-grid solutions as there is a margin of error due to no knowledge of which factors are applied, such as discount rate for example.

The price is somewhat fluctuating, but besides 3rd and 4th quarter of 2013 it has been between 220-230 UGX/kWh since the start of 2013. The price in 2nd quarter of 2015 is 226.1 UGX/kWh (0.063 Euro/kWh). (Electricity Regulatory Authority, 2015)

However, there are still some factors that have to be taken into consideration regarding the LCOE of grid generation. These being distribution grid loss and availability and reliability of the grid.

Grid loss has an impact on how much electricity reaches the end user, and thus makes it more expensive because more has to be produced. The distribution loss in Uganda is 21.3 % (Bena, 2015) and therefore these extra costs are factored in by adding 21.3 % to the kWh price.

The other aspect is the reliability and availability of grid. As mentioned in 4.1 "Potential parameters for LCOE calculation" 5 % of commercial consumption from LCOE costs of diesel generators are added to the LCOE costs of grid to show the monetary effect lack of reliability has on local communities. It shows, however, that the monetisation of reliability and availability is not notable as commercial consumption makes out 26.5 % of total consumption and 5 % of this cost is 0.002 Euro/kWh.

Although diesel power plants generate 9.9 % of annual grid electricity (Ministry of Energy and Mineral Development, 2015), external costs are not taken into consideration as large diesel power plants are not expected to be as close to the population as diesel generators are, as well as having better filters for cleaning smoke.

This gives a LCOE of grid electricity of 0.078 Euro/kWh.

Grid extension costs
Calculating LCOE of grid extension is easier as it can be broken down to an initial km cost of grid along with component replacement and general maintenance. Besides the installation price per km no data has been found, however. For that reason 1 % of initial investment is used for maintenance costs, as they are higher than 0 but it is not known how much.

There is also a 10,150 Euro cost for a substation, however as only 68 of these were installed in Uganda in 2011 for a total distribution line length of nearly 15,000 km (GIS sources 1 and 2) it is considered that the cost of these for the total grid line length is not notable as well as it would be difficult to assess the relationship between km and kWh price along with substation costs and is therefore limited from.

5.2.2 Solar PV

The LCOE of Solar PV is based on two different projects in Uganda. One in a village near Kampala from TASS (15 kW) and one on Kalanga Island (10 kW). (Appendix B)

CAPEX includes initial investment as well as replacement of components. These being batteries, inverter and charge controller.

OPEX includes maintenance and operator salary. Operator salary is based on that of Kayanja, which is 100.000 UGX/month (27.8 euro/month). This is because once the system is set up it runs by itself without much supervision, and thus not a high expertise is needed. If something breaks it is regarded to be cheaper to call a technician than having one supervise the system daily. As none of the projects give maintenance costs it is decided to use the average of 1 % of initial investment cost, as mentioned in 4.1 “Potential parameters for LCOE calculation”.

A lifetime of 25 years is chosen as that is the lifetime of the solar panels.

As there are nothing but estimates for the generation of solar power, it is decided to use the modelled mini-grid to determine the output of the two systems according to their individual peak capacities. Due to several internal losses, storage among others, generation is at 65.8 % of peak capacity.

One issue with the data from the 15 kW system is that installation costs cannot be broken down and therefore include internal village grid, which means it is not limited to installation costs of system only. Installation costs include components such as alarm, fence, junction boxes, cables, fuses, temperature controls and more. Another aspect is that the specific area of the solar system is very large and hence also costlier installation. (Parekh, 2015) As this cost alone makes out 42.35% of initial investment it is decided to make an estimation on how much is used for installation of system only. It is decided that 20 % of installation costs are used for the system only.

The calculation for solar PV mini-grid systems is thus:

$$\frac{\sum_{t=0}^{25} \frac{CAPEX(Battery, inverter, charge\ controller)_t + OPEX(operator\ salary, maintenance)_t}{(1+0.11)^t}}{\sum_{t=0}^{25} Annual\ electricity\ consumption}$$

This gives a LCOE of 0.205 euro/kWh (15 kW) and 0.073 euro/kWh (10 kW) giving an average LCOE for solar PV mini-grid systems of 0.139 euro/kWh.

5.2.3 Hydro

The LCOE of hydro power is based on two hydro power projects in Uganda. One 64 kW system in Bwindi and a 20 kW Suam. (GIZ, 2012) (GIZ, 2012)

CAPEX includes initial investment as well as replacement of components. These being civil structures, alternator and generator.

OPEX includes operator salaries as well as maintenance costs.

As the hydro power plants have a somewhat steady and no-cost production they can produce more power than is actually needed, which is unique compared to the other technologies that either have fuel use or batteries as a constricting factor. They generate 245.9 MWh and 122.6 MWh on an annual basis, respectively. However, if these values are used to calculate LCOE they give the cost of produced electricity and not the cost of consumed electricity. As the excess electricity would otherwise not be consumed in a completely off-grid setting[18], it is considered to be an advantage to hydro power, which would not be seen in a real life scenario. Instead the expected consumption of villages with peak consumption fitting the power plants are used to calculate the LCOE.

A lifetime of 25 years is also chosen for hydro.

$$\frac{\sum_{t=0}^{25} \frac{CAPEX(civil\ structures, generator)_t + OPEX(operator\ salary, maintenance)_t}{(1+0.11)^t}}{\sum_{t=0}^{25} Annual\ electricity\ consumption}$$

This gives a LCOE of 0.093 euro/kWh (64 kW) and 0.232 euro/kWh (20 kW) giving an average LCOE for hydro power mini-grid systems of 0.162 euro/kWh.

5.2.4 Bio gasification

Bio gasification LCOE is based on two systems. One of them a 10 kW system that has been attempted implemented by CREEC several times, but has failed. Among other reasons due to not fitting the climate or environment of Uganda (Miria, 2015). The other system is a 32 kW system installed in Muduuma. As mentioned in 3.6 “Bio gasifier” the systems cannot run continuously for 24 hours and therefore need battery storage capacity. This is modelled as a system (see appendix A) and storage costs are added to LCOE costs of the gasifiers, which does make the LCOE more theoretical, as batteries are not originally part of either of the two systems. However, to overcome this issue, battery costs from the solar LCOE’s are used, as they are costs of implanted projects, albeit solar PV and not gasification.

[18] If the mini-grid were to have customers with the same theoretical demand as the rural load profile then all generation above the consumed electricity would be wasted. This is because the system is seen as an island system, where the only consumers are the ones in the demand node, having the same consumption pattern. In a larger grid where all generated electricity could be consumed hydro power would be the cheapest solution, but not for the scenario of an island system.

CAPEX for the bio gasification system includes battery storage replacement every five years.

OPEX includes fuel costs, maintenance and operator salary.

The operator salary (including medical bills, accommodation and meals) for the 32 kW system is 194 Euro/month (700,000 UGX) for two operators, which is also applied for the 10 kW system.

Monthly maintenance is based on a CREEC report (Miria, 2014) on the GEK 10 kW gasifier with specific components and smaller fuels needed for good service of the gasifier. This is also applied for the 32 kW system with a factor three as it is three times larger.

Finding a cost of fuel is especially difficult as different sources of biomass have different prices, different means of processing, and different amounts of biomass needed to generate a kWh. (Miria, 2015) However, for the 32 kW gasifier the fuel cost is 0.02 Euro/kWh, which is also applied to the 10 kW gasifier.

As it has not been possible to find fuel consumption for different loads of the gasifiers, they are treated as running on average kWh costs and not specific costs correlating to specific demand. As fuel costs are low this is not expected to have a notable impact on overall LCOE.

Gas production is severely dependent on operating temperature and quality of biomass, as well as other parameters, some of these being controllable by the operator, and some of them not. Therefore it is not possible to reach the 10 kW capacity as the quality of gas is not high enough. For the 10 kW gasifier the maximum runtime capacity is 65 %. The 32 kW gasifier has similar issues and the 65 % is also applied here. (Miria, 2015)

Lifetime of gasifiers is dependent on the material they are made of, operating conditions, and running hours, and thus varies, but it should be a minimum of 5-10 years (Miria, 2015). For this calculation 10 years are used.

The annual consumption is based on the modelled consumption fitting the sizes of the two gasifiers. For further detail see appendix A.

$$\frac{\sum_{t=0}^{10} \frac{CAPEX(batteries)_t + OPEX(operator\ salary, maintenance\ cost, fuel\ cost)_t}{(1+0.11)^t}}{\sum_{t=0}^{10} Annual\ electricity\ consumption}$$

This gives a LCOE of 0.266 euro/kWh (10 kW) and 0.129 euro/kWh (32 kW) giving an average LCOE for gasification mini-grid systems of 0.197 euro/kWh.

5.2.5 Diesel generator

The diesel generator is based on a single case of a 50 kW diesel generator. It is not an implemented generator from a real life scenario, but a procurement offer along with theoretical details on expected runtime. This is considered acceptable due to the local knowledge and experience with this specific technology being higher than the other solutions.

CAPEX for the diesel generator system is limited to a single initial investment only. This means there is no component replacement as the generator system has the included components installed within the generator. Therefore these are expected to be part of maintenance costs.

OPEX is large for diesel generators as it includes several factors. These being maintenance, operator salary, fuel costs and external health costs. All these being explained below.

For maintenance, Intelligent Energy (2012), state that for a case of an 8 kW diesel generator running 8 hours a day it is 1.55 Euro/day. The larger size and runtime of the 50 kW diesel generator is factored in to that cost as the 50 kW generator is 6.25 times larger and runs for 3 times as long.

No data has been found on operator salary but it is set to be 194 Euro/month (700,000 UGX/month) (the same level as the gasifier) as the generator system needs a certain level of maintenance and servicing for a longer lifetime (Kyalimpa, 2015).

The price of electricity is based on the modelling of diesel mini-grid as to find the expected costs of fuel consumption for different demands, as they vary. This is also due to the diesel generator being able to meet consumption at all times, therefore its annual production being equal to consumption, which is decided by the rural consumption and load profile found in 3.2 "Rural electricity consumption". A 50 kW diesel generator will thus fit the exact consumption of 50 kW peak. Fuel costs however, is not a constant litre/load but varies dependent on load, which is part of the modelling, where the fuel costs are in intervals. For further detail see appendix A.

There are sources for diesel prices in Uganda however, these do not compare with the actual prices noticed in Uganda between July 2014 – July 2015, and are therefore not used. As there are no sources stating the actual average diesel fuel price, the ones noticed in the above time span are applied. They vary between 2900 UGX/litre – 3300 UGX/litre, but it is regarded that the most common value was 3100 UGX/litre (0.863 Euro/litre), which is used in the analysis.

A special cost for the diesel generator system is the external cost of health. This is applied as burning diesel in a generator in a village has potential impacts on the health of the local villagers.

Wijaya and Limmeechokchai (2010) state that there are three emissions from diesel generators that have potential health effects (NO_x, SO_2, and Particle Matter 10 (PM_{10})) and CO_2 which damages climate. The costs coming from the European Union ExternE project, pricing external costs of energy generation (ExternE, 2014), and the kg/kWh values are from Wijaya and Limmeechokchai (2010) on an Indonesian study.

As pricing differences of health issues in different countries are expected not to be found in exchange rates, GDP per capita (Power Purchase Parity) of the European Union and Uganda are used to create a factor to better show the applicability of the ExternE external health costs of diesel in Uganda. The factor is 0.047 based on 2014 estimates for 1,800 USD (Uganda) and 38,300 USD (European Union) (CIA, 2014).

	Kg/kWh	Euro/kg	Annual external cost (Euro)
NOx	0.0086	9.1	594
SO2	0.002	12.2	185
PM10	0.0003	58.1	142
CO2	0.772	0.019	110

Table 4.1: Overview of annual external costs for diesel generators

Table 4.1 shows that the annual health and climate costs are not very high, which is due to the factorisation with the large difference in GDP/capita between Europe and Uganda (a factor of nearly 20), as they would otherwise be 22 thousand Euro's.

If maintained and serviced well, the diesel generator has an approximate lifetime of 20 years. (Kyalimpa, 2015)

$$\frac{\sum_{t=0}^{20} \frac{CAPEX_t + OPEX(operator\ salary, maintenance\ cost, fuel\ cost, external\ cost)_t}{(1+0.11)^t}}{\sum_{t=0}^{20} Annual\ electricity\ consumption}$$

This gives an LCOE of 0.143 Euro/kWh.

5.3 Conclusion

Looking at the below table 4.2 it shows that diesel generators is the off-grid solution with the lowest cost by far, with a distance of 0.021 to the second cheapest off-grid solution (hydro power). Grid electricity is still the solution with the lowest cost at almost half the cost of diesel generators. The off-grid technology chosen as the technologically most feasible (solar PV) is the off-grid solution with the third lowest cost – 0.027 more costly than diesel generators.

Solution	**Euro/kWh**	**Euro/m**
Grid	0.078	23.01
Solar PV	0.170	
Diesel generator	0.143	
Hydro power	0.162	
Gasification	0.197	

Table 4.2: Overview of LCOE's for the different solutions

One questionable aspect of the grid electricity however, is that it is not a calculated LCOE like the other solutions, but the price sold by UETL to distribution companies, accepted as LCOE, under the premise that it is not a higher cost than the LCOE as generation and transmission companies want to make a profit. However, this makes the grid cost more vulnerable compared to the off-grid solutions as for example discount rate has no effect on it. It is thus deemed that the cost of grid electricity is lower than what is shown above, thus making grid more feasible. However, as no other data gives a more precise kWh cost for grid, the above is accepted.

The calculation method and choices made about parameters and off-grid aspects are key components in the findings and another view on these could radically change those. The LCOE of gasification is the highest, for example, due to the extra battery storage. However, the LCOE for gasification in a theoretical scenario of running 24 hours, meeting demand at all times, is 0.099 Euro/kWh, making it the least-cost off-grid solution. The same goes for hydro power when looking at kWh costs of generation and not consumption, which means in a theoretical scenario where every possible kWh produced by hydro power is consumed, the LCOE is also 0.099 Euro/kWh. This is not taken into account as those scenarios do not compute with the findings of the report, however, it shows the difference in LCOE's calculation choices mean for this analysis.

6 NATIONAL ELECTRIFICATION

With the findings of the analyses of the most feasible solution technologically and financially the last sub-question is answered in this chapter through discussing which off-grid solution is the most feasible overall, which is then used along with costs of grid extension in a GIS to show which demand nodes should be electrified through which of the two solutions.

6.1.1 CHOICE OF MOST FEASIBLE OFF-GRID SOLUTION

From the findings of the Chapter 3 “Technology catalogue”, the most feasible technologies for rural electrification were solar PV, diesel generators and grid extension, with grid extension being the most feasible of the three. This among others, is due to human factors of larger technical capacity in the country compared to the off-grid solutions, as well as potentially unlimited power for consumers, where off-grid solutions are limited by installed capacity. One large downside however, is that the grid at its current state is not as reliable as the off-grid solutions and thus the potentially unlimited power is not always available.

Therefore, when determining EDL and which demand nodes should be electrified through which solution, the next step is to choose the most feasible off-grid solution to be compared with grid.

Through the financial analysis it is concluded that diesel generator has the lowest LCOE cost of all the off-grid solutions. As such it is 16 % lower than that of solar PV. Testing the difference on EDL (explained in later in this chapter) the effect on price difference is 8.7 % after a payback period of 10 years and 6.1 % after 20 years[19]. Therefore the impact the price difference has on national electrification is not large.

The conclusions from the technology analysis is that diesel generators work fine technically, however there are some potential issues regarding price change in diesel prices (elaborated on in Chapter 7 “Sensitivity analysis”) as diesel prices have risen approximately 100 % within the last 12 years, and a similar trend the next 12 years would have a large impact on financial feasibility. Another aspect is that diesel generators are not modular, and as such cannot be expanded to fit future consumption. In other words this means that a diesel generator that fits current consumption of a demand node will not be able to accommodate the near future rise in consumption[20], which is general for all off-grid solutions, but since it is not modular and entire new generator has to be installed every time consumption rises. Solar PV does not have the same issue as it is modular and thus easy to add to installed capacity for both storage and generation. Another positive aspect is that there is no fuel and the solar mini-grid is thus easy to maintain. Due to the negative technology consequences of diesel generators and the positive consequences of solar PV, together with the fact that the impact of difference in LCOE is minor, solar PV is chosen as the most feasible off-grid solution.

A theoretical bonus of solar PV being modular and thus possible to incrementally accommodate rising consumption without major reinvestment is that demand nodes can be electrified through an off-grid solution while waiting for grid extension to arrive, as grid is still better given the unlimited consumption possibility. Grid extension is also inevitable for most demand nodes as an implemented grid extension, as mentioned in 2.5 “Project understanding of rural electrification”, would mean a new EDL and thus shorter distance to the new grid, complemented by demand nodes having higher consumption due to a rise in population. Using this approach demand nodes, initially too far away from the grid, can have access to

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[19] Solar PV 20 years payback period has 36931 demand nodes electrified through grid and Diesel Generator 20 years payback period has 34675 – a difference of 2250 or 6.1 %.Solar PV 10 years payback period has 32038 demand nodes electrified through grid and Diesel Generator 10 years payback period has 29246 – a difference of 2800 or 8.7 %
[20] Regarded here as population growth

electricity until the grid arrives, and as the demand node gets connected to the grid so does the installed solar capacity, which can be used to generate power for the national grid, and other close demand nodes.

6.1.2 EDL APPLIED

With the above off-grid solution found, the next step is to apply it and calculate the most feasible electrification form for all the demand nodes.

As mentioned in 2.4 “GIS method” the EDL is when overall costs of consumption and km extension of grid electricity are lower than overall costs of consumption for off-grid solutions. With distance from demand node to grid along with demand node consumption (in form of demand node population and rural consumption per capita from 3.2 “Rural electricity consumption”), and the costs of grid electricity and solar PV, the EDL can be calculated for all village sized demand nodes in Uganda. The method for the GIS can be seen in appendix A, and the sources are GIS sources 1 and 3, which can be found in the bibliography.

However, the per capita consumption is on a monthly basis, and a 100 % electrification scenario of Uganda, although seen as an overnight investment, cannot be decided on initial consumption alone, as the ratio between grid extension and off-grid solutions is determined by overall consumption, as well as electrification form being a long term choice. This means that as total demand node consumption grows, grid extension becomes more feasible, and a payback period is necessary to decide on for a limit of consumption and which demand nodes should be electrified through which solution. Otherwise total consumption is not limited and will continue to grow, eventually resulting in all demand nodes being electrified through grid extension. The off-grid solution is therefore always the least-cost option until a certain point of consumption due to the high cost of extending the grid. With a chosen payback period, the GIS shows feasibility of electrification form after the payback period for demand nodes, i.e. for a 20 year payback period the GIS shows which demand nodes are feasible to extend the grid for after a 20 year period, given an overnight investment. In other words it shows which demand nodes are feasible for grid extension from a here-and-now point of view, although not necessarily paid back until after 20 years.

For this, different years can be used to show total consumption. With a monthly per capita consumption of 12.7 kWh, which gives:

Year	**Per capita annual consumption in kWh**
1	145
5	724
10	1448
20	2896

Together with the payback period consumption, the EDL can be calculated for the different demand nodes. For example, the costs of electrifying a demand node that is 13.3 km away from the grid and has a population of 1,275 with a 20 year payback period are:

Grid extension: $0.078\frac{Euro}{kwh} \cdot 1{,}275\ inhabitants \cdot 2{,}896\ kWh/inhabitant + 23\frac{Euro}{m} \cdot 13{,}357 = 596{,}803\ Euro$

Solar PV: $0.170\frac{Euro}{kWh} \cdot 1275\ inhabitants \cdot 2{,}896\ kWh/inhabitant = 628{,}097\ \ Euro$

For this example grid extension has the lowest cost of electrification and should thus be chosen over solar PV.

The payback periods have a substantial impact on feasibility of grid extension as the following shows, starting with 1 year and ending with 20:

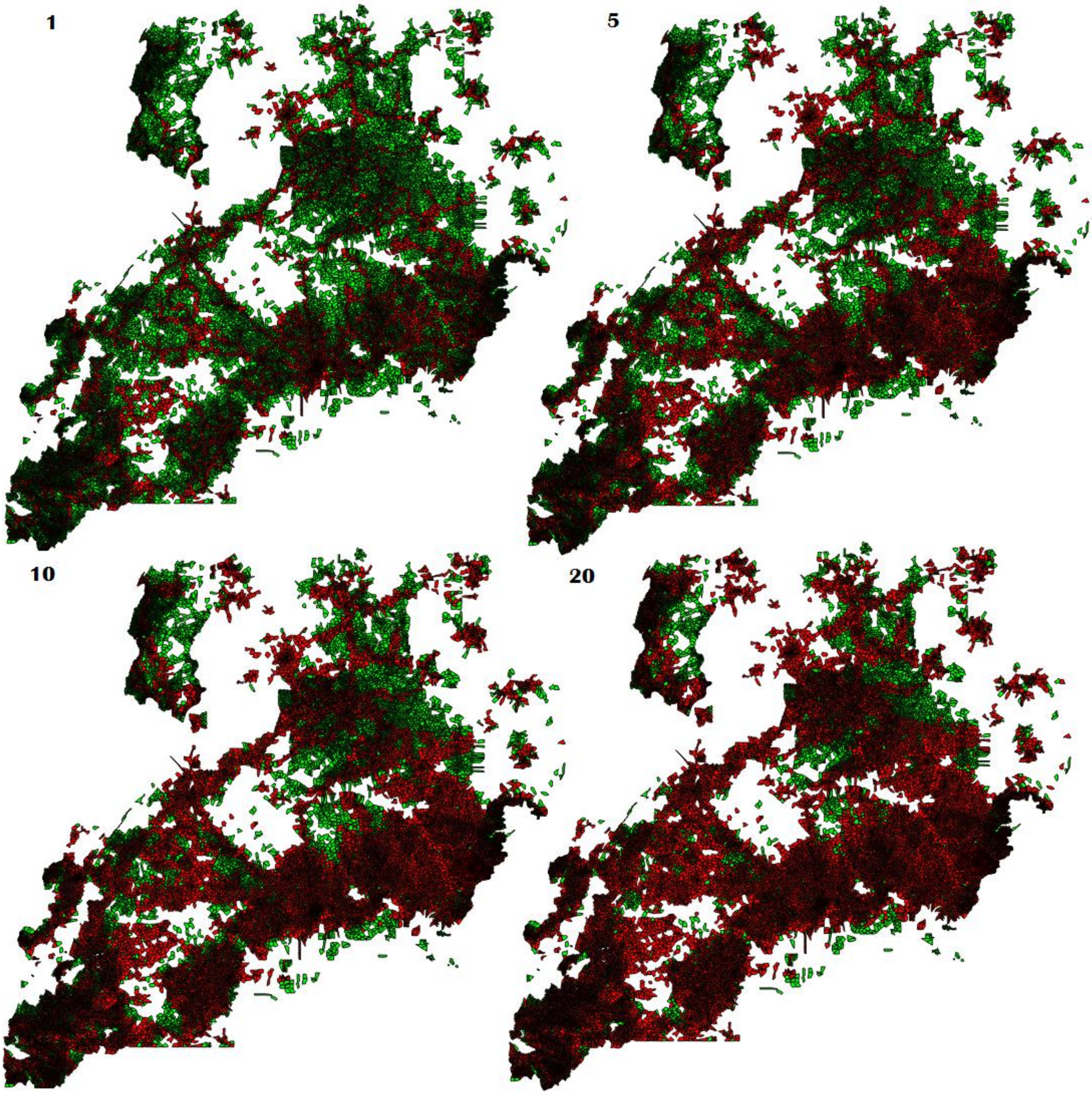


Figure 6.1: The red demand nodes are electrified through grid extension and the green through solar PV. In order from 1 year payback period to 20 years.

The first GIS with a payback period of 1 year shows that only the demand nodes in close proximity to the existing grid are electrified through grid, whereas the rest are through solar PV. As the payback periods rise so do the amount of demand nodes that are electrified through grid extension. As electrification form is a long term choice and investment, since it takes time before grid extension becomes feasible, it is deemed that either 10 or 20 year payback periods are the most feasible. There is no ultimate choice regarding payback period, however, as that depends on the needs of policy and decision makers regarding rural electrification of Uganda. The above simply shows the development of feasibility.

There are a few islands who are set as having grid extension. As mentioned earlier in 5.1 “Potential parameters for LCOE“ geographical aspects are not taken into consideration for the analysis, although these islands should probably not be electrified through grid extension as it is expected that grid extension over water is costlier than over land.

Looking at the number of grid electrified demand nodes being more feasible per year of consumption, it shows a non-linear trend. For the 20 year payback period it showed that 15,000 more demand nodes were electrified through grid extension from year 1 to 10 but only 5,000 more were electrified through grid extension from year 10 to 20. Below is shown the annual payback period development of grid electrified and solar PV electrified demand nodes.

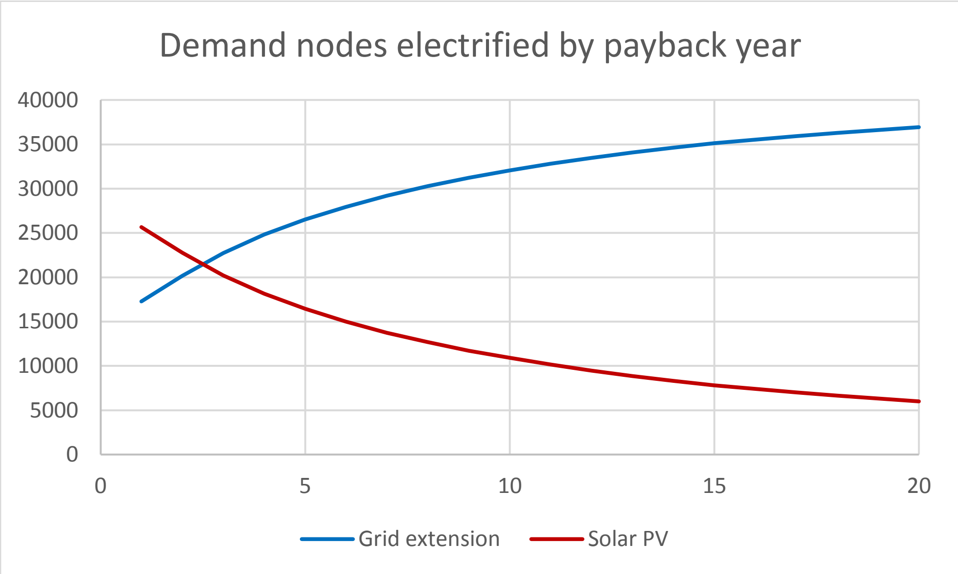


Figure 6.2: Number of demand nodes per payback year being electrified by grid is an exponential decline

The decline in annual grid electrified demand nodes per payback year is expected to be because the demand nodes which are further away from the grid, are those that need a higher consumption to be grid electrified. Thus the higher consumption needed, the longer away from the grid, and the longer away from the grid, the higher costs, which shows as an exponential decline. This also shows that distance to grid is a more determining factor than consumption as the years with many grid extension demand nodes are those were the demand nodes close to the grid change from off-grid to grid. The opposite goes for the ones far away from the grid where annual connections for year 20 are less than 20 % of year 1, as they are further away from the grid and it takes a higher consumption to reach those demand nodes.

This also shows when comparing grid extension costs with the kWh costs. Taking the EDL equation of $0.078X + 23Y < 0.170X$ (X being kWh and Y being meter), and isolating Y gives an EDL kWh/m cost of 251, meaning that the relationship between consumption and distance is 251 kWh/m. If this number is compared to consumption to find necessary demand node population it gives the following:

Payback period	People in demand node/km
1	1,733
5	347

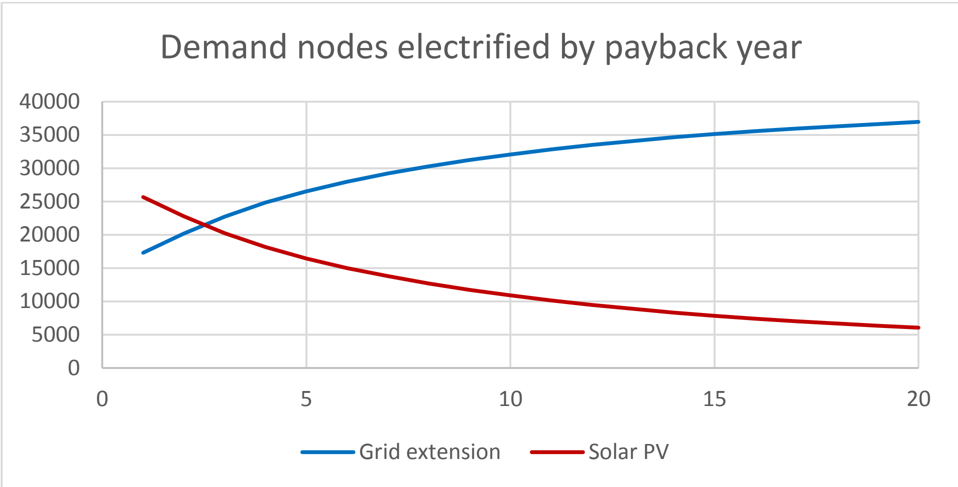
10	173
20	87

This shows why very few demand nodes outside of grid vicinity are electrified through grid extension for year 1. The same goes for year 20 as a demand node 10 km away still need a population of 870 people.

6.2 Conclusion

With the data available in GIS, EDL is possible to calculate for all demand nodes, thus determining which electrification form they should have. This however, is also determined by the overall consumption costs of demand nodes, which is difficult to assess as it changes per year with more kWh consumed. Therefore a payback period in form of total consumption by payback year is necessary. This payback period shows grid extension feasibility of a here-and-now investment in the time span of the payback period. As investments in electricity infrastructure is a long term investment the recommendation is that payback periods should be between 10 and 20 years. Nevertheless there is no final payback period and it is up to whichever agency, authority or NGO looking at rural electrification to choose the one best fitting their agenda.

It shows that the correlation between payback periods and number of demand nodes electrified through grid extension is not steady, but shows an exponential decline, as can be seen below.



This is expected to be because distance is a more determining cost factor than consumption. Thus the further demand nodes are away from the grid the higher their consumption has to be to cover the large rise in costs due to the km cost of extension. Therefore the demand nodes being electrified through grid in the later payback periods are those the furthest away from the grid, whereas the ones in the first years are the ones close to the grid, where costs of grid electrification is low. This also shows in the aspect of the EDL equation of $0.078X + 23Y < 0.170X$ (X being kWh and Y being meter), where the relation between distance and consumption shows as 251 kWh/m for a break-even point. A demand node 10 km away thus needs a total consumption of 2,510 kWh before grid extension is feasible. Looking at demand node population needed to accommodate the kWh/m EDL it also shows a large population necessary before grid extension becomes more feasible than off-grid solutions.

Payback period	**People in demand node/km**
1	1,733
5	347
10	173

20	87

7 Discussion of results

With results of analyses found, used to answer sub-questions and research question, it is chosen to look at those results from a more critical point of view as well as discuss them. This is done by discussing the reliability and validity of findings and then testing them through sensitivity analysis to assess how sensitive the findings are.

7.1 Reliability and validity

For data and analyses, reliability and validity are both important factors. Reliability means that the same output of a survey for example, would be found by repeating the data gathering method, either by the same or a different scientist – thus the data is reliable when it is not easily affected by repetition, showing that it is not dependent on changeable factors, and is not a specific one-time data-set. Where reliability is how reliable and sturdy data is in a scientific way, validity is how close the output is to reality, meaning that high validity shows a conclusion that is close to how it is in real life. Although data is reliable, analyses and conclusions can still be wrong if data is not used correctly, thus validity is important. (Andersen & Andersen, 1994)

7.1.1 Reliability and validity of data and findings

As mentioned in the data gathering section, retrieving good quality data in Uganda is difficult and this is also expected to have an impact on the validity of results. Internally the project and its findings are thought to be matching and correct, but as most of the data is most likely not representative of how aspects such as costs and consumption, for example, are in reality, it is possible that the results of the different analyses are not representative, and thus valid, either.

There are several qualitative sources in technology catalogue that state the same and overall it is regarded as having high reliability and validity, although it is seen as possible to find an expert who might have a different view on a specific technology.

The data from the demand profile are found through a sample of 5 households, one coffee factory and average village and trading centre data from a governmental master plan. This means that the validity is questionable, as the sample above is not expected to be fully representative for the population.

As the data used in the financial analysis are costs of actual projects, these should not change, and the reliability of this data is therefore decent. The validity however, is somewhat questionable as few sources are used for a national average, as no further larger study has been carried out in this field. Those that have been carried out and are somewhat applicable are based on assumptions and procurement prices, but not on costs of implemented projects, as there are few in Uganda (Bena, 2015). The choice of using costs of real projects is chosen in order to heighten the validity of the findings, as these are the actual costs that one are likely to encounter when applying the different solutions in reality. Therefore it is expected that the validity of attainable data is low (seen from a national average point of view) but higher than it would be to use theoretical procurement data. It is hard to find good data, and especially for the off-grid solutions as there are not many implemented, and of those that are even fewer are publicly known. This is best exemplified with financial data on diesel generators where, on a list of 11 possible companies selling generators, six were found usable and contacted, and one accepted to provide the data (although only on one generator). Even the Rural Electrification Agency has not yet heard of a fully well-functioning solar PV mini-grid in Uganda and know of but a handful of other implemented off-grid projects. As Bjergegaard (2015) and Abbo (2015) also mention, this is because off-grid solutions in Uganda are in the early stages of a technological transition – as such the oldest off-grid solutions found in appendix B are the two hydro power projects from 2012.

Had the research question been about whether one solution was better than one other, conservative estimates could have been used, and uncertainty of quality of data would thus be minimised. Unfortunately this is not possible for this report as all the solutions are compared to each other on an equal level, thus meaning that one is not inherently better or worse than another.

Quality of data is not the only issue regarding data however, as much time, and much more than initially expected, has been spend on retrieving the data found in appendix B. This also limits how much data can be retrieved as more data might have been possible to find, had it not been so time consuming.

Due to the potential low reliability and validity of data, which can have an effect on findings, sensitivity analyses are carried out. This is done to test findings and see how sensitive they are to changes of different factors. If the overall conclusions of the analysis holds, it is seen as heightening the validity of findings as changes of the data does not change the overall output.

7.2 Sensitivity analysis

There are many parameters that have a potential notable impact on results regarding rural electrification and LCOE calculations, and which impact their margins of error might have should be tried through sensitivity analyses. (Mahapatra & Dasappa, 2012)

The parameters tried in this analysis are:

- Discount rates
- Fuel costs
- Salaries
- Penetration and consumption

7.2.1 Discount rates

As it has not been possible to calculate the LCOE of grid generation of electricity, sensitivity analyses cannot be performed for this cost and will only be applied to the other solutions. The sensitivity analysis thus only shows sensitivity to discount rates for the off-grid solutions.

Solution	7%	9%	11%	13%	15%
Grid[21]	0.079	0.079	0.078	0.078	0.078
Solar PV	0.204	0.185	0.170	0.159	0.150
Diesel generator	0.188	0.163	0.143	0.127	0.114
Gasification	0.217	0.207	0.197	0.189	0.182
Hydro power	0.190	0.174	0.162	0.153	0.146

It is not as much the absolute LCOE value of solutions that is interesting as it is the relationship between them and which effect the discount rate has on feasibility of solutions. As can be seen, the diesel generator with its low CAPEX but high OPEX benefits more from the higher discount rate than the other technologies. At 7 % discount rate the LCOE of diesel generator is 0.002 Euro/kWh lower than the LCOE of hydro power,

[21] The reason why the kWh price of grid electricity changes marginally is because the lack of reliability price of 5 % commercial consumption comes directly from diesel generator prices which is discounted.

but at 11 % that is 0.019 Euro/kWh and at 15 % it is 0.032 Euro/kWh. This is because initial costs are not discounted and therefore a higher discount rate favours low initial CAPEX and high OPEX over the opposite.

Looking at the ranking of the solutions, nothing changes due to discount rates, as the solutions keep their rank through the sensitivity analysis, and in that the analysis is not sensitive to discount rate.

When it comes to EDL and potential villages being electrified through grid extension or off-grid solution the discount rate has a larger impact and the analysis is thus sensitive to discount rate. As mentioned before this is mainly a consequence of not having a calculated LCOE of grid electricity, and thus no difference when changing the discount rate. For 7 % discount rate the difference between grid and cheapest off-grid solution is 0.107 Euro/kWh and for 15 % it is 0.036 Euro/kWh – more than three times the difference.

7.2.2 Fuel costs

Fuel prices vary and it is therefore important to look at which impact different fuel prices have. As mentioned in 5.2 "LCOE costs of solutions", fuel price used for the calculation of LCOE for diesel generators is based on noticed diesel prices, which varied between 2900 UGX/litre – 3300 UGX/litre. In the below in Euros.

Fuel price (UGX)	Fuel price (Euros)	LCOE
2,900 UGX/litre	0.80 Euro/litre	0.137 Euro/kWh
3,100 UGX/litre	0.86 Euro/litre	0.143 Euro/kWh
3,300 UGX/litre	0.92 Euro/litre	0.149 Euro/kWh

As can be seen the difference between the lowest and highest diesel price is a difference of 0.012 Euro/kWh, which is not a large difference, and not enough to make a difference. Diesel generator is the least cost solution with a distance and the variation in noticed diesel prices do not change that. However, as mentioned in 4.8 "Technology catalogue" diesel prices have doubled in the last 12 years and if that was to happen again (bringing litre prices to 6,200 UGX (1.7 Euro)) the LCOE of diesel would become the highest with 0.240 Euro/kWh. Although a radical development it is based on historic prices and a possible continuing trend.

This makes the output of the analysis not sensitive to smaller fuel costs of diesel, although a radical change does have an effect.

Fuel costs of gasification is already low and giving a fuel costs of 0 brings LCOE down to 0.186 Euro/kWh, which shows that gasification also is sensitive to fuel cost change, however, it is still the most expensive solution and thus the output and ranking of the financial analysis is not sensitive to this change.

7.2.3 Operator salary

The operator salary depends on work load and expertise of job, but it is difficult to assess as limited data is available. As can be seen below doubling and halving salaries have different impacts on technologies. For gasification there is a large difference as the majority of OPEX comes from operator salary. It has no effect on gasification feasibility compared to the other technologies, however, as it is still the most expensive solution. The prioritisation of solutions does not change with difference in salaries unless one is doubled and another is halved, and for that reason it is deemed that the analysis is not sensitive to operator salary. Again, however, as grid electricity is not broken down difference in salaries has no effect on kWh costs and the difference between grid and off-grid becomes smaller or larger.

Solution	Double salary	Normal salary	Half salary

Solar PV	0.176 Euro/kWh	0.170 Euro/kWh	0.167 Euro/kWh
Diesel	0.149 Euro/kWh	0.143 Euro/kWh	0.140 Euro/kWh
Gasification	0.245 Euro/kWh	0.197 Euro/kWh	0.173 Euro/kWh
Hydro power	0.161 Euro/kWh	0.162 Euro/kWh	0.163 Euro/kWh

7.2.4 Penetration and consumption

Penetration and consumption do not have an impact on LCOE of solutions, but they do have an impact on EDL and which villages should be electrified through which technology. They are not the same parameter, but they do have the same effect on EDL. This is because calculations, as mentioned in 1.3 "Research question", are done from a 100 % electrification point of view, and lower penetration would thus mean lower demand node consumption – as would lower per capita consumption in general. Therefore penetration and consumption are treated together. However, consumption could also be higher, which is also analysed here, although the most realistic scenario is considered to be a lower penetration. The following GIS's show the outcome of demand node consumption (regardless of lower general consumption or penetration) of 60 % and 120 % consumption.

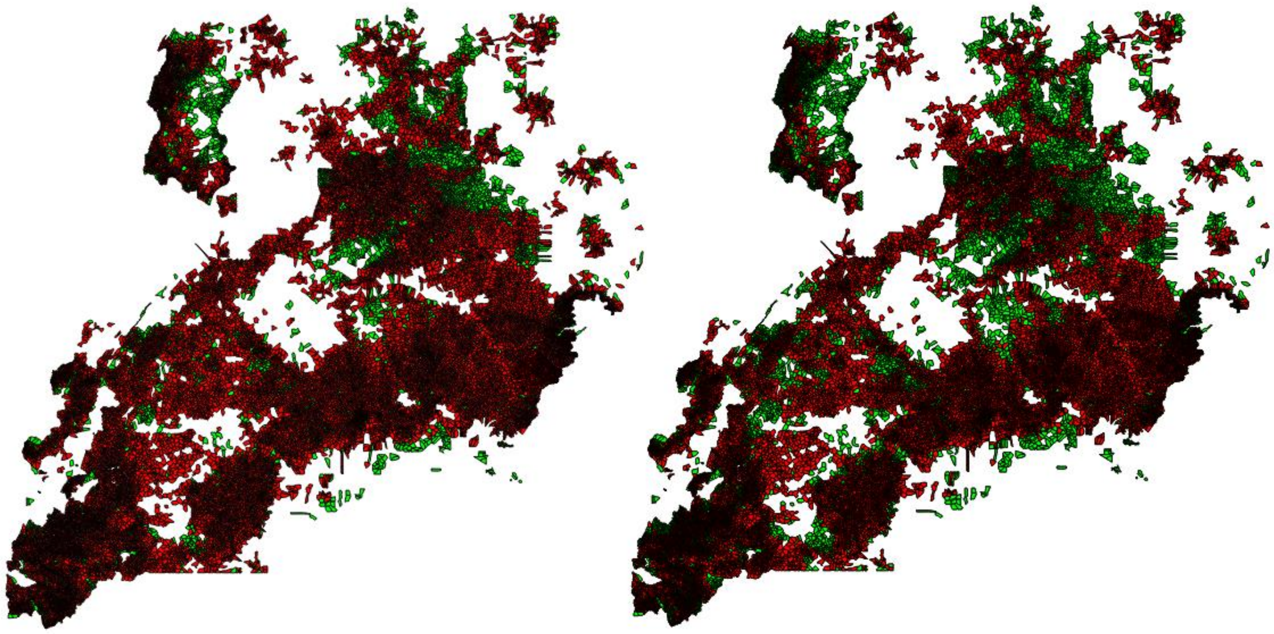


Figure 7.1: To the left is the 120 % consumption scenario and to the right is the 60 % scenario. Red demand nodes are electrified through grid, green through off-grid.

Although there is a difference of factor two in consumption between the two scenarios, the difference is not major, as can be seen below:

Consumption	Demand nodes electrified through grid
60 %	33,500
80 %	35,500
100 %	36,900
120 %	37,900

This supports the explanation from Chapter 6 "National electrification" that distance is a more determining factor than consumption, as the difference in grid electrified demand nodes is 4,400 on half the consumption. Smaller penetration is not expected to have a notable impact on results

7.2.5 Conclusion

Several of the parameters have a small impact on numbers, but unless under radical change no major impact on results and conclusions of analyses are found. The discount factor is the parameter with the largest impact, but besides the flaw of not having an impact on grid costs, the ranking of the solutions stay the same. This is mainly because diesel generator is the cheapest solution with a low discount rate and the only solution with high OPEX and low CAPEX, which benefits from high discount rates. This supports the overall results of the financial analysis to a certain degree, as no larger impact has been found no smaller numbers.

Slightly surprising is the result of the sensitivity analysis of consumption as half the consumption of 120 % only had a 4,000 demand node difference in grid electrified demand nodes, thus proving the assumption that the cost of extending the grid is a more determining factor than kWh costs, or in other words: distance from grid is more important than consumption. This also strengthens the findings of the EDL and GIS in Chapter 6 “National electrification” as a higher or lower consumption does not have major impact on national results.

8 CONCLUSION

Sustainable energy is seen as the foundation of development for developing countries, and without it, development, is expected to be difficult. Alongside this there are social and health consequences of lack of access to modern energy services – consequences that can be alleviated through giving access to these services. This is especially an issue for the rural populations of developing nations as their electrification rates are lower than the ones of the urban populations.

Sub-Saharan Africa is the least electrified region in the world, with Uganda having one of the lower rates. In Uganda the overall electrification is 15 % with 7 % for the rural population – less than half the rural and overall electrification rates of average Sub-Saharan Africa – leaving more than 26 million rural people without access to electricity.

For many decades grid extension has been the main tool to solve rural electrification but in recent years there has been a change of mind towards off-grid solutions, as they by some are regarded as being more financially and technologically viable. There is no clear answer however, to which solution should be used for rural electrification of a country as it can be locally specific.

This brings the research question of:

"How can rural Uganda be electrified in the most feasible way?"

In this context "feasible" covers the aspects of being technologically and financially feasible, which gives the following sub-questions:

1. How can rural Uganda be electrified in the most technologically feasible way?
2. How can rural Uganda be electrified in the most financially feasible way?
3. Using answers to sub-questions 1) and 2) which off-grid solution is most feasible overall and which impact does it have on national electrification?

Rural electrification of Uganda is seen from the point of view of a 100 % electrification rate.

The first sub-question is answered in the below.

8.1.1 THE MOST TECHNOLOGICALLY FEASIBLE SOLUTION

There are several feasible technologies which can be used to electrify rural Uganda. The technical aspects of technologies, however, are not as important as the human factor behind the technologies. As such the largest success factor for technologies have to do with, among others, knowledge of how to design, install and run plants. The technologies that are found feasible are:

- Solar PV mini-grid
- Solar Home Systems[22]
- Hydro turbine mini-grid
- Bio gasifier mini-grid

[22] For household solutions only

- Diesel generator mini-grid
- Grid extension

There are different technological aspects that make some of the solutions more fitting than others. Hydro power is too site specific, gasification is not technically mature yet, and SHS's are for individual households only. This leaves the off-grid solutions of diesel generators and solar PV (both seen as mini-grids) and grid.

Diesel generator is a mature technology that has proven itself feasible in Uganda before, however a negative aspect is the burning and dependency of fossil fuels, which have several negative consequences, such as health impacts on consumers.

Solar PV is a more complicated system than the other mini-grids as it needs battery storage, however, as long as the system is designed to accommodate consumption at all times, there are no technical issues. Solar PV is modular and it is thus easy to meet future demand as PV modules and batteries can be added to the system, which is unique. For the other solutions future consumption means reinvestment in a larger generator to meet demand.

Grid extension is the most used and well known solution in Uganda. It is the most feasible solution in ways of consumption as there is an unlimited amount of electricity available for consumers, although there are current issues with black outs and thus availability and reliability of power, at the same time making it the most unfeasible. Grid is and has been the main method of electrification in Uganda for decades. This means that the human factor behind it is more developed than that of the off-grid solutions, which makes it the most feasible technology for rural electrification

The most technically feasible off-grid solutions are diesel generators and solar PV. From a more broad technology point of view however, solar PV is chosen as the most feasible as it is modular and the dependency and negative consequences of burning fossil fuels makes diesel generators less attractive.

The answer to the second sub-question is given here:

8.1.2 THE MOST FINANCIALLY FEASIBLE SOLUTION

Using Levelized Cost of Electricity (LCOE) to determine the least-cost solution for rural electrification, diesel generator is found to be the most financially feasible off-grid solution, having 16 % lower costs than solar PV. Below are the LCOE's.

Solution	**Euro/kWh**	**Euro/m**
Grid	0.078	23.01
Solar PV	0.170	
Diesel generator	0.143	
Hydro power	0.162	
Gasification	0.197	

One questionable aspect of the grid electricity however, is that it is not a calculated LCOE like the other solutions, but the price sold by the transmission company UETL to distribution companies, accepted as LCOE under the premise that it is not a higher cost than the LCOE as generation and transmission companies want to make profits at the sold price. However, this makes the grid cost more vulnerable compared to the off-grid solutions as for example discount rate has no effect on it. It is thus deemed that the cost of grid electricity is lower than what is shown above, making grid more feasible. However, as no other data gives a more precise kWh cost for grid, the above is accepted.

The calculation method and choices made about parameters and off-grid aspects are key components in the findings and another view on these could radically change those. The LCOE of gasification is the highest, for example, due to the extra battery storage. However, the LCOE for gasification in a theoretical scenario of running 24 hours, meeting demand at all times, is 0.099 Euro/kWh, making it the least-cost off-grid solution. The same goes for hydro power when looking at kWh costs of generation and not consumption, which means in a theoretical scenario where every possible kWh produced by hydro power is consumed, the LCOE is also 0.099 Euro/kWh. This is not taken into account as those scenarios do not compute with the findings of the report, however, it shows what the difference in choices for the LCOE's calculation mean for this analysis.

The answer to sub-question three is given here:

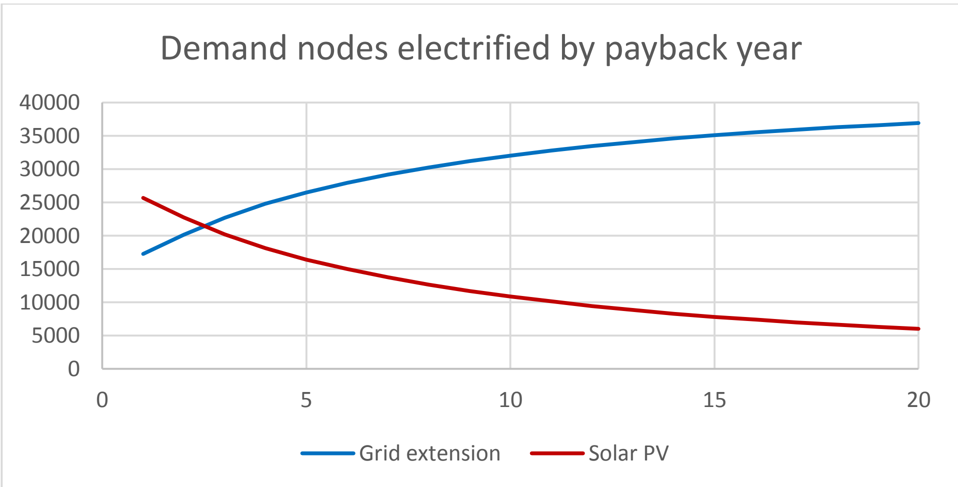
8.1.3 National electrification

Through the financial analysis it is concluded that diesel generator has the lowest LCOE cost of all the off-grid solutions. As such it is 16 % lower than that of solar PV. However, the difference in amount of demand nodes being electrified through grid of off-grid is small and therefore the impact the price difference has on national electrification is not large.

The most feasible off-grid solution in the technical analysis is solar PV due to its modularity and the negative consequences of diesel generators, such as unstable fuel prices, potential health impacts of consumers, not being modular, i.e. needing reinvestment in generator every time consumption rises. This together with the small impact of difference in LCOE constitutes the reason for choosing solar PV as the overall most feasible off-grid solution.

With the data available in GIS, it is possible to calculate electrification form for all demand nodes. As that is determined, among others, by consumption of demand nodes a payback period is applied as consumption per month is not a feasible measure. 10 and 20 years are recommended as payback periods due to electricity infrastructure investment being a long term investment, however, there is no accurate decision as the payback period has to fit the needs of whichever NGO, authority or agency who use it.

The payback period shows that the correlation between payback periods and number of demand nodes electrified through grid extension is not steady, but an exponential decline, as can be seen below.



This is expected to be because distance is a more determining cost factor than consumption. Thus the further demand nodes are away from the grid the higher their consumption has to be to cover the large rise in costs due to the km cost of extension. This also shows in the aspect of the Economical Distance Limit (the measurement of when grid extension becomes less feasible than off-grid solutions), where the relation between distance and consumption shows as 251 kWh/m for a break-even point. A demand node 10 km away thus needs a total consumption of 2,510 kWh before grid extension is feasible. Looking at demand node population needed to accommodate the kWh/m EDL it also shows a large population necessary before grid extension becomes more feasible than off-grid solutions.

Payback period	People in demand node/km
1	1,733
5	347
10	173
20	87

8.1.4 Sensitivity

Numbers and calculations are somewhat sensitive, but unless a radical change is applied no major impact on results and conclusions of analyses are found. The discount factor is the parameter with the largest impact, but the financial LCOE ranking of the solutions stay the same. This is mainly because diesel generator is the cheapest solution with a low discount rate and the only solution with high OPEX and low CAPEX, which benefits from high discount rates.

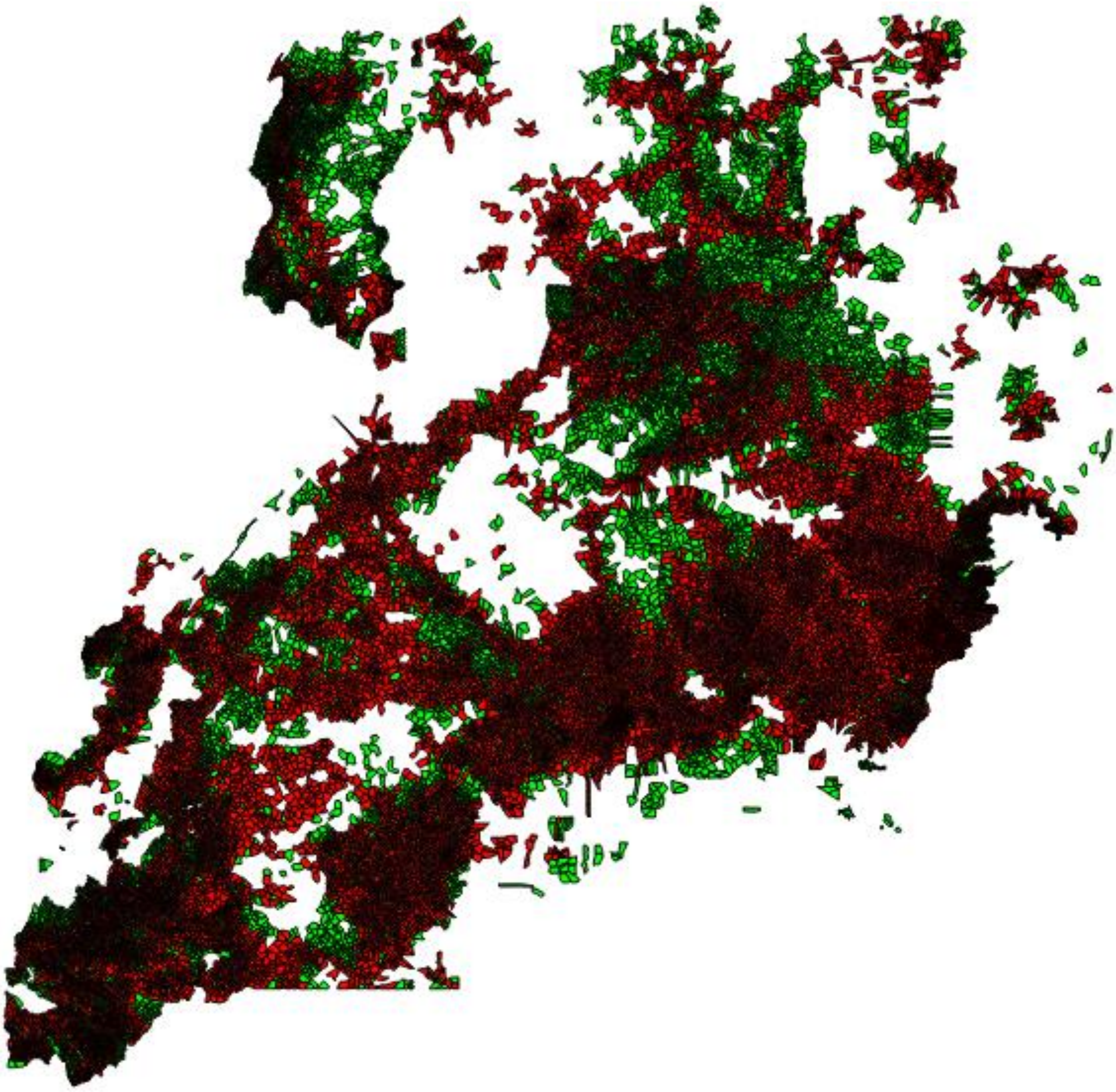
Slightly surprising is the result of the sensitivity analysis of consumption as half the consumption of 120 % only have a 4,000 demand node difference in grid electrified demand nodes, thus proving the assumption that the cost of extending the grid is a more determining factor than kWh costs, or in other words: distance from grid is more important than consumption. This also strengthens the findings of the EDL and GIS in Chapter 6 “National electrification” as a higher or lower consumption does not have major impact on national results.

8.1.5 Answer to research question

The most feasible technologies for rural electrification are grid extension (0.078 Euro/kWh + 23 Euro/m) and solar PV mini-grids (0.170 Euro/kWh) for off-grid settings.

As it turns out the choice of off-grid solution is not as important as the cost of extending the grid extension as it has such a high impact on demand node electrification. Distance from grid is thus more important than demand node consumption. This is also because no major difference between costs of solutions is found, as all the solutions have costs between 0.14 and 0.20 Euro/kWh.

Below is a GIS showing the potential feasible rural electrification of Uganda after a 10 year payback period. The red areas are demand nodes electrified through grid extension, the green through solar PV:



Above is shown an answer of how Uganda can be electrified the most feasible way.

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3: Villages_2011_Jahid_2006_UBOS.shp. Made by Uganda Bureau of Statistics

10 APPENDIX A MODELLING AND CALCULATIONS

In this appendix are all the explanations of the modelling and calculations. In order:

- Rural consumption
- Consumption pattern
- Solar modelling
- Gasification modelling
- Diesel generator modelling
- LCOE calculation
- GIS

10.1.1 RURAL CONSUMPTION

The overall rural consumption in kWh is calculated by adding the three different parts of rural consumption together. These being commercial consumption, household consumption and public consumption. The output is a per capita monthly consumption which is used to create the consumption pattern and along with this pattern used to model rural consumption.

Public consumption is calculated through three public consumption parts found in (Ministry of Energy and Mineral Development, 2009). These parts being health centre consumption, water pumping consumption and educational consumption (secondary and primary schools). These can be seen below:

Public	Health ce	Level 3	Level 2			Education	Secondary	Primary sc	Total		
	Number	904	2273			Number	3645	18422			
	kW/day	8	0.8			Percentag	54%	82%			
	kWh	12	6			kW	1.6	0.8			
	Total kWh	10848	13638	24486		kWh/day	20	5	114,896.2		
			Divided by	0.023	kWh/month/capita			Divided by	0.114	kWh/month/capita	
	Water										
	Minimum	Average k	Monthly c	Average kWh/month/capita for water							
Trading ce	4800	50	0.3125	0.40							
Trading ce	1920	29	0.453125								
Trading ce	480	7	0.4375								

Household consumption come from (Bena, 2015) who state a consumption of between 30-50 kWh/month/household, which gives an average monthly per capita consumption of 8.333 kWh, given an average household size of 4.8.

Commercial consumption is found through data in (Ministry of Energy and Mineral Development, 2009) about average trading centres in Uganda, as can be seen below:

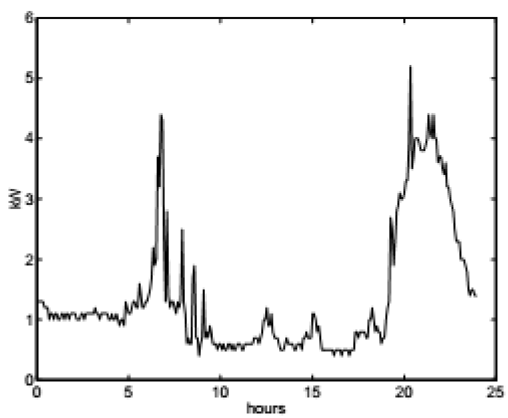
Commercial			Connections			Per capita kWh monthly					Per capita	
	Maxmimu	Hours/day	Trading ce	Trading ce	Trading ce	Trading ce	Trading ce	Trading ce	Tranding c	Trading cen	Trading cent	Trading centre D
Shops	0.08	3	24	49	95	0.36	0.18	0.14	Quantity			
Salon	0.29	3	2	3	5	0.11	0.04	0.03	1143	1017	410	265
Drug Shop	0.45	3	1	1	6	0.08	0.02	0.05	Households			
Battery Ch	0.45	24	1	1	2	0.67	0.17	0.13	>100	>400	>1000	>5000
Carpenter	0.45	8		1	3	0.00	0.06	0.07	People	(4,8 people/rural household)		
Fish Store	0.53	5		1	2	0.00	0.04	0.03	>480	>1920	>4800	>24000
Post Offic	0.50	4				0.00	0.00	0.00	Total people			
Police Sta	0.59	5				0.00	0.00	0.00	548,640	1,952,640	1,968,000	
Bars	0.65	6	2	2	4	0.49	0.12	0.10	Total per capita consumption daily			
Computer	1.70	14			1	0.00	0.00	0.15	0.107			
Video Hall	0.70	4	1	1	1	0.17	0.04	0.02	Total per capita consumption montly			
Hotel	1.19	6			1	0.00	0.00	0.04	3.197	kWh/month/capita		
Restauran	0.85	6	1	2	3	0.32	0.16	0.10				
Bakery	0.79	6		1	1	0.00	0.07	0.03				
Grain Mill	14.05	5	1	2	3	4.39	2.20	1.32				
Welding V	4.05	5			1	0.00	0.00	0.13				
Total						6.59	3.10	2.34				

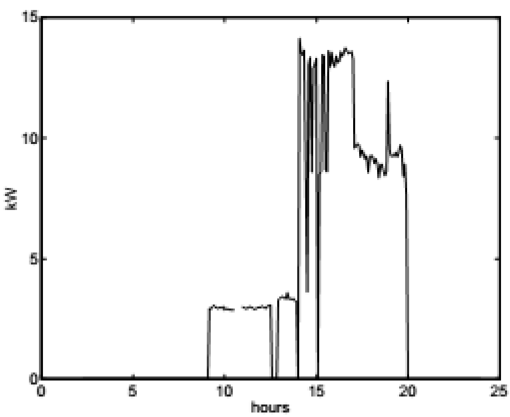
The per capita consumption is found through taking the average per capita weighted consumption from the different trading centre sizes and populations. This means that the three sizes of ”trading centres” have the ”per capita kWh monthly” multiplied with ”total people”, which are then added together and divided the aggregated ”total people” for an average per capita monthly commercial consumption.

Added together the rural per capita consumption is: 0.538+8.333+3.197 = 12.069 kWh/month/capita.

10.1.2 CONSUMPTION PATTERN

For the load profile, the first step is to recover the data from the household and commercial loads curve from (Sprei, 2002), which can be seen below.

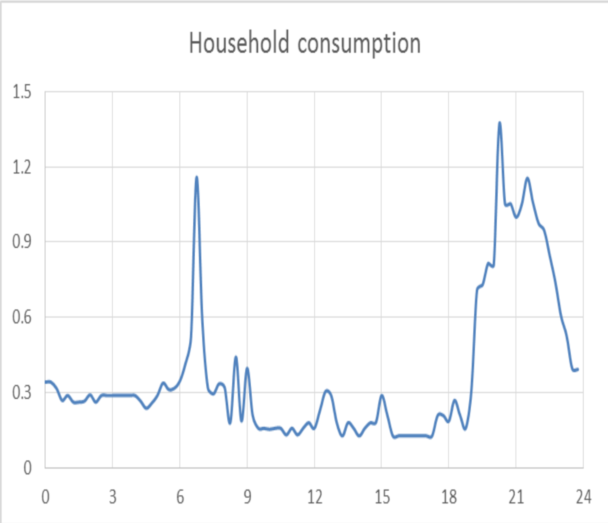


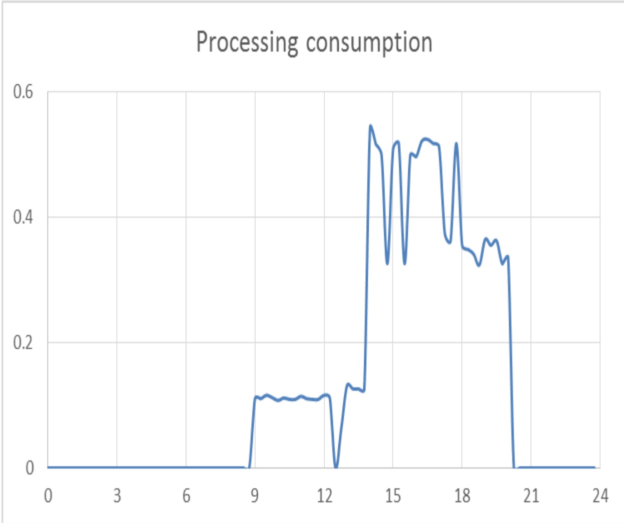


This is done through a graph digitizer software called ”GetData Graph Digitizer”, which allows to manually copy x and y values of a graph into Excel data. There are therefore some minor errors on x and y values, although they are expected to be minimal as the software allows for zooming in on the values, making it more accurate.

The above is a sample size of five households and one coffee factory and is thus not representative of rural consumption of Uganda, although it is used as such in this report as no other data is available.

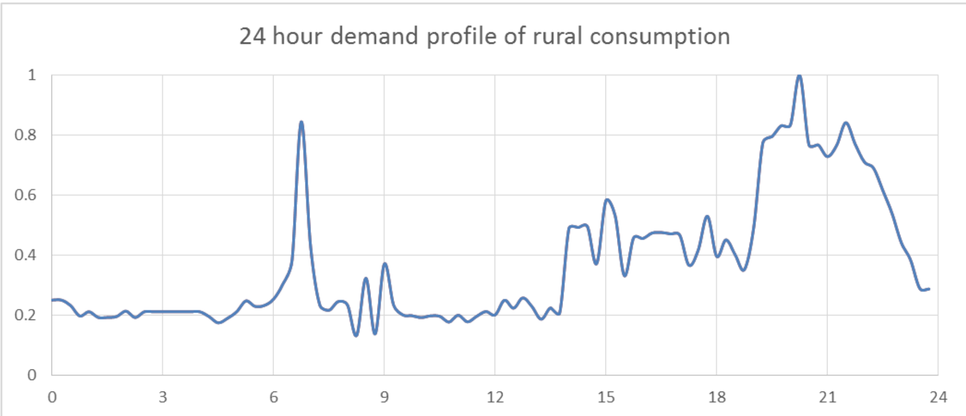
This data is then turned into average quarterly (15 minutes) values to make a common value which can be used for modelling of other data, such as potential solar generation. This gives the following graphs:





As can be seen when comparing the graphs, minor fluctuations have disappeared but all in all the data is compatible. It is deemed that the quarterly values make the data more valid when using it as representative for all rural inhabitants as minor fluctuations are considered to be coming from the small sample size, and would not be present if the sample size was larger.

The next step is to combine the load profiles into one general per capita load profile, which can be used for modelling of solutions. This is done by using simple integral calculation to determine the area under the graph which shows the kWh of each of the graphs. The capacities (y-value) of consumption is then changed for the two graphs until the kWh consumption fits those of commercial and household consumption, so the different size between them is taken into account. Due to no load curve for public consumption it is decided to add public consumption to household consumption, thus using the same load. When that is done a total load profile of rural consumption per capita is available, as can be seen below.



10.1.3 Solar modelling

The first step for the solar modelling is to assess the solar data needed for electricity generation. This data is taken from (European Commission, 2012), from the centre of Uganda. Although solar irradiation differs from region to region in Uganda the centre of Uganda is chosen as reference point to simplify the analysis and having a central point is expected to be more representative than that of outer points.

As the system is supposed to work every day, data for the days with least potential generation in the year should be used. (Wade, 2008)

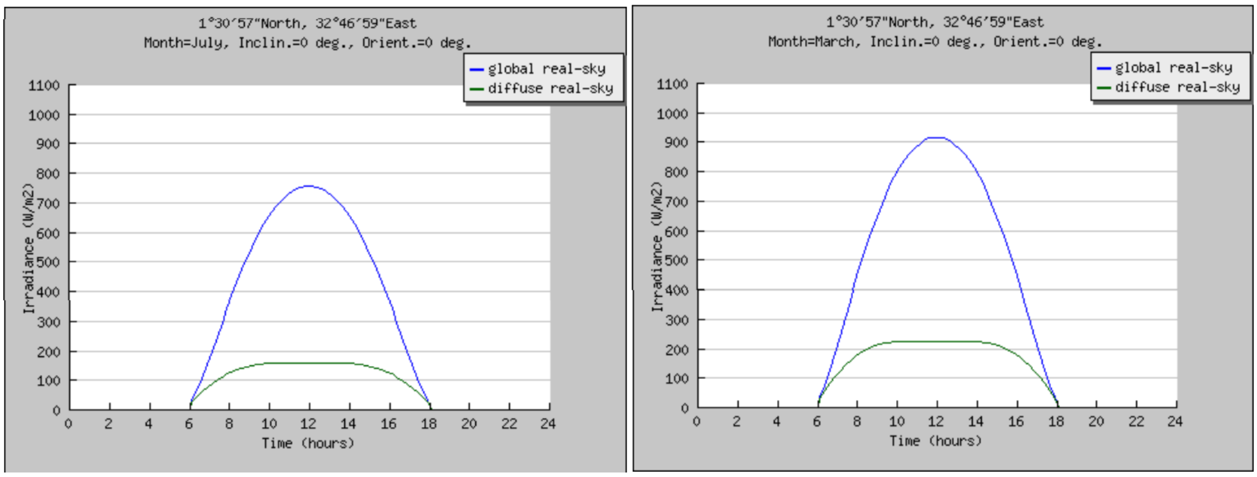


Figure A.1 (European Commission, 2012): Irradiance of the months with lowest and highest irradiance (July and March).

There is a significant difference between irradiance and therefore potential electricity generation between July and March, as can be seen from figure A.1. Therefore data from July is used in order to design the system after the lowest generation. The data is taken from European Commission (2012).

The solar generation shows close correlation to a second degree equation and, using the regression function in Excel, is y=-0.0296X^2+0.7106X-3.285. The x-values are then calculated by using the y-values according to the quarterly values for 24 hours, giving a 24 hour potential solar generation data set consistent with that of consumption. All negative values are removed as there can be no negative generation.

With data for generation and consumption ready, the next step is to design the model for the solar mini-grid system. In itself the design of the system is simple: When generation is larger than consumption the batteries are charged with excess electricity and when consumption becomes larger than generation the stored electricity in the batteries is used to cover the deficit. The only difficult aspect is to decide the size of installed PV and storage capacity, so the system can meet demand continuously. The input parameters for this are:

Time, Consumption, Generation, and Storage

The common y-value is time (hours) in the quarterly values, as mentioned before.

Consumption is based on the load profile and thus gives a load matching the time of day.

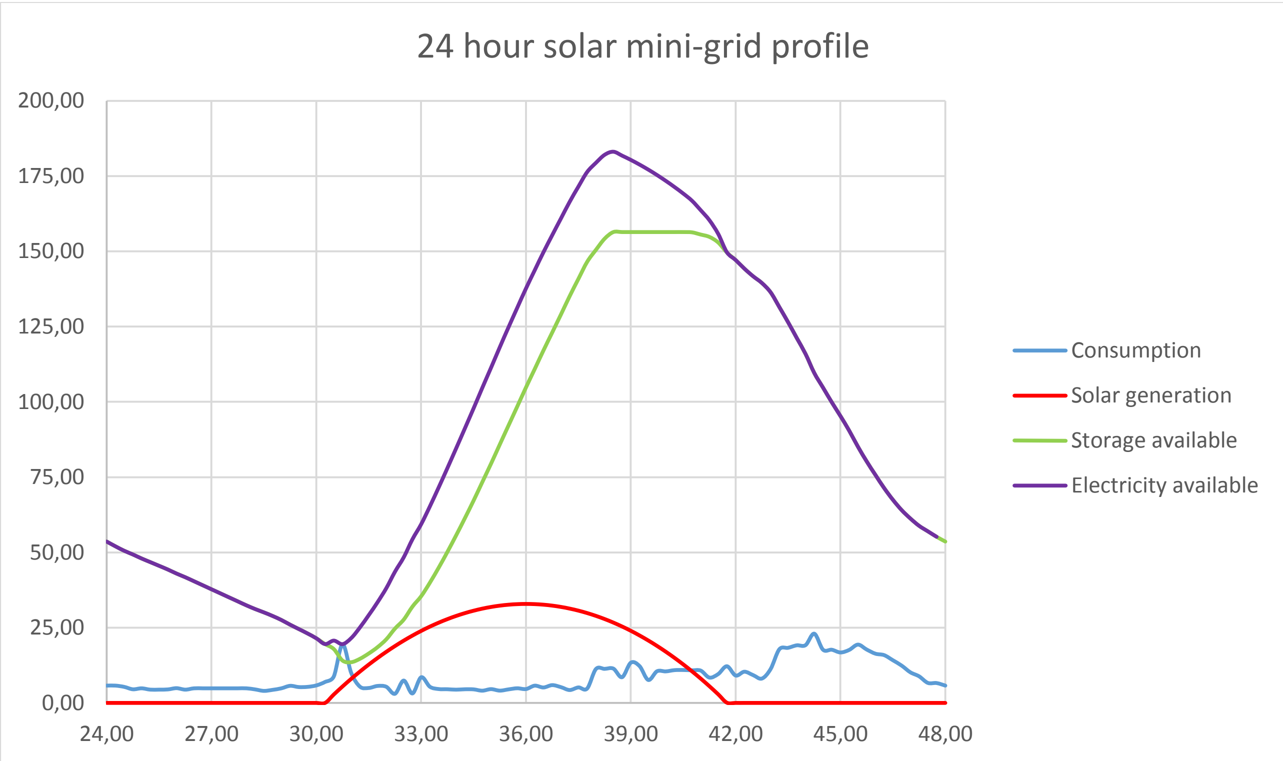
Generation is the solar generation, also matching the time of day. Generation however has several losses due to the technical design of the solar PV mini-grid, which means that generation is at 65 % of installed capacity (modelled as all generation values being timed with 0.65). The losses can be seen below. (Wade, 2008)

Internal system losses	10 %
Sunlight not hitting the panel correctly	5 %
No maximum power point controller installed	10 %
Dirt on panels	5 %
Ageing	10 %
Total generation factor after losses	0.65%

One loss that is not accounted for is 15 % when temperatures are above 25° C. This is because the average temperature for Entebbe (Uganda) is between 20-22 degrees over the year, and it is difficult to know which hours the temperature would be above and to calculate the loss.

Storage is defined by the difference between consumption and generation. When that difference is positive storage gets filled with the excess electricity available and when it is negative storage covers the deficit. Storage however also has some extra parameters. One is that due to longer lifetime of batteries they are not supposed to be discharged to less than 20 % of their capacity (Wade, 2008). This is modelled as having 20 % less capacity and 20 % is therefore removed from installed battery capacity (leaving 80 %). Another aspect is storage losses, which are a total of 20 % (Wade, 2008). There is a 10 % charge loss which is modelled as excess electricity being timed with 0.9 so the storage only holds the electricity that would actually be stored. Another 10 % is lost due to discharge and is modelled by timing discharged electricity with 1.1 to remove the electricity that would actually have been removed from storage.

For the generation and consumption it does not matter that the loads are in quarterly values as the average load value of one hour gives a kWh value, however for the storage this means that excess quarterly electricity are added to each other, thus creating a higher kWh value than should be. Therefore the excess electricity is divided by 4 (15 minutes = ¼ of an hour) to get a kWh value in storage.



As long as “Electricity available” is higher than consumption, the system is functioning.

10.1.4 Gasification modelling

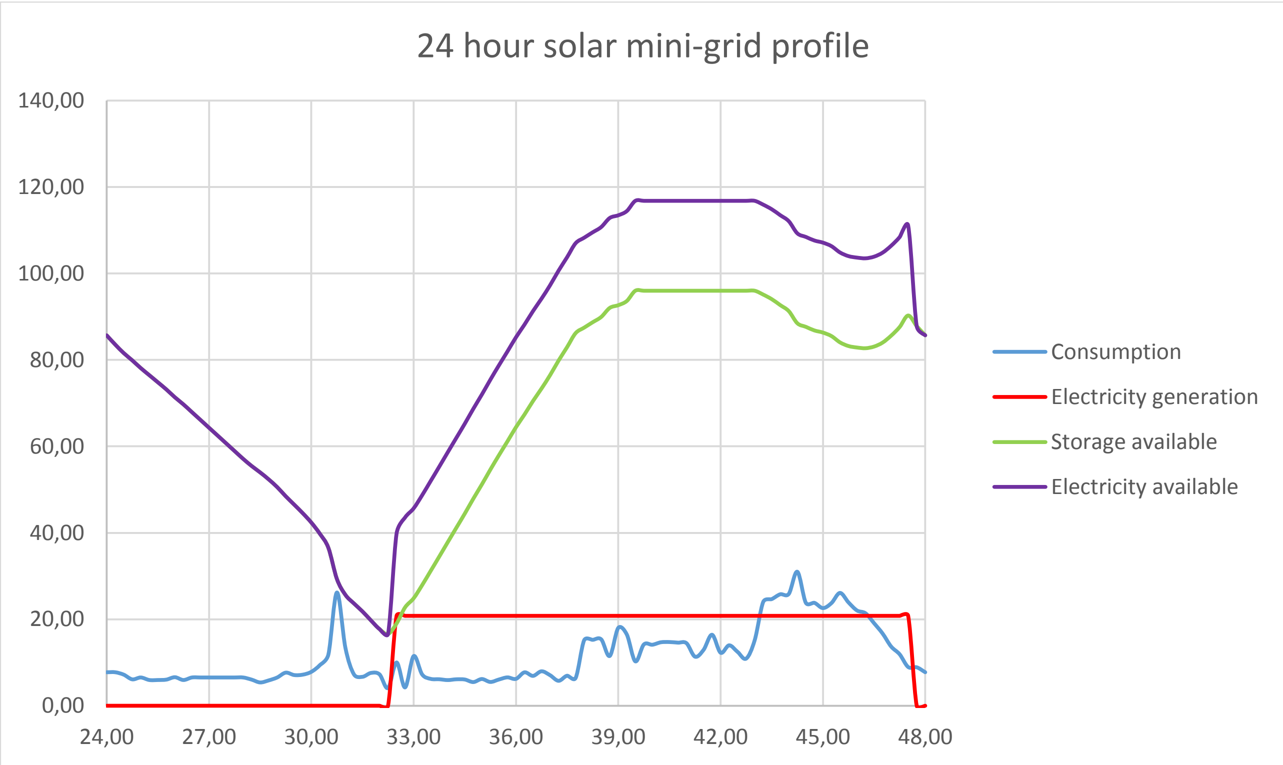
The modelling of gasification is done in a similar way as solar with battery storage being charged when there is excess electricity and discharged when having to cover the deficit between consumption and generation.

This also means that the same battery data and modelling is used in this model, i.e. 20 % storage losses.

For the generation a 65 % maximum of installed capacity is used as it is difficult to achieve 100 % due to gasses not reaching good quality. The 65 % capacity is only measured for the 10 kW gasifier, but as the 32 kW gasifier also has issues it is used for both. (Miria, 2015)

The 10 kW gasifier has a maximum runtime of 8 hours and the 32 kW gasifier has a maximum runtime of 16 hours, which means that the remaining 16 and 8 hours, respectively, have to be covered by battery storage. The maximum runtimes are modelled to cover the highest part of daily consumption (afternoon and onwards) to minimise storage losses and capacity, which would be higher if runtime was set at lower consumption hours, thus storing more energy for the higher consumption hours.

The model shows that 8 hours runtime (10 kW gasifier) is difficult to accommodate consumption as consumption covered was down to 5.25 kW peak. This is because there is not enough excess generation to store enough for a higher consumption, regardless of storage capacity. For 16 hours (32 kW) accommodating consumption was easier as peak consumption covered was only down to 31 kW.



As long as "Electricity available" is higher than consumption, the system is functioning.

10.1.5 Diesel generator modelling

The diesel generator is not modelled to the same extent as the solar PV mini-grid. The reason for modelling the diesel generator is to assess its fuel use as that is done in intervals of litres/load.

It is thus not modelled as a flowing consumption but as intervals of 25 %, 50 %, 75 % and 100 %, due to the data available. To better fit expected realistic fuel consumption the intervals do not change on their quarterly values as above, but on the median number between those. For example: instead of changing from interval 1 to 2 on 50 % load, it is done on 37.5 % (middle of 25 % - 50 %). This is because it is expected that the loads closer to 50 % than 25 % will be more likely to have a fuel consumption similar to that interval.

Hereunder the consumption loads can be seen (Kyalimpa, 2015):

Consumption	Load
10.7 litre	100 %
8.2 litre	75 %
5.7 litre	50 %

Since no data was given about fuel consumption of less than 50 % load, which means all loads below 50 % would be treated as 50 %, giving a too large fuel consumption in the model, it is decided to estimate a 25 % load. This is done for a more accurate calculation of fuel consumption, and the uncertainty of the estimated consumption of a 25 % load is outweighed by the uncertainty of one not being present. This is done by using the theoretical factor difference between fuel consumption/load of 25 % and 100 % for 40 kW and 60 kW generators from (Diesel Service and Supply, 2013).

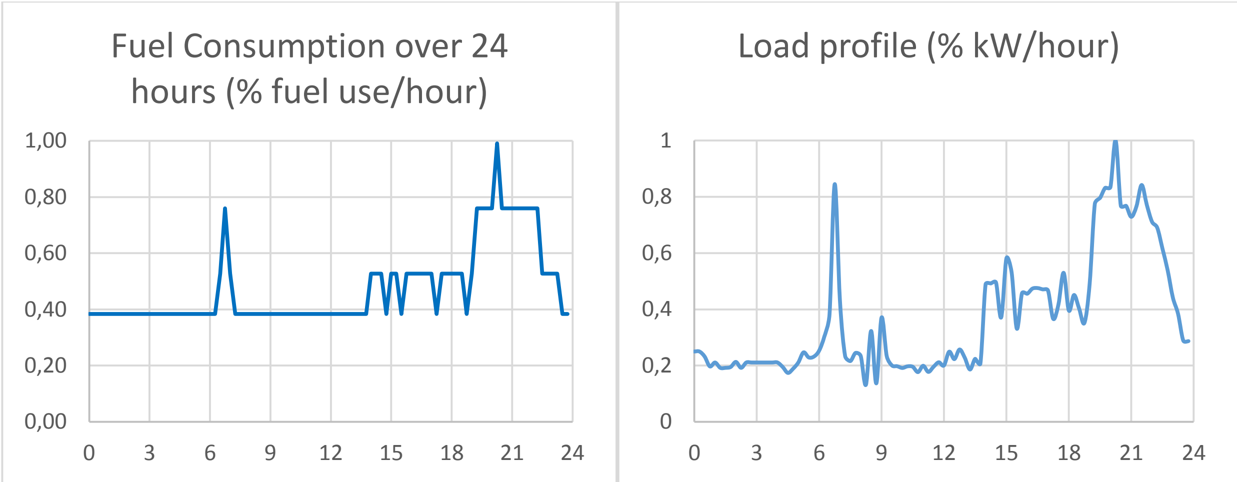


Figure A.2: To the left is the fuel consumption level of the generator and to the right is the equivalent electricity consumption load. As can be seen modelling of fuel consumption has limited it to four intervals, and it is not as dynamic as if it would follow electricity consumption. The reason for the intervals not being of equal size is that fuel use per load is not linear.

10.1.6 LCOE CALCULATION

The LCOE calculation is done per year and then summed up in the end, with total Net Present Value being divided by total electricity generation giving Levelised Cost of Electricity. Underneath is an example of the LCOE calculation of the 64 kW hydro power plant. The inflation factors are to make the numbers match the 2015 baseline year. The exchange rate is due to some of the numbers being given in Uganda Shillings. As can be seen, every 10 years there is a component replacement, which has an effect on the “Discounted annual costs”. Here the effect of the discount rate can also be seen as the replacement costs has more than halved between year 10 and year 20.

Parameters	Amount
Discount rate	11%
Lifetime	25
Exchange rate Uganda Shilling	0.000278493
Inflation factor 2012 Euro	1.02
Inflation factor 2012 UGX	1.225
CAPEX	
Initial investment	339,217.32
Component replacement	In table 1
OPEX	
Operator salary	
Maintenence cost	5975.116197
Total electricity consumption	5139200
NPV (total)	493031.0598
Lifetime cost of electricty	0.10

Calculation

Table 1

Year t	Component replacement	Component cost	Discounted annual costs	NPV per year t
1			5383.0	344600.3
2			4849.5	349449.8
3			4369.0	353818.8
4			3936.0	357754.8
5			3545.9	361300.7
6			3194.5	364495.3
7			2878.0	367373.2
8			2592.8	369966.0
9			2335.8	372301.8
10	Civil structures and genera	217322.22	78641.9	450943.7
11			1895.8	452839.5
12			1707.9	454547.4
13			1538.7	456086.1
14			1386.2	457472.3
15			1248.8	458721.1
16			1125.1	459846.2
17			1013.6	460859.8
18			913.1	461772.9
19			822.6	462595.5
20	Civil structures and genera	217322.22	27696.4	490292.0
21			667.7	490959.6
22			601.5	491561.1
23			541.9	492103.0
24			488.2	492591.2
25			439.8	493031.1
Total				493031.1

10.1.7GIS

Two data layers are used for the GIS analysis. A village layer of Uganda with villages as areas of different sizes, and among others, data on number of inhabitants and a layer of grid distribution lines in Uganda.

Using a function to determine distance, the distance from the distribution grid to all villages (demand nodes) is found and added to the attribute table of the village layer.

With this done, in the layer is then spatial information on distance to grid and population of demand node, both necessary for the EDL. This information is copied into Excel, where the 2002 population is calculated into a 2015 population using population growth rate from (UBOS, 2014). Here the demand node's distance to grid is timed by the cost/distance of grid extension and the number of inhabitants are timed with expected consumption as found in the above "Rural consumption" and then timed with kWh costs of grid and the least cost off-grid solution, giving total costs of electrifying the specific demand node. After this, it is calculated which solution has the lowest cost depending on the distance and consumption. Using an IF-function in Excel all demand nodes which should be electrified through grid extension gets a value of 1 and those which should be electrified through off-grid solutions get a 0, as can be seen in the below.

OBJECTID	NEAR_DIST	POP 15	Solar 20
200	2,124	849	1
201	945	397	1
202	2,289	285	0
203	3,191	500	1
204	2,796	246	0
205	3,387	727	1

OBJECTID is the village ID, NEAR_DIST is the distance between village and grid in m, POP 15 is the 2015 population and Solar 20 is the solar costs after 20 years. If the value is 1 it means grid extension and 0 means solar PV mini-grid

With this differentiation of demand nodes the Excel data is joined with the village layer, thus giving all villages a value of 0 or 1, which shows on the GIS which village should be electrified through which solution. This also has the benefit that the summation of the solar column tells how many demand nodes are electrified through grid extension.

The consumption (total costs) per year determines how many demand nodes should be electrified through grid. As can be seen in the below the difference between the years has an exponential decline.

Years	Amount of demand nodes electrified through grid	Amount of demand nodes electrified through solar PV	Difference
1	17272	25671	
2	20184	22759	2912
3	22735	20208	2551
4	24812	18131	2077
5	26515	16428	1703
6	27947	14996	1432
7	29190	13753	1243
8	30272	12671	1082
9	31236	11707	964
10	32038	10905	802
11	32801	10142	763
12	33483	9460	682
13	34073	8870	590
14	34633	8310	560
15	35131	7812	498
16	35541	7402	410
17	35933	7010	392
18	36298	6645	365
19	36626	6317	328
20	36931	6012	305

11 Appendix B Data on generation sites

11.1.1 Varun Parekh

15 kW solar mini-grid outside Kampala:

Component	Expected lifetime	Price in UGX
Lead acid battery	5 years	110000000
Inverter and charge controller	10 years	70000000
Panels	25 years	65000000
Installation (incl. Internal village grid)		180000000
Total		425000000

The price for installation is for a large area and includes costs of internal village grid as well as lights, alarm, fence, cables etc.

Battery capacity is 3600 Ah x 48 V (172.8 kWh)

11.1.2 Andrew Ssentongo, Renewable Energy Process Engineer, Kitobo Island Mini-Grid Project, Kalangala District

10 kW solar mini-grid on Kitobo Island.

Purchase Order

March, 2014

Item	Quantity	Price (US Dollar)
Batteries, dry, sealed	24	6,500.00
285 watt solar panels	30	5,586.00
Inverter & accessories	2	3,338.90
Steel support structures		2,239.06
Charge controllers	4	1,600.00
Tools & Work Lights (Temporary Use Only, for Installation)	-	1,123.94
Wire spools	-	1,922.52
Battery monitoring kit	1	175.50

Circuit breakers & Panelboards	-	647.00
Acrylic Paint	2	42.70
Ceramic paint 5 gallons	1	225.00
Hardware & Accessories		665.34
Total		**24,065.96**

Inverter life is expected at 8-10 years. Lifetime for battery is 5-10 years depending on maintenance regime. Lifetime for panels is 15-25 years. Battery bank is 57 kWh.

11.1.3 Opio Innocent Miria, former CREEC head of pico hydro power and gasification

GEK 10 kW gasifier, attempted installed by CREEC.

Amount of fuel use depend directly on the designed consumption and expected gas yield based on the number hours of operation. For the GEK it varies from 6-13kg/h

Majorly the durability depend on the material, operating condition and number of running hours, but should at least last for 5-10 years in operation.

For the GEK 10 kW gasifier we had major upset with their output. The manufacturer may indicate 10kW but you will never generate that even at full load. To run the generator at full operating speed. The quality of the syngas need to be very good. But the gas production depend majorly on operating temperature &the feedstock quality and other operating parameters. So if the operator cannot control some. Then it becomes an issue although others are beyond operators

Operators salary mainly depend on his level of education & skills

Bigger power plants can run for 24 hours continously but most micro gasifiers cannot as their materials cannot withstand longer hours of operation since the reactor goes up to 900-1200 degrees C.

11.1.4 Jerome Nuwabaasa, Renewable Energy Researcher Uganda Industrial Research Institute

32 kW gasifier mini-grid in Muduuma

I have been told that the initial investment of the gasifier is around 192,000 USD, is that correct?

Muduuma Power Plant

HPS gasifier 32 kWe

HPS plant	$	40,000.00
Transportation	$	12,000.00
Taxes	$	7,200.00
Civil work	$	4,660.19

Total	$	63,860.19

Power distribution system

Unit		
Micro grid	$	96,026.56
Prepaid metering system	$	19,780.00
Total	$	115,806.56

Total Power Plant Invesment

Gasifier & Setup	$	63,860.19
Micro-Grid	$	115,806.56
Grand Total	$	179,666.76

Also if you could give me the monthly operator salary as well as monthly maintenance costs. If monthly is not available then annual is also ok.

Monthly operator salary is 230,000 ugx... we also cover their medical bills, accomodation and meals. this amounts to about 350,000 per operator. We have two operators.

Do you have the kWh cost of fuel for the gasifier? Or an estimate no it?

4 kg per kwh each kg is 70 ugx

What is the longest timespan the gasifier can run continously? Can it run for more than 24 hours?

It can only run for 16 hours a day in two shifts of 8 hours.

11.1.5 Benon Bena, Manager Off-Grid Renewable Energy Development, Rural Electrification Agency

Grid electricity and extension

- How much the kWh cost is on grid electricity. Not for the consumer but to produce (including labour):

The bulk supply tariff which is the price at which Uganda Electricity Transmission Company Ltd (UETCL) sell electricity to Umeme and other distributors is about USD Cent 0.085 and the details can be obtained at http://www.era.or.ug/index.php/statistics-tariffs/tariffs/bulk-supply-tariffs.

- How high the expected transmission and distribution loss is:

Transmission is 4% and distribution loss is 21.3%

- How much the per km cost is of grid extension (that means labour, transmission lines, poles, etc.).

The cost of distribution Grid per km for 33kV is USD 23,000, for low voltage 415/240V is USD 16,000. The Distribution Substation (transformer) 100kVA 33kV/415V is USD 11,000. The grid is extended for the existing 33kV line and the transformer step power down from 33kV to low voltage.

- The expected rural household consumption of energy.

The consumption range between 30-50kWh per month. The 30-50 kWh per month is for wealth rural consumers but if varies from region to region. This does not include the commercial loads like Maize mills, welding machines and milk coolers

Do you know what the densification is for grid in Uganda (i.e. which percentage of people are connected to the grid within an area of access to grid)?

I don't know the densification rate because the population density vary from area to area.

11.1.6 Joseph Kyalimpa, Mantrac Uganda

50 kW diesel generator procurement

A 50kw will cost USD 20,100
For an average person who maintains and services it well, it should last
more than 20 years without any major repairs.
Fuel consumption entity depends on the user and running hours, however
below is the generator consumption Vs load
FUEL CONSUMPTION (LITRES/HR)

LOAD			
110%	100%	75%	50%
12.0	10.7	8.2	5.7

11.1.7 CREEC survey of diesel generator backup capacity

The surveyed experts are and their answers are:

- Vianney Tumwesige: 5 %
- Eileen Lara: Below 5 %
- Dorothy Lsoto: 5-10 %

The surveyed all agree that the 5 % is only for shopkeepers as there has to be some kind of financial benefit of investing in the diesel generator, and they only invest in it when benefits become larger than costs.

Done on the 2nd of July 2015

12 APPENDIX C INTERVIEWS

Interview Mary Suzan Abbo, director of CREEC, on feasibility of technologies

I am working on the technical feasibility of different technologies used for rural electrification of Uganda. So all technologies are seen as mini-grids, and for a village. Not just for farmers, trading centre or household electricity, but for all.

1: Which factors should be included in rural electrification (where technical design might have an effect)?

Technical is more than just the technology. 1) It is important to consider the demand that is required for the chosen technology, for example productive use if it is 1 or 10 kW – which scale. Rural electrification is virgin land and interviews have to be done with consumers about what the use is for, unlike companies for example who already consume power and know their consumption. This means the demand should be quantified, which gadgets are used at which time and so on. The villagers come from nothing and then you have to guess what people will use of power. 2) There are a lot of technologies that are available. Rural electrification is not a direct path, because of other factors, which are not connected with technology. It should be looked at from a transitional point of view. The engineer is tasked with the task of which technologies can be applied at which time. For example there are many options of hydro but experienced engineers from developed countries do not understand the scale of the small ones that are applicable here. It is also important to find the technology that can be expanded because demand will increase with time. The modular technologies are therefore better. There are also differences in designs. One turbine might be better for seasonal fluctuations, and one might be better at steady flow, which is locally specific. 3) Expertise of sizing and design of technology. There is theoretical information available in university courses, but still the experience is that obvious steps are overlooked in this field. For example a plant of 50 kW capacity but the consumers only use 10 kW. A lot of the solar plants have issues with undersizing and the hydro of oversizing. 4) Technical expertise is an issue in Uganda. There are engineers who have learned from school, but not that many with good experience, and there is not enough expertise capacity. That also goes for O&M. Even understanding that dust on the PV panel can affect the output is an issue. Sizing is the easy part, where O&M is the difficult part. When companies from other countries come and install systems they leave after it is done, along with the expertise of maintaining as well. Even data and sharing of it is an issue. Good management really matters. Plant management and efficiencies on the plant. Expertise is needed, as well as management tools, including software, which is very important. Having a market of local artisans who can do maintenance and repair small things close by is also important and that might be why Asia have reached their goals much faster than Africa, as they have this. 5) Procurement is also an issue as the right suppliers for technologies is important, especially when the technology is not produced locally. Warranties are important – some who can provide initial support, regarding the above. Some of the companies from EU and US are just looking to sell and do not care about the dynamics of rural electrification, whereas supportive and innovative solutions and packages are needed. 6) Standards are lacking and are important for systems, as they have an impact on quality of technologies.

Currently off-grid projects are done based on current needs because of resource and logistical limitations. However, the technologies installed are modular and projections for future demand are made for upscaling once resources are available.

2: Which factors most often cause issues?

Lack of local expertise is the main issue. Standards and quality of equipment and components is the second one. There is not a culture of looking at what is already written by others in the field.

3: Is productive use an issue regarding some technologies?

If one was to run a maize mill on a solar system it would not be appropriate, as it is more expensive than other technologies. To invest in 1 kW of solar the cost would be 8 dollars/W. For all the technologies solar is the most expensive of the renewables, and gasification is cheaper. Solar is the easiest to install, and training for maintenance is easy, however. Solar is also not as dynamic as generators, but the main reason is the finances.

4: Pros and cons of different technologies

Solar PV mini-grid
Good for lighting and sockets. Not the first choice of productive use (the grain mill). But for public use it is fine because that is normally steady.

Hydro turbine mini-grid
The hydro turbine can be used for all loads, including productive use.

Bio gasifier mini-grid
It is more applicable for productive use, but not the steady lower loads such as for lighting. They also have a lot of logistical issues due to fuels and having to farm them, etc.

Diesel generator mini-grid
It is good for productive use, but should be looked at from a business case point of view, compared to other generators. CREEC has never dealt with diesel, and therefore have limited knowledge about this.

Solar PV-diesel generator hybrid mini-grid
Hybrid systems could have potential for solar for steady consumption such as for households, and the generator (diesel or gasifier) for productive dynamic loads.

5: Which technology is in your experience the best and which one is the worst?

The best is hybrids, and a combination of all technologies. This is because one is better for lighting and household consumption and one is better for productive use. It depends on the demand and place. In several cases hybrid solutions would be most applicable, instead of using one source only.

30th of June 2015

Interview Opio Innocent Miria, former CREEC head of pico hydro and gasification, on feasibility of gasifiers

What are the benefits of gasification for rural electrification?

They maximise the rural agricultural waste, such as for example saw dust or rice husks. The electricity can be used for productive use. There is an example in Gulu, where there was no electricity and a gasifier was installed for productive use, which had the consequence that the locals made more money.

What are the issues of gasification for rural electrification?

It is a good technology. The problem is the technology gap in Uganda. You have to train someone to run the gasifier properly, and especially in the village it can be a challenge to get people to understand the technology and how to operate it properly. This also comes from the fact that the technology has not been sold in a wider range. Another issue is that sufficient feed stock and waste materials have to be available, and they might not always be so, locally.

Is gasification a feasible technology for rural electrification?

Yes. Based on the feedstock. Rice husks, maize cobs, wood chips, and alike are the most commonly available feedstock. Most gasifiers are designed for just one specific feedstock, but dual gasifiers can use all kinds. It is an issue if the technology is too complex. Especially if a component breaks as there probably will be no spare parts available. These things have to be ordered from the U.S. or other places abroad, and it can take a long time. Rural people do not want to wait for three months for spare parts to fix the broken gasifier. This is something that also damages the reputation and trust in the technology and it is bad for morale. A good system for procuring spare parts locally in Uganda is necessary. Self-reliance can be important and consumers are not with this technology because of not having parts locally.

Are there specific sizes which are better than others?

Micro gasification can work based on how it is designed, as gasification is size based. If it is designed to work for a 10 kW engine, then it can do so, but it cannot go above that.

One gasifier at CREEC has a very innovative design, but fail often and need special components from overseas, which is an issue, but the simple ones have lower efficiency. Is this correct, and can you say some more about this?

One issue of this specific gasifier is that the material of the gasifier was made for lab testing, and not in the “field”, where it is affected by Ugandan weather and climate. The materials melt, when used in Uganda.

The more simple gasifiers work fine, but as they are not electronically controlled as the other one, it is upon the operator to know how to maximise the output of it, which as mentioned is also an issue.

The main step forward for gasifiers in Africa is to research a design that fits materials and feed stock of local context.

7th of July 2015