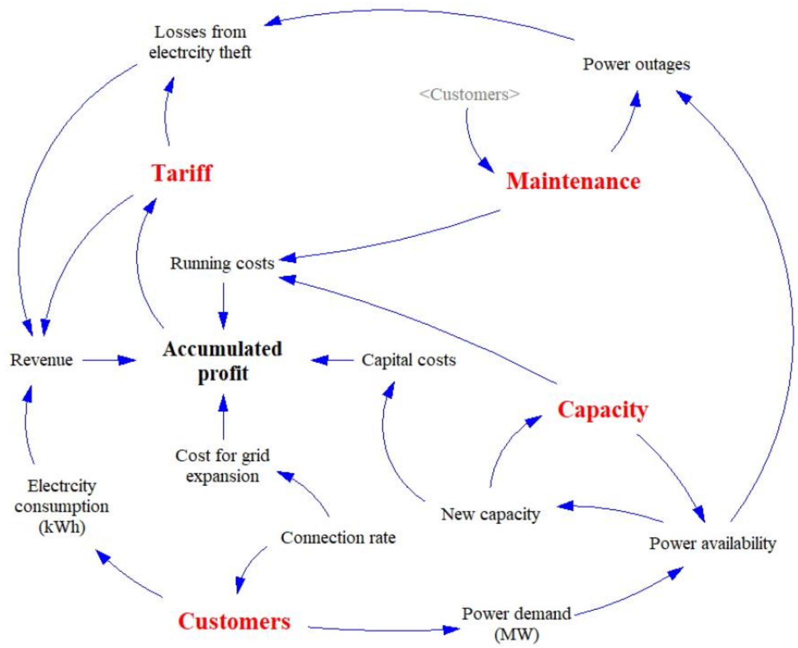

Analysis of how universal access to electricity may impact the long-term viability of the electricity sectors in Ethiopia and Kenya

A field study of grid maintenance followed by system dynamics modelling and simulation

Master's thesis in the Sustainable Energy Systems and Industrial Ecology programs

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CHALMERS UNIVERSITY OF TECHNOLOGY
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Cover: Conceptual model of feedback loops between different factors in the electricity sector.

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Abstract

Ethiopia and Kenya are two of many countries that are currently making efforts to increase access to electricity within their countries, in line with the United Nations sustainable development goal about universal access to affordable, reliable and modern energy services by 2030. The countries have targets to reach universal access to electricity by 2030 and 2022, respectively. This master thesis consist of a qualitative analysis based on field studies and interviews to investigate how maintenance of the grid is performed in Ethiopia and Kenya. It also consist of a quantitative analysis and simulation of grid expansion to investigate how universal access to electricity would influence the financial viability of the electric power sector in each country. The allocation of investments in grid expansion, such as new connections or maintenance, may determine the long term reliability and financial viability of the power sector. According to simulations in this thesis the grid expansion in Ethiopia will have to increase further in order to exceed the large population growth. Maintenance efforts and electricity tariffs also need to increase in order to maintain reliability and financial viability. The simulations show that Kenya are likely to reach universal access to electricity in the near future with maintained financial viability, mainly due to the increased maintenance efforts and improved grid design. The conclusion is further that more research is required in order to better understand the system behavior for large grid expansions.

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Lastly we would like to extend our heartfelt thanks to our friends Cristina, Diego, Marc, Mikael, Nima and Sonja for many lunches and fika breaks, crucial components for a successful master thesis.

Lisa Jodensvi and Niklas Torstensson, Gothenburg, (December 2019)

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1 Introduction

In 2015 UN adopted the 2030 Agenda with seventeen goals for sustainable development (SDG). The seventh goal is focused on access to energy. The first target of SDG 7 aims to *'By 2030, ensure universal access to affordable, reliable and modern energy services'* [3]. One way to supply people with green and modern energy services is to provide grid access and then make sure the electricity generation will reach SDG7. Considerable work has been done and by 2016 the proportion of the global population with access to electricity reached 87%. However, about 13% or one billion people out of the global population still lack access to electricity and many of them live in Sub-Saharan Africa [4]. Alternative fuels in these areas often have adverse impact on human health, both indirectly from carbon emissions and directly by fire hazards and indoor air pollution [5]. The population in the poorest parts of the world, where electricity access is low, is expected to increase substantially over the century. For electricity access to grow faster than the population the amount of household connections will have to increase substantially [4]. Such a dramatic expansion in the electric power sector can have an impact on the long-term financial viability of the electric power grid.

When increasing access to electricity, it is also important to make the electric power sector economically sustainable and the electricity reliable and affordable. In Sub-Saharan Africa the price of electricity is high compared to other developing regions, making it unaffordable for parts of the population. At the same time the income from electricity sales cannot cover the costs of production, transmission, distribution, maintenance and expansion. In general, the electric power supply in the region suffers from frequent interruptions and poor reliability. This forces some consumers to invest in backup generators, which increases their overall energy costs [6]. This can add up to several percent of GDP, which can have an impact on the overall economy and the utilities lose much needed revenue. That along with other financial inefficiencies will leave less money available for operation and maintenance. In the long run it can lead to degradation of assets, which leads to less operational efficiency and decreasing reliability. Financially viable utilities in the electric power sector is needed to increase access to electricity and improve reliability in SSA. Some of the factors hindering this is underpricing, insufficient bill collection and transmission losses [1]. Without improvements in these factors it may be difficult for the electric sector as a system to cope with the required expansion and to become viable in the long run.

Sub-Saharan Africa is a diverse region and there are wide discrepancies in the local circumstances, both with respect to the available energy resources and the financial situation. Many of the Sub-Saharan countries now work in line with the sustainable development goals from the United Nation and some have set the target to reach universal access to electricity by 2030. Ethiopia and Kenya both have targets and strategies to reach universal electricity access by 2030 [7, 8] but there are some notable differences in their electric power sectors. In Ethiopia capital expenditures related to investments dominates the cost for electricity. The government have made large investments in transmission infrastructure and power capacity increases through development of hydro power plants, but the running costs for the system are low. In Kenya on the other hand, the cost is almost evenly distributed between capital and running costs. The cost recovery, how much of the total cost of operation and capital investments that is covered by the cash collected, differs considerable between Ethiopia and Kenya. Ethiopia recover the running costs and a very small part of the capital cost, which means a cost recovery of only a small part of the total cost. In Kenya the situation is similar but also different, they recover the running cost and a part of the capital cost. But in this case it is a cost recovery of a much larger part of the total cost, although not a full cost recovery. This means that much of the capital cost in Ethiopia is not recovered, whereas in Kenya it is almost recovered [1]. Comparing two different countries in their attempt to reach universal access by 2030 can provide important knowledge about how the goals affects the long-term financial viability of their electric power sectors.

In both Ethiopia and Kenya the current levels of electricity access are quite low. Looking at the total population, 44% in Ethiopia and 64% in Kenya have access. *Table 1* highlights the large difference between rural and urban areas. The last years the connection rates have gone up rapidly especially in Kenya [9]. To keep the current level of electrification may nonetheless prove challenging, considering that between 2017 and 2050 the population of Ethiopia and Kenya will almost double, going from 105 to 191 million and from 50 to 95 million people, respectively [10].

Table 1: Percentage of population with electricity access in Ethiopia and Kenya. (World Bank 2017)

Country	Urban	Rural	Total
Ethiopia	97%	31%	44%
Kenya	81%	58%	64%

Many development agencies and NGOs are working with improved energy access and electrification in developing countries. The Swedish International Development Cooperation Agency (Sida) have been funding many electrification projects throughout the years and some of the funds have been allocated to increase access to electricity through grid extension [11]. In Ethiopia and Kenya the World Bank and the government, respectively, have promoted connections to the electricity grid by favourable loans to utilities and customers [12]. But to the knowledge of the authors, there is a lack of research on how the funding of connections affects the economy in other parts of the electric power system.

1.1 Aim

The aim of this project is to investigate the differences between the electric power sectors in Ethiopia and Kenya, with particular focus on how operation and maintenance is performed. This is done in order to understand how universal access to electricity influence different factors within the electric power sector in the countries. The project should contribute to increased knowledge and understanding of how the pursuit of universal access to electricity may impact factors such as connection rate, tariffs, electricity theft and cost recovery in developing countries.

1.2 Limitations

The comparative study of the electric power grids in Ethiopia and Kenya is limited to investigate the electricity sector of grid utilities in the two countries. A simplified model is used and the model only includes factors with strong (direct or indirect) relationship to the financial viability of the electric power sector. Many factors that influence the electric power sector is modelled, such as tariffs, maintenance and reliability, but the depth of detail is limited.

1.3 Research question

In this project the following research questions are answered:

- How is maintenance of the grid performed in Ethiopia and Kenya? Which factors are dominant?
- How does universal access to electricity influence the financial viability of the electric power sector?

2 Background

In this section the information in the introduction is expanded and additional background knowledge is provided.

2.1 Energy and access to electricity

Energy access can have different definitions but generally involves energy supply, energy services and energy consumption. There are also many different kinds of energy. Energy is used as electricity to power light and other electronic equipment for household, commercial and industrial use. Energy is also used for heat, transportation and more. In this study, electricity is the only form of energy investigated. The concept of access to electricity or household access to electricity can be defined in a variety of ways and have different meanings, from an actual household electricity connection to an electric pole in the village [13]. Grid connection in itself is not sufficient as it excludes information about whether the consumer actually can afford to use electricity or if the power supply is sufficient. Newly connected households often have low consumption in the beginning, but this may increase over time [14]. Simple definitions and binary metrics, such as access or no access, fails to take in the complexity of the electricity access. Concepts like the electricity quality, amount of electricity, reliability and affordability are typically not included. Efforts are underway to define and measure access to electricity by household interviews within a more detailed multi-tier framework (MTF) developed by the UN and the World Bank, but this initiative is recent and historic data on access to electricity within the framework are not available [13].

2.2 Connections

One of the big challenges for increased access to electricity is to increase the number of grid connections. While high tariffs can be a problem, many households can afford monthly bills for consumption especially considering that the cost of the alternatives (kerosene, batteries or candles) often are more expensive. It is generally harder to afford the grid connection charge, which in many countries in SSA must be paid up front. If this cost is distributed over time it is easier for customers to afford it [12]. In both Ethiopia and Kenya connections have been subject to different levels of subsidises over the years and different programs have been and are present. In the programs, the customer typically has to pay a smaller part of the connection cost up front and pay the rest over a couple of year to a low interest rate [12]. In both countries there is much variation in the total cost of connection, where the most important factor is on distance to the grid [8, 7].

Often higher standards and expensive over-dimensioned material and equipment than required are used. It is possible to lower connection costs and connection charges by implementing cheaper technologies and materials, buying material in bulk and properly dimensioning the equipment for the lower loads that are common in households in poor urban and rural areas [12].

2.3 Financial situation in African utilities

Few countries in SSA cover all costs in the electricity sector and many fail to cover even operational expenditures. Without performance improvement it will be difficult for the utilities to subsidise and make electricity affordable for the poor [15]. The quasi-fiscal deficit (QFD) is an important concept when discussing financial viability and is used when analysing the electric power sector finances and measuring hidden costs in state owned utilities. For power utilities the QFD can be seen as the difference between the revenue charged and collected by the utility and the required revenue to cover operating costs and capital depreciation. An example of quasi-fiscal activities can be when a government subsidise utility finances and it can have a large effect on the economy of a developing country. The QFD is difficult to measure but some important contributing hidden costs are underpricing, transmission and distribution losses, bill collection and overstaffing. Their contribution to the total QFD is shown in *Figure 1*.

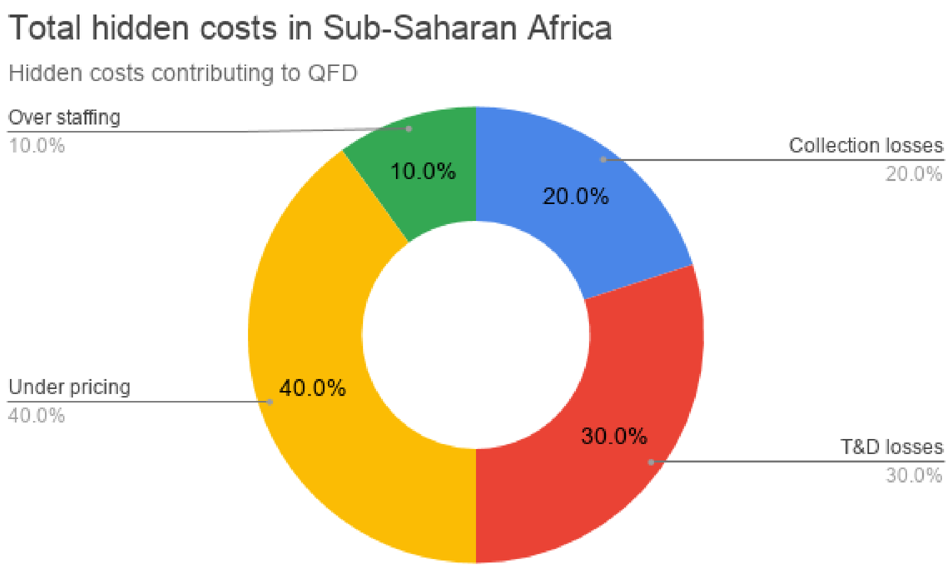

Figure 1: Hidden cost in utilities in Sub-saharan Africa [1]

Underpricing is the largest contributor to the QFD. Non-technical losses associated with transmission and distribution follows close behind. The non-technical losses is not measured directly, but there are international benchmark values available for technical losses in the grid. The non-technical losses in the network can then be defined as all losses above the benchmark value for technical losses. The non-technical losses includes meter tampering and theft and can be substantial in SSA, while close to zero in well managed power systems. Losses from bill collection are also significant, although this can be limited by using pre-paid meters. Staff costs can also be a substantial part of the utility operating cost. Many utilities in SSA have high staff levels, with an overstaffing range from 25 to 65% in most countries.

The QFD is not static but overall the pattern have been reasonable steady over several years. Countries with low QFD have in general kept improving where as high QFD countries see little positive changes. If the QFD is divided according to consumer category, residential consumers are the largest contributor while commercial and industry are significant but about half as large as the residential share [1].

2.4 Tariffs and pricing

In general, the average electricity tariff in Sub-Saharan Africa is high, even though the tariff is heavily subsidised and few utilities in the region cover more than operating costs. Utilities only gather a proportion of the required revenue, making it difficult to afford maintenance and investments which in turn limits the possibilities for network expansion and quality improvements. Governmental interventions in the tariff structure are heavily influenced by political considerations and people already with access tend to have large political influence and appreciate continued low tariffs [6].

The most common electricity tariff structure in the region is block tariffs, where consumers belong to different blocks depending on how much electricity they consume in a certain amount of time. The price of electricity change depending on which consumption block you belong to. One way to cover subsistence needs for poor households is to use lifeline tariffs, where consumers using low amount of electricity get lower rate by cross-subsidies. There is evidence that lifeline tariffs can help reduce household costs for energy [14]. The lifeline tariff can be the first tariff block and is often limited to about 50 kWh/month in SSA. Typically in the following tariff blocks, the cost increases with higher consumption and this tariff structure is called increasing block tariff (IBT). In some countries the threshold for lifeline tariff is very high and only customers with a very high consumption pay sufficient for the utility to achieve cost recovery [6].

In Ethiopia, electricity prices are low and studies have shown that consumption there is not to a large extent sensitive to the increasing electricity price in the current IBT structure. The reasons for this is suggested to be poor knowledge of the tariff structure or low prices [16]. In many countries in SSA it is common to share meters and this is especially common in Ethiopia. There is a risk that the households that share meters ends up paying more for electricity than they should, if they end up in a more expensive tariff block [15].

Consumption subsidies are common in Sub-Saharan Africa, but research suggests that focus on connections can be a more fair and cost-effective way forward. It is often more difficult for consumers to afford a large lump-sum connection charge compared to continuous charges on consumption. The large upfront costs sometimes required can force consumers to choose other energy sources, more expensive in the long run compared to electricity. With targeted subsidies towards connection costs rather than consumption, evidence suggests that tariffs in SSA in general could be increased to some extent without significant effect on poverty levels [6].

2.5 Reliability

Reliability is another important aspect when discussing access to electricity and there are several ways to measure reliability in the electric power system. In this context, it measures the ability of the power system to perform its function [17]. If you have a grid connection but suffer from frequent or long outages the consumer cannot rely on electricity. This can result in the use of other, less sustainable energy sources. To increase access to electricity in order to reduce the use of unsustainable energy sources, one must therefore also increase power reliability. In this report two kinds of outages are considered. One is load shedding and power outages that occur due to insufficient power generation, when supply is less than demand. The second is outages due to interruptions in the transmission and distribution grid, cutting off the connection between the power generation and the consumer.

In order to make it possible to make comparisons between different systems, three well defined reliability indices is used. The common indices give equal weight to each customer, meaning that a residential customer is given the same importance as industrial users [18]. The System Average Interruption Duration Index (SAIDI),

$$SAIDI = \frac{\sum[Customer\ Interruption\ Durations]}{Total\ Number\ of\ Customers\ Served}[h/yr]$$

measures how many hours the average consumer will be without power in one year. The number of interruptions is often presented in the System Average Interruption Frequency Index (SAIFI),

$$SAIFI = \frac{Total\ Number\ of\ Customer\ Interruption}{Total\ Number\ of\ Customers\ Served}[/yr]$$

which describes the number of interruptions for an average customer during one year. The average length of an interruption is measured by the Customer Average Interruption Duration Index (CAIDI) which is calculated according to

$$CAIDI = \frac{\sum[Customer\ Interruption\ Durations]}{Total\ Number\ of\ Customer\ Interruptions}[h]$$

Even though interruption of the power supply is prevalent in SSA and the frequent outages can be considered a very serious problem, few utilities measure quality of service and report data on reliability indices. Average outage duration, total number of outages or system interruptions is reported to varying extent [15]. SAIDI and SAIFI are rarely reported and methods for measurements and methodologies may differ [1]. In theory these indices makes it easy to compare and benchmark reliability for different utilities, but the real world is more complex. In practice many factors makes comparison difficult, among them differences in geographical circumstances, data gathering practices, index definitions and accounting for major events can be mentioned. Some distribution networks can cover complex terrains, for example dense forests and mountains, or be subject to severe weather conditions. Definition of what kind of major events that validates exclusion of particular large interruptions vary as well, and rural and urban areas are subject to very different challenges when it comes to reliability. Reliability indices are important when comparing utility performance, but the mentioned complexities must be kept in mind. Customers connected to the distribution network have little possibility to change network if reliability is poor. Utilities can be under pressure to cut costs which can lead to network deterioration and diminished reliability. To protect customers from this, regulatory authorities can set targets for reliability and incentivise utilities to improve indices like SAIDI or SAIFI [18].

2.6 Maintenance

Maintenance is required in the electric power system to prevent failures and interruptions. Systematically, maintenance can be categorised into run-to-failure, periodic, condition based or reliability centered strategies. Run-to-failure maintenance is the least complex of the strategies and means that equipment is repaired after breakdown. This type of strategy does not increase reliability as it does not prevent future interruptions. There is also periodic maintenance, with this strategy maintenance is simply done periodically whether it is needed or not. This can improve reliability, but could be costly if the periodic maintenance is done too often. Condition based maintenance requires more monitoring of equipment and is done when necessary according to certain criteria, where as reliability centered strategy also weighs in other factors like equipment condition, how important the equipment is to the system and cost [18]. Maintenance can also be divided into planned and reactive maintenance [19]. Run-to-failure is then a type of reactive maintenance (RM) where the other can be considered types of planned or preventive maintenance (PM).

Tree trimming, control of vegetation close to power lines, is an important maintenance activity and one of the largest operational costs in many distribution systems. It can be done periodically but is quite well suited for reliability centered maintenance where trees with large impact on customer reliability are prioritised [18].

2.7 Electricity theft

The power system is subject to transmission and distribution (TD) losses of both technical and non-technical character. Technical losses concerns electric power loss during transmission and distribution when electricity pass through transformers and lines. Quality of equipment and the amount of maintenance performed influence the amount of technical losses [20]. Non-technical losses involves electricity the utility produces but get no revenue from, i.e. electricity that is consumed somewhere but not registered due to reasons like theft, tampered meters or under-reading of consumption [1]. The total TD losses range from about 6% in very efficient systems to over 30% in some places. Total TD losses at 16% can be regarded as a system with extensive theft [20]. There are four categories of theft: fraud, stealing electricity, billing irregularities and unpaid bills. For the utility this means that income is reduced and customers that does pay may have to pay more to make up for the shortfall. Measures to reduce theft include technical methods to prevent electricity meter tampering, managerial methods e.g. better paid workforce or system change e.g. privatization to incentivise the utility to make profit [20]. The importance of cultural aspects should also be taken into account when investigating electricity theft. This can be done by using a relational approach and paying attention to socio-technical factors. Customer moral, relationship and trust between consumer and supplier are some key concepts involved in this approach [21].

Research indicates that electricity theft can influence both tariffs and power shortages [22]. Electricity theft is elastic, especially with respect to electricity price but also to some extent with respect to reliability. If interruptions are frequent the theft may increase and utilities heavily burdened by this can not cover their costs. This can in turn affect investments in capacity and lead to electricity shortages. Lower losses from theft can increase efficiency and limit the utility needs for increased tariffs.

3 Theory

In this section some of the theory behind the chosen modelling tool used for simulations and data analysis is described. Important concepts such as casual loop diagrams, stock and flows and reinforcing and balancing loops are explained.

3.1 System dynamics

System dynamics is a modelling tool used to apply system thinking when studying and modelling systems. It has been used for many years to model generation capacity expansion and the behavior of the electric power sector regarding costs and energy choices. System dynamics can also be used to model other aspects, such as assessing environmental and economical impacts from different energy mixes or policies [23]. In system dynamics the interaction between factors within the system is in focus. When the governing rules and the relationship between variables in the system are specified it is possible to explore how changes in rules and relationships affect the system. This generates an endogenous, internal, explanation for the system behaviour as opposed to exogenous explanations that concerns input from factors outside the system boundary [19]. Current research at Chalmers about socio-economic effects of electrification in developing countries incorporates system dynamics in some models [24].

The electric power sector can be modelled in various ways using different methods depending on what part or what function of the system that is being studied. The full system of the electric power sector is complex and dynamic, influenced by factors such as politics, economy, weather, climate as well as social and environmental aspects. To capture some different factors and the dynamic system behavior, systems thinking and system dynamics modelling can be helpful. Sterman describes the challenge of modelling our complex society with a metaphor: *'We are all passengers on an aircraft we must not only fly but redesign in flight'* [19, p. 4]. We are changing the electricity system while we are using it, living within it and depending on it.

In system dynamics, relevant factors and relationships between them can be visualised with a causal loop diagram (CLD) to show the feedback structures within the system. The causal relationship between different variables (factors) are visualised by arrows and signs, indicating a positive or negative relationship. A positive sign means that if the factor at the arrow base increase, the factor at the arrow point will increase as well, and the other way around. If the change takes time a delay can be indicated with text on the arrow. The two most important feedback loops appearing in a causal loop diagram is the balancing feedback loop and the reinforcing feedback loop. Both of them can be useful and troublesome in different ways. One example of a balancing loop is the one of traffic congestion (*Figure 2*) and one example of a reinforcing loop is the one of study stress (*Figure 3*) [19].

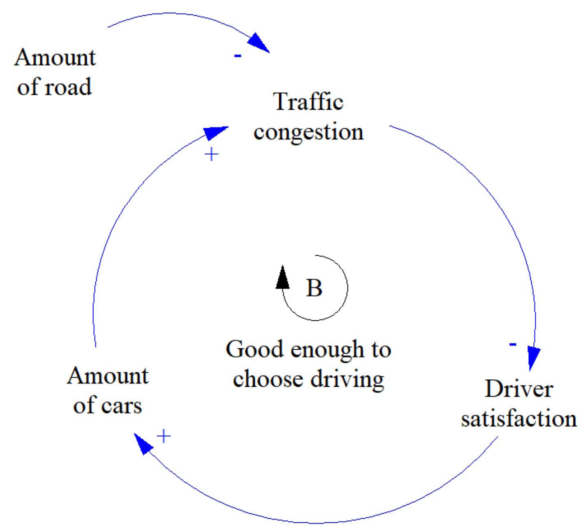

Figure 2: Causal loop diagram describing traffic congestion with a balancing loop

Too many cars and too little road will create traffic congestion, this will decrease the amount of new drivers joining that system. The solution to traffic congestion is usually to build more road. This will reduce the amount of traffic congestion, but only for a while. As the driving situation gets better more people will like to drive in this system and after some time we will get back to the same ratio of cars per road and the same traffic congestion. Self balancing loops are hard to change since their natural behavior is made to change back again.

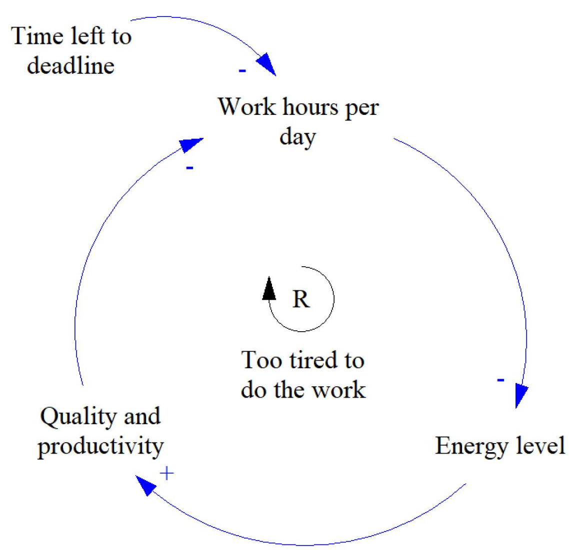

Figure 3: Causal loop diagram describing study stress with a reinforcing loop.

As deadlines are approaching students need to work harder and longer hours, which makes them tired. Being tired will lower the quality and productivity of their work which means they will have to work even harder and even longer hours than before to finish on time. Reinforcing feedback loops will eventually cause a system breakdown if they continue long enough, and if they are not compensated by a balancing part in the system.

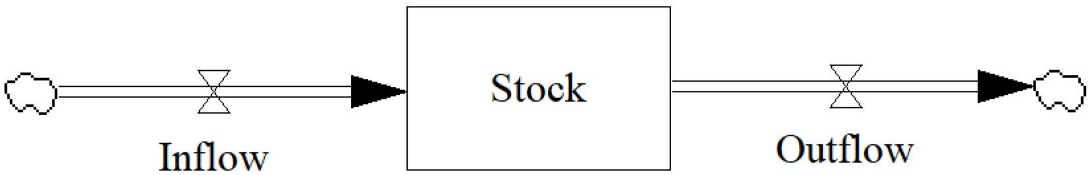

Figure 4: A simple stock and flow diagram

Casual loop diagrams are good for visualising mental models and to capture interdependencies and feedback loops [19]. In order to fully model and simulate a system, apart from variables and arrows also levels (stocks) and rates (flows) must be added. The stock-and-flow diagram (*Figure 3.1*) is used to describe the state and physical structure of flows of the system. The stock may be any kind of unit like time, material, customers etc, and the rate describes how the stock is either increasing or decreasing. The stock and flow may add delays and inertia to a system. One example is if we want to keep a steady long term average of our stock but accept short term variations, then we do not have to fill and empty the stock at the same time. And if the stock is large enough, a change or intermittency in the inflow does not necessarily have to cause any change or intermittency in the outflow. Time delays and non-linearities may also be added through equations.

Positive feedback generates growth and negative feedback cause a goal seeking behaviour [19]. If there is a delay in the system negative feedback will cause oscillations. There is also other complex behaviour that are caused by a non-linear combination of feedbacks and delays, such S-shaped growth. Mathematically this resembles a sigmoid or logistic function.

4 Method

In order to answer the research question for this project, the relationship between cost recovery, economic sustainability, tariffs and reliability were investigated through a literature study, a field study, data gathering and system dynamic modelling. The two research questions formulated in the introduction are quite different, with focus on maintenance and on financial viability. System dynamics are useful for both questions, but the first question is of qualitative character not easily explored by simulation. The question about financial viability is suitable to model and simulate. For this reason, there is one chapter for qualitative analysis and one for quantitative.

The project work was divided into five main tasks: *literature study and preparatory interviews* - to gather information and increase understanding of the electricity sector in Ethiopia and Kenya; *data gathering from public databases* - where open access databases were searched for relevant model data, to define what data was lacking and needed to be gathered during the field study; *Interviews in Ethiopia and Kenya* - to learn more about operation and maintenance in the electricity sector, how repair work is conducted and also to gather specific missing data for the model; *initial maintenance sketching* - based on background information and to use as a base for further information and data gathering; *model verification and result analysis* - the part where qualitative and quantitative results are produced and analysed. The electricity systems of Ethiopia and Kenya are here being qualitatively modelled in causal loop diagrams and analysed, to gather the qualitative results about the system behavior. The system is then quantitatively modelled, simulated, calibrated and tested in the system dynamics model, to gather the quantitative results about the system behavior. In both parts the results are discussed and answer to the research questions of the project are sought. The project work has been performed in the order mentioned. But as the modelling process developed more additional information and data requirements arose. It has therefore also been an iterative process, where all steps (except for interviews in Ethiopia and Kenya) have been dealt with more than once.

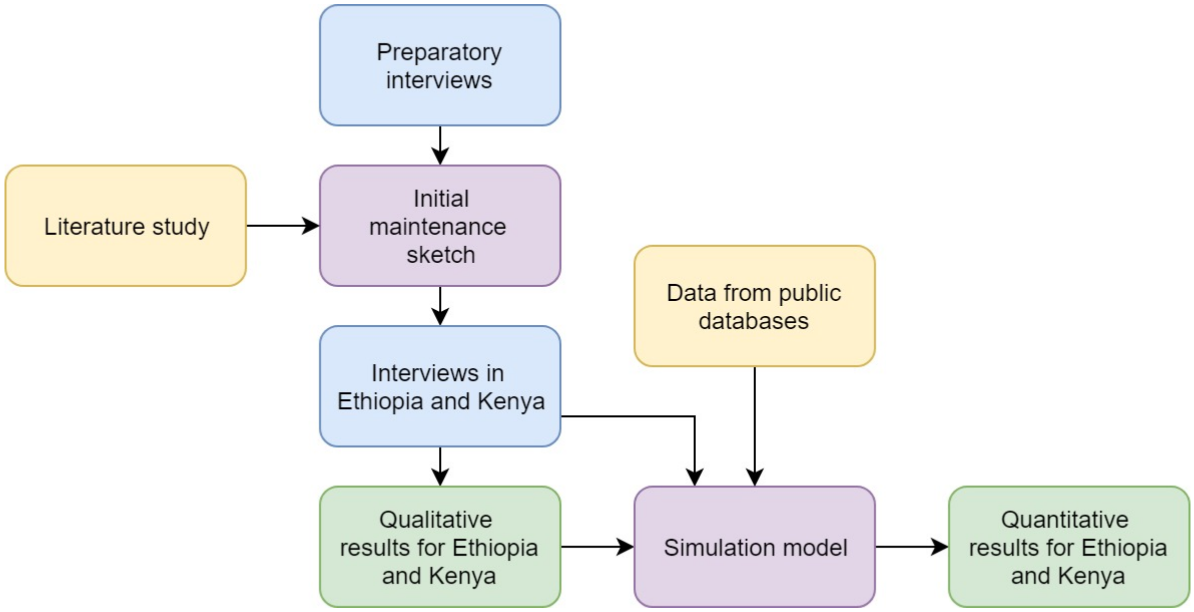

Figure 5: Flowchart describing the Method process. Interview work in blue, data work in yellow, modelling work in purple and results in green.

4.1 Literature study and preparatory interviews

When modelling and simulating any complex system, it is important to first of all develop an initial understanding about the system. This is important in order to construct relevant models that describes and closely resembles the actual systems being modelled.

The literature study consisted of knowledge and information gathering as well as some specific data gathering for general understanding. Most of the initial reading was articles about electrification projects in sub-Saharan Africa from the world bank group, research from different universities and also a few master thesis project investigating specific grid characteristics (see section background) as well as other papers.

Apart from reading, information was also gathered through some preparatory interviews and discussions with professors and PhD students at Chalmers and a few others. This was done to help us focus our work and to prepare for interviews during the field study in Ethiopia and Kenya.

4.2 Data gathering from public databases

Gathering data from public databases was an iterative processes done continuously during the study. To begin with, data was gathered to map what data was currently available and easy to access. This made it possible to see what data was comparable and not for Ethiopia and Kenya and also to understand the historical development of the electric power sector in the two countries. Some data was difficult to find and other data needed further verification before use. Specific questions regarding this data were formulated for the interviews to be carried out in Ethiopia and Kenya. Most of the data was gathered from large public databases, such as World Bank database, UN database and Africa Infrastructure database.

4.3 Interviews in Ethiopia and Kenya

For further understanding as well as additional information and data gathering for the modelling and simulation, a field study was required. The planning of the field study was done at Chalmers University of Technology in Sweden. The field study was fully planned and carried out within the project. No external participants or organisations were part of the planning but funding through scholarships was obtained. During preparations of the field study, meetings were set up with companies and organisations in Addis Ababa, Ethiopia, and in Nairobi, Kenya. The study was carried out between the 8th of May and the 5th of June 2019. Approximately two weeks were spent in Ethiopia and two weeks in Kenya.

After arriving to Addis Ababa in Ethiopia, more meetings were set up with assistance from Addis Ababa Institute of Technology (AAiT). Interviews were carried out with the Ministry of Water, Irrigation and Electricity (MoWIE), Ethiopian Electric Power (EEP), Ethiopian Electric Utility (EEU), together with the previously planned meetings with AAiT, ABB and an independent consultant. A guided tour of the electric grid in Addis Ababa was also done.

In Kenya, through Jaramogi Oginga Odinga University of Science and Technology and Strathmore University, meetings were set up with the Energy Regulatory Commision (ERC) and with the Kenya Power and Lighting Company (KPLC) at the financial department, department of grid management and the Institute of Energy Studies and Research (formerly known as the KPLC Training School). Three study visits were also done, to the geothermal power plant Olkaria VI operated by Kenya Electricity Generating Company (KenGen), to the solar product company M-Kopa Solar and with help from the organisation Wale Wale, a guided tour with residents from the neighbourhood Kibera in Nairobi. Kibera is the largest urban slum in Nairobi where electricity theft is common.

During the field study the approach of scheduling interviews in Ethiopia and Kenya varied. In general, flexibility in schedule and a lot of traveling time was required. The accessibility and quality of required information and data varied. Not all required data was available and not all of it was measured according to international standards, but improvements for documentation and measurements are being implemented continuously.

The interviews carried out were qualitative and semi-structured. Focus was on words and meanings rather than numerical data and standard methods for this type of interviews were used [25]. With this approach we tried to create a closer relationship with the person interviewed, to get a deeper understanding of the their viewpoint. The interview focus would often change depending on how the interview developed. In a semi-structured interview it is possible to use more open questions and follow up with further questions to clarify. An advantage with this approach was that it allowed us to explore unexpected answers regarding new topics that were unknown to us. There was a risk that the answers given were adapted according to social desirability bias, where the participant will try to find the socially correct answer to the question. Therefore, the people interviewed were selected from different parts of the sector and their answers were compared.

In a semi-structured interview the researcher typically follow an interview guide but the questions can be open. The interviewer is flexible and can respond and adapt questions depending on the intervieweeâĂŹs answers [25]. During the preparations of the interviews a long list of questions and followup questions were prepared and organised into different categories regarding the different parts of the electricity sector. An interview would begin by asking the participant to describe the electricity sector and their role and function in this. Before asking any specific questions general and open questions would be asked about each topic to let the participant share as much as possible of their own experience and knowledge. A general plan was always prepared before each interview for what categories of questions should be in focus. But this would often change during the first description of their role in the electricity sector. One example was at the Energy and Petroleum Regulatory Authority (formerly the Energy Regulatory Commission) in Kenya, where questions about the tariff were prepared to be in focus. It turned out that the interview subject had worked in many different parts of the electricity sector for several years and could therefore answer many questions from different categories.

Interviews are considered an effective way to gather data when modelling system dynamics and semi-structured interviews are deemed particularly effective [19]. To get a broader understanding of the system, many different stakeholders with different viewpoints and positions were interviewed. These interviews were later complemented with information from other data sources and from the gathered data a causal structure of the system could be constructed.

4.4 Initial maintenance sketching

To model relevant factors and their relationship in the electric power sector the system dynamics approach was used in the Vensim® modeling software. System dynamics modelling is a helpful tool for this kind of complex and dynamic modeling and it was used to investigate how the different factors and feedback loops interact with each other.

An already initiated model built on research at Chalmers [24] was used as a base in this project. This model was refitted according to the five steps of the system dynamics modelling process [19]:

1. Problem articulation
2. Dynamic hypothesis
3. Formulation
4. Testing
5. Policy formulation and evaluation

The base model used in this project describes the linkage between some critical parts of the electric power sector in developing countries [24]. The first three steps of the system dynamics modelling process (problem articulation, dynamic hypothesis and formulation) had to some extent already been implemented in the base model. These steps were performed again for this project to ensure model validity. Then the model was adjusted to fit present project requirements. Step three (formulation) was performed again for additional parts of the model in order to get relevant results to answer the research questions. The step of testing involved both qualitative testing and quantitative testing. The policy formulation and evaluation step is represented by the conclusions in this report (see *Figure 6*).

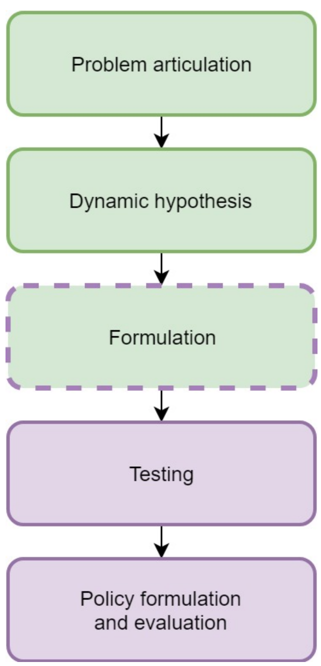

Figure 6: System dynamic modelling process.

There are four important subsystems in the system modelled:

- Number of customers
- Tariff
- Capacity
- Maintenance

These four parts, along with other factors, are all coupled to each other in the model and also to the system economy. The part of the model regarding maintenance was in need of further development and this required additional information about that part of the electricity sector. The first sketch of the extended maintenance part was a causal loop diagram constructed from relationships described in the information gathered through the literature study and preparatory interviews. This is further described in *Section 5*.

4.5 Model verification and result analysis

The qualitative result analysis was done with the information gathered during the interviews in Ethiopia and Kenya. This data and information was used to analyse and validate the qualitative model behavior, to adjust relationships and feedback equations and to see what factors and what loops were dominant regarding maintenance in the two countries electricity sectors. Qualitative causal loop diagrams were constructed to describe the maintenance process for each country.

The causal loop diagrams from the qualitative analysis were used as input to the final maintenance part, to be used in the full simulation model for the quantitative analysis. There was not sufficient quantitative data for calibration of all the factors described in the qualitative maintenance model. Therefore it had to be simplified further to be used in the final model. The maintenance model was adjusted according to available data and the other parts of the model. It was then combined with the other parts to create the final model used in the simulations.

The final quantitative testing for the modelling of the electricity sector in Ethiopia and Kenya was done through calibrations and quantitative results were gathered trough computer simulations. Historical system data was used to calibrate the model so that the model would behave in line with data for each country. Two different scenarios were simulated to analyse how the target of universal access to electricity by 2030 is affecting the electric power sector in Ethiopia and Kenya respectively and results from simulations were compared and analysed.

5 Qualitative Analysis

The qualitative analysis of the project is done to map and verify system behaviors in the electric power sector in Ethiopia and Kenya. This is done to increase knowledge and understanding of this system and system changes and to not just answer the question of what happens but also gain some understanding of how and why it happens.

5.1 Initial maintenance sketch

In the initial model sketching (see section Method initial model sketching) a more detailed sketch for the maintenance part was constructed to be used as a base for interviews and further mapping of the maintenance part of the electric power sector. The initial maintenance sketch is based on the literature study [19].

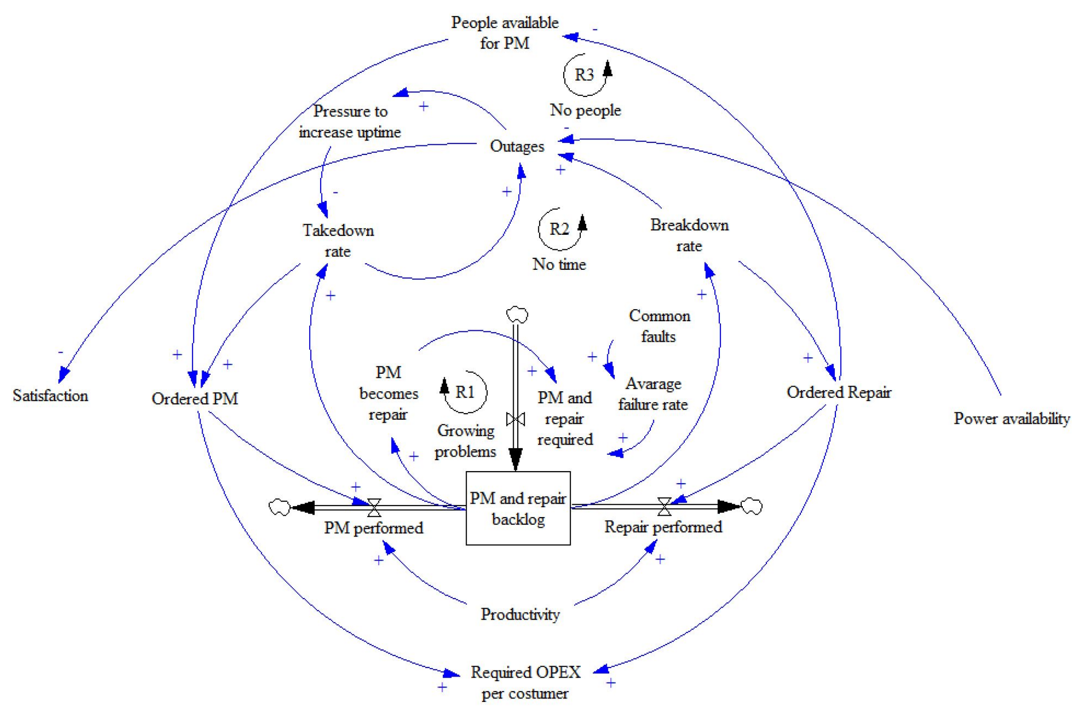

Figure 7: Initial maintenance sketch presented as a causal loop diagram.

Three reinforcing loops are identified. R1 is the reinforcing loop of *Growing problems*. If an insufficient amount of preventive maintenance (PM) is performed on a grid, the quality of the system will start decreasing and this may lead to a higher failure rate and more problems for the system. Insufficient maintenance performed is represented by an increasing *PM and repair backlog*. If the backlog increases then more and more small problems in the system will start to break down and turn a cheap and simple planned maintenance problem into a more extensive, costly and time demanding repair problem, which will further increase the backlog and so on.

R2 is the reinforcing loop of *No time*. This describes a scenario when there is a pressure to keep the system downtime as low as possible. If the power availability is low or the grid design is poorly done then planned maintenance of the grid could lead to many customers being without electricity. If there is a maximum amount of total downtime and if the *Breakdown rate* of the system increases then *Takedown rate* will have to be decreased as a short term solution. But less *Takedown rate* leads to less *PM performed* which will lead to a higher *Breakdown rate* and so on.

R3 is the reinforcing loop of *No people*. Most technical systems have a limited amount of people working with maintenance. Repairs usually have to be dealt with at once while planned maintenance can be put off for some time. A so called run to failure-scenario may occur where everyone has to deal with the most urgent problem. If the same people are working with both planned maintenance and repairs then an increase of repairs could lead to a lack of people available for the planned maintenance work, and therefore decrease the amount of planned maintenance performed.

5.2 Qualitative data and results

In Ethiopia and Kenya interviews with stakeholders resulted in qualitative data and information about the different factors and system behavior of the electric power sector in each country. The qualitative information in this section was visualised in conceptual causal loop diagrams to describe the repair and maintenance process for each of the countries.

5.2.1 Ethiopia

The overall maintenance process was described by staff from the EEU and is in general run-to-failure maintenance [26]. Interruptions are reported by customers to a call centre. When a number of customers have called in a problem, crew is dispatched to inspect and repair or in other ways solve the problem. According to an interviewed technician, preventive maintenance work is mainly in the form of changing oil and silica gel in transformers. Both preventive maintenance (PM) and reactive maintenance (RM) add to the *Repair and maintenance work* required in *Figure 9*. There is no general routine for documentation of component condition and *Required PM*. Common planned maintenance activities such as tree trimming are not done regularly, even though trees falling on power lines is a big problem *Figure 8*. Another example was protection against lightning strikes in transformers. This type of protection equipment is considered quite cheap and easy to install, compared to repairing the common and expensive transformer faults due to lightning strikes. The problem, according to the technician, is the lack of available documentation describing which transformers does or does not have this protection today [27]. The reason mentioned for the low amount of planned maintenance is mainly financial, but there is also the lack of documentation of the grid condition and the lack of *Skilled personnel* to perform PM [26]. Increased *PM* will typically lead to lower *Average failure rate* and lower *RM*. The actual *Repair and maintenance work performed* will have influence over *Total cost for maintenance work*, along with *Cost per maintenance*. The difference between the *Total cost for maintenance work* and the allocated *Maintenance budget* affects the PM being done. The interviewed subject from

EEU described lack of resources and budgetary constraints as a limiting factor in the maintenance and repair work. Lack of resources influence the choice of materials and components used, where usually the cheapest option is used [26]. This is often imported equipment from China which is perceived to be of lower quality and to have shorter lifetime. The *Size of component stock* followed by *Good parts available* are also influenced by lack of resources and will influence the *Quality of maintenance*. There are some plans to gain domestic capacity to manufacture electric power equipment but nothing is decided.

Figure 8: Example of maintenance and tree trimming needs in Addis Ababa, Ethiopia

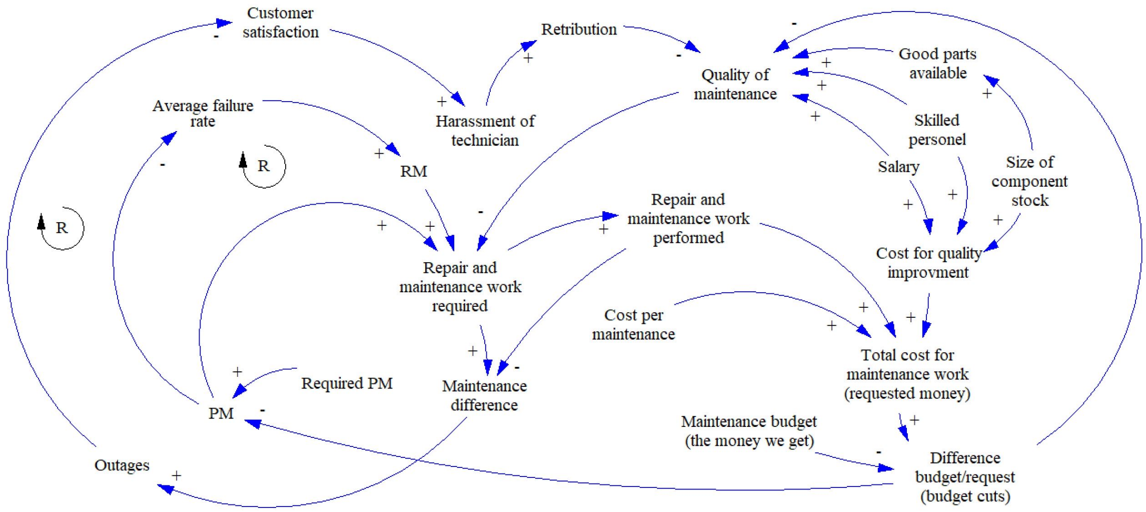

Figure 9: Causal loop diagram visualizing interview data about grid maintenance in Ethiopia.

Both engineers and technicians in EEU and others mention that knowledge level will have an influence on the connection of new customers, where technicians routinely put all load on the lowest hanging line available which often results in unbalanced phases and overload on the transformer [26, 27, 28]. This lack of *Skilled personnel* influence the *Quality of maintenance* and *Cost for quality improvement*. It is possible to balance the phases on a transformer retroactively, but this is not done systematically. Not balancing the phases is also considered as a lack of PM. According to technicians, this will often cause a fuse to blow, which is also the most common fault reported. Many technicians cannot afford daily expenses with only one job due to a low *Salary*, making it necessary to have several jobs. Technicians that either lack the skill or motivation and time will often fix the problem by installing a fuse of higher capacity, since it is the quickest solution to the problem. This on the other hand will then cause the next fault to damage the transformer instead of the fuse, and that is a much more expensive and complex problem to fix.

EEU perform reliability analysis of the electricity transmission and distribution, such as which feeders are suffering from the largest number of interruptions. Efforts to improve the problematic feeders will then take place and a decrease in the number of interruptions have been observed. Previously some data for outages and interruptions have been collected and recently also SAIDI and SAIFI have been reported. This data is however not on customer level but rather on feeder level.

In the interviews with EEU, it was described how the same stock of materials and components are used for many projects. Often components were taken to one project and then those components were out of stock when needed somewhere else. This resulted in the use of other components than what was actually required and this could lower the quality of the repair even if the component itself was of high quality. So the *Size of component stock* and *Parts available* influence the *Quality of maintenance* and the *Cost of quality improvement*.

This will then affect the rest of the system through the factors *Repair and maintenance required* and *Total cost for maintenance.* Large rehabilitation projects, where new substations are constructed, transformers are exchanged or common wood poles are switched to concrete ones are underway. But this kind of activities is performed on selected parts during a fixed project time. And even if it will greatly improve the reliability in Addis Ababa, it does not increase the amount of continuous planned maintenance performed. This type of project is typically financed by development aid from donors or favourable loans. Some donors require that the equipment used will be purchased from manufacturers from their country of origin, and in some cases this had resulted in lower quality in the equipment procured.

During the field study there were blackouts in Addis Ababa. According to both AAiT and EEU, the main reason for this was lack of water in the dams and this can happen before the rainy season [26, 29]. Power was rationed, exports was halted and some parts of the city was periodically disconnected. This is conceived as a lack of supply and the main solution is to increase power production by adding new production units and to lower system losses. Other interviews with persons outside the Ethiopian power companies indicate that although supply is a problem, cheaper and quicker measures to improve the situation could be done. Such as improving reliability and efficiency in production and distribution, demand management and better metering of power consumption.

According to personnel in EEU, electricity theft is low in Ethiopia among residential customers because people are afraid of getting hurt by electricity and they do not want to meddle with it. Also the low tariffs makes theft less interesting. The current cost of electricity is considered tolerable by consumers and most of the theft that does exist is mainly due to bad metering, problems related to collecting tariffs and corruption where industrial users pay to bypass the meter. A technician mentioned that industry engage in theft by bribing technicians to bypass the meter. There is an incentive for technicians to accept bribes due to the low salaries. In the causal loop diagram for Ethiopia theft today is considered negligible and is hence excluded in *Figure 9.* Technicians will also prefer to make repairs in richer areas, where they can obtain a tip for fixing an outage. In less fortunate areas, the quality of components used for repairs can be lower and the outages last longer. If an area has been subject to a long outage, this can result in harassment and threats towards the technicians. If an outage lasts more than a week the technicians run the risk of being kidnapped and held by residents in the area until power is restored. If this happens the power is usually restored quickly, but the crew sometimes exact revenge using bad parts which can result in future outages. This is visualised in the CLD where increased Outages lead to lower Customer satisfaction, which leads to Harassment of technician which is followed by Retribution and deteriorating Quality of maintenance. This will in the long run lead to additional Repair and maintenance work required which leads to increasing Outages, and does thereby create a reinforcing loop.

According to both EEP and EEU the tariff should have been raised in Ethiopia many years ago. The tariffs are considered quite low and have been low for a long time. The plan has been to make most of the profit from export, where the revenue/kWh is much higher than it is for domestic electricity sales. But due to low power production at times the amount of export can vary. According to the current plans domestic tariffs will now be increased slowly over the next few years, although the lowest block tariff will not be revised. In *Figure 9* tariffs do not affect customer satisfaction today, since they have historically been set at a fixed value. The cost of electricity is not something people are discussing, but rather the connection cost and the amount and duration of outages.

Regarding the power production in Ethiopia, the current situation and future developments were discussed mainly with EEP. The Ethiopian power system is highly dominated by hydro power. There is a large potential for increased production from hydro but also complementary power production from geothermal, wind and solar. Some diesel plants have been dismantled recently. There are plans for a number of new interconnections to neighbouring countries where electric power will be exported. Historically the government has been involved in financing generation expansion, but this will not be the case in the future. New generation will be financed and constructed by private investors in the form of independent power producers (IPPs) and several projects are underway. The projects are mainly solar and hydro but also some wind and geothermal (some of them are listed in appendix). Historically hydropower is the cheapest option but the interest for solar have increased as costs are dropping. Hydro power can be built in a few years after the decision is made, but the large projects often get stuck in different phases of development. The potential for delays in the large projects under construction was also emphasised in interviews in the EEU [27].

5.2.2 Kenya

From interviews with KPLC the actions taken when a service interruption occurs was described [30]. When there is an interruption, customers will call in to a call centre and a repair crew will be sent out to fix the problem. Reactive maintenance to repair equipment failures are common but some *PM* is also performed. Programs exist for inspection of the power lines and for tree trimming where land owners can be paid to clear trees close to power lines. A pilot project to balance the load on different transformer phases are underway [31]. According to both ERC and KPLC the big improvements seen in Nairobi during the last fifteen years regarding outages and power availability were due to large investments and design improvements of the grid [32, 30]. More substations have been constructed which have added redundancy in the distribution grid and thus improved reliability. It was expressed that although the investments had been costly, they were expected to generate lower costs in the future. With increase in power supply, the problems with load shedding and scheduled rolling outages occurs less frequently. There is currently sufficient spare production capacity in the system and a reinforced grid design to accommodate planned interruptions for maintenance of power plants. The overall structure for PM and RM in Kenya follows from *Figure 10* where PM influence *Average failure rate* which is followed by *RM*. According to interviewed engineers, some funds are allocated towards PM and some documentation is done by *Skilled personnel* which influence *Quality of maintenance*. Data have historically been collected on CAIDI and outage restoration time, but since year 2015 also more detailed data on SAIDI and SAIFI are collected. Most of the data and information about the grid is from Nairobi, but it was emphasised that the grid quality, grid design and maintenance work varies a lot around the country.

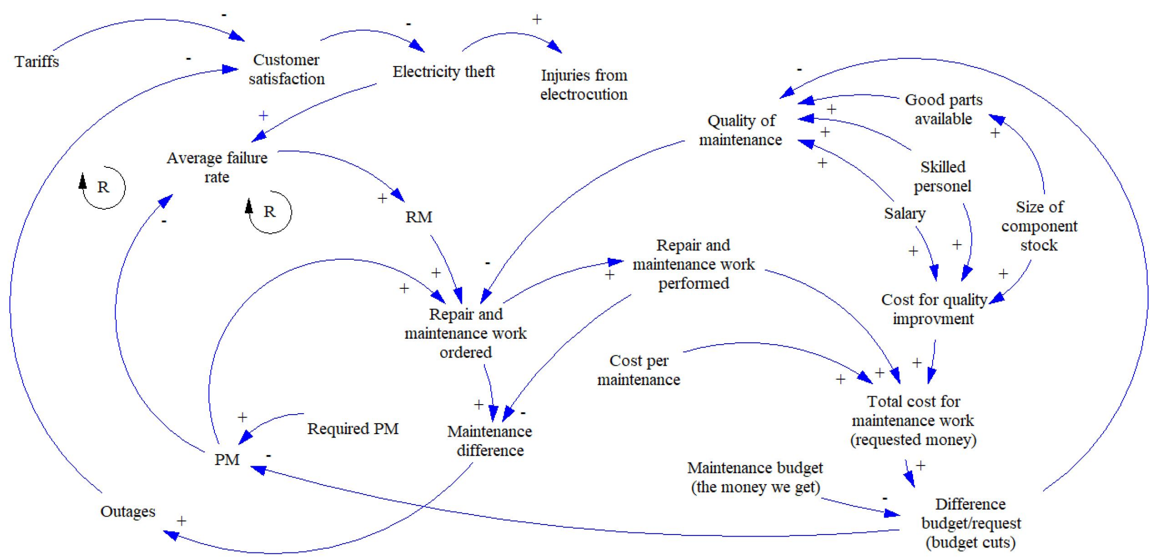

Figure 10: Causal loop diagram visualizing interview data about grid maintenance in Kenya.

In general, the factors contributing to the *Quality of maintenance* in the Kenyan electric power system in *Figure 10* is described to be influenced by a lack of *Skilled personnel*, which suffer from somewhat low *Salaries*. Also, a large problem with lack of *Good parts available* was described. According to KPLC they have recently lowered their number of employees and instead use contractors for many of their projects. Again the lack of *Skilled personnel* for maintenance work was pointed out to to cause quality problems, especially among the contractors. This lead to more *Repair and maintenance work required*, followed by increasing *Repair and maintenance work performed* and *Total cost of maintenance work*, and the interviewed kept track of especially the latter factor. Often the contractors have not been pre-qualified to do certain types of jobs, but there was hope that this will improve in the future as this is quite a new market. There is sometimes a competition between grid expansion projects and the maintenance department regarding the use of material and components in stock. So in reality all grid work was described to depend on a shared *Size of component stock* and material and this affects the *Good parts available* for maintenance. It was mentioned that this in turn will have implications for *Quality of maintenance*.

According to KPLC, cheaper equipment of lower quality is often used in Kenya [31]. High component quality (*Good parts available*) is not perceived to warrant the additional cost. KPLC mention budget cuts due to lack of finances as a big problem. ERC also describe the lack of finances as a problem, even if it is slowly improving, and both KPLC and ERC are working on raising the *Tariffs* further even if they are already quite high [32, 33]. There is a broad understanding among the personnel interviewed, however, that this influence *Customer satisfaction* and that this can lead to *Electricity theft*. Kenya utilise increasing block tariffs and the tariffs are adjusted every third year (with some exceptions, notably during election years since tariff revisions are politically sensitive). KPLC have a revenue cap that is decided by the ERC and this is considered along with input from customers and politicians when ERC sets the tariff. Pass through costs and adjustments in the tariff have been implemented, where costs for changes in inflation, exchange rate between currencies and global fuel prices are passed directly to the consumer. In interviews with KPLC it was mentioned that there is a general sense among the population that tariffs are high and that electricity and water are things that should be supplied almost for free by the government. The current lifeline tariff is below the cost of generation and is cross-subsidised by consumers in the higher consumption block. The tariffs are not fully cost-reflective, mainly due to the large expansion of the electricity sector that have been taking place, and KPLC is pushing for tariffs to be increased in the future. Politicians are trying to keep tariffs low to gain popularity among the public, and the residents interviewed certainly would prefer lower tariffs.

Electricity theft in Kenya is mostly connected to the *Tariff* in *Figure 10*, as well as social and cultural factors [34]. Grid reliability and *Outages* are also influencing electricity theft somewhat, or more accurate, the increased reliability have increased customer satisfaction and those who can afford the tariff does not complain much about it. In the large slum area Kibera in Nairobi, electricity theft is the most common way of getting electricity. According to residents interviewed in Kibera, the cost of illegal electricity can be about 3 USD (300 KSH) per month no matter how much electricity is used. Power from a legal connection would cost about 30 USD (3000 KSH) per month for normal household consumption. In the slum few households have a legal connection to the grid and distribution is handled by cartels that have put up a network of poles. Equipment are often stolen and accidents are common, some of which results in electrocution and death among local residents. A lot of the houses and the grid do not follow any technical standard or safety requirements. Circuit breakers and transformer oil can be stolen to be used in the illegal network or for other applications, creating interruptions and lots of additional work for KPLC. KPLC are still managing and maintaining the transmission grid passing through Kibera from which the electricity is stolen. Residents describe the complexity in the problem of the electricity theft in Kibera, where it is hard to get a legal connection even if you want to. Distribution grid, cables, meters and other equipment put up by KPLC is quickly removed by unofficial technicians in Kibera. A customer with a reliable and safe, legal connection, will soon have cables and components stolen or just an overloaded meter due to illegal extensions and additional load to their connection.

The electric power generation in Kenya was discussed with ERC [32]. There is currently much geothermal and hydro power production, but hydro have no potential for increased production. Geothermal is considered a stable source of power. To balance the intermittent power production from wind and solar, natural gas may also be needed. Some thermal power plants have been constructed recently to lower the average electricity cost, but the wish is to not expand this type of generation due to the adverse environmental impact.

5.3 Discussion

Some common practises and some differences regarding maintenance in Ethiopia and Kenya was found. In both countries RM and run-to-failure maintenance was common and PM was not fully implemented. This maintenance culture is likely to increase the *Average failure* *rate* and further increase the following *RM* in *Figure 9* and *Figure 10*. PM is, however, more common in Kenya, where typical PM efforts such as tree trimming is done. Tree trimming is, as mentioned in Section Background/maintenance, important PM in the west where utilities get penalties when there is an outage. More PM could influence reliability and the interviews does indicate higher reliability in Kenya compared to Ethiopia. In the countries studied, other indirect costs may be more important than possible penalties. Outages that are not repaired in time are here followed by decreasing customer satisfaction. The feedback of a direct consequence such as a penalty incurred when there is an outage is likely to have a quicker response, and the effect of the response can then be adjusted by the penalty. An indirect feedback may have a delay and may be complicated and difficult to adjust. Introducing a penalty may on the other hand create other indirect and unforeseen feedback loops. The indirect feedback of lower customer satisfaction has been seen to have different implications for the two countries.

In Ethiopia, there is a reinforcing loop in *Figure 9* where technicians run the risk of being harassed or even kidnapped when customer satisfaction reaches critical levels. Unattended, this reinforcing loop will at the moment make things worse and worse and is better adjusted and balanced as soon as possible. The efforts of increased planned maintenance done in Kenya did bring positive impact on reliability with a lower amount of unplanned outages and decreased load shedding. Increased planned maintenance in Ethiopia is likely the best balancing response to the reinforcing loop of low customer satisfaction. However, the tariff will sooner or later have to increase for investments to increase in planned PM and reliability.

In Kenya it is instead electricity theft that increases when customer satisfaction decreases. The tariff has the major impact on customer satisfaction in Kenya compared to Ethiopia. This is probably because both tariff and reliability is much higher in Kenya and the impact of the high tariff is even more notable for people with a low income. Increasing reliability would therefore probably have less impact on the electricity theft in Kenya. Changing tariffs would perhaps have an impact. But even with high customer satisfaction and a willingness by residents to get legal connections, the social and cultural aspects will make it hard to decrease electricity theft in a place like Kibera. The tariffs are significantly lower in in Ethiopia, especially for consumers with small loads, and this is probably one of the reasons why theft was not considered a large problem there. If tariffs are increased it is important to prevent this kind of organised electricity theft since it might otherwise be troublesome to get rid of. It is also possible that electricity theft will be delayed or lower in Ethiopia due to social and cultural factors. The effect of tariff increase on theft is difficult to determine, but it is likely that behavioural change among customers is delayed on implementation.

The most important factors affecting the quality of maintenance was similar for both countries, but there was some difference in the level of impact from the different factors. The lack of sufficient salaries and work experience for technicians was emphasised as a major problem in Ethiopia while in Kenya the size and logistics for the component and spare part stock seemed to have the largest impact.

6 Quantitative Analysis

In the quantitative analysis, the simulation results for the electricity sector in both Ethiopia and Kenya are presented. For each country two different electricity expansion scenarios are presented, simulated and analysed.

6.1 Quantitative data

In this thesis different sources for data have been used, some from databases and other from financial reports, national planning reports or scientific papers. Important databases was the Africa Infrastructure Country Diagnostic [35] and World Bank [36] and some of the literature and quantitative data was obtained from interviewees during the field study.

Much of the data is related to the economy of the electric power sector. The inflation rate in both Ethiopia and Kenya is high and variable (see Appendix). The data is presented in both local currency and USD, but later in the model all monetary values are converted into USD by using historical exchange rates [37]. This is done to enable a comparison of the two countries. Nominal USD values are used and no adjustment for inflation in USD have been made. The USD is assumed to be stable compared to the local currencies and suitable for modelling the future economy of the electric power sector and to perform comparisons between the electric power sector Ethiopia and Kenya, respectively. The tariffs used in the modelling is an average value derived from company revenue and the number of customers, sources for this was Africa Infrastructure Country Diagnostic [35] in the case of Ethiopia and KPLC annual reports [38] in Kenya.

6.1.1 Ethiopia

The number of formalised connections in Ethiopia is about 3.1M, but there is significant difference in the number reported by the EEU compared to values found in recent household surveys. The households with non-formal connections is about twice as many and this is possibly explained by extensive meter loading and sharing [8]. Previous growth in number of connections have been less than 10% per year [35] but the goal for the coming five years is about 15% per year [8]. The total average cost of a new connection is 650 USD but there is a large variation, explained mainly by distance to the centralised grid [8].

In Ethiopia, electricity prices are low and evidence suggests that customers do not respond to marginal increase of prices in the current increasing block tariff structure. The monthly electricity consumption is not significantly affected by electricity price and the reasons for this is suggested to be poor knowledge of the tariff structure or low prices [16].

The first consumption block is up to 50 kWh, for this lifeline level of about 0.01 USD/kWh (0.273 ETB/kWh) there will be no changes in the next few years but tariffs in other blocks will be increased *(Table 2)*. A more elaborate tariff structure with breakdown also for industrial consumers can be seen in Appendix.

Table 2: New electricity tariffs in Ethiopia (ETB/kWh)

Tariff amendment	Dec-18	Dec-19	Dec-20	Dec-21
Tariff category (kWh/month)	Birr/kWh	Birr/kWh	Birr/kWh	Birr/kWh
1st Block < 50 kWh	0.2730	0.2730	0.2730	0.2730
2nd Block < 100 kWh	0.4591	0.5617	0.6644	0.7670
3rd Block < 200 kWh	0.7807	1.0622	1.3436	1.6250
4th Block < 300 kWh	0.9125	1.2750	1.6375	2.0000
5th Block < 400 kWh	0.9750	1.3833	1.7917	2.2000
6th Block < 500 kWh	1.0423	1.4965	1.9508	2.4050
7th Block > 500 kWh	1.1410	1.5877	2.0343	2.4810

Future tariffs will be set every four years and there are plans to implement pass-through tariffs for fuel costs and inflation in the future [39].

Research on willingness to pay for reliable electricity show that customers would pay up to 25% more for improved electricity supply in Ethiopia (tariffs have changed since then) [16]. For manufacturing firms in Ethiopia the cost of power outages is considered substantial and for a reduction of the average outage length by one hour the firms were willing to increase tariffs by 33%, although there was considerable variation among respondents [40].

6.1.2 Kenya

In Kenya, the number of customers has increased by an average of almost 700 000 or 22% per year since 2010. The previous goal to obtain universal access to electricity by 2030 have been revised to 2022. Households too distant from the centralised network will be served by mini-grids or standalone solar photovoltaic systems. The aim is to make 5.7M new connections until 2022, where about 3.4M consumers will be connected to the grid and 2.2M consumers will connect by solar home systems. The cost of an average grid connection is assumed to be about 1000 USD [7]. As in Ethiopia there is large variation and connection of rural areas with long distance to the centralised grid are more expensive.

Table 3: New electricity tariffs in Kenya 2018 to 2019 (KShs/kWh)

Tariff amendment	1st July 2018	1st Nov 2018
Tariff category (kWh/month)	KShs/kWh	KShs/kWh
DC1 0-10 kWh	12.00	10
DC1 11-100 kWh	15.80	10
DC2 >100 kWh	15.80	15.80

Recently, the tariff blocks for domestic consumers (DC1 and DC2) was revised and the lifeline tariff was lowered from 0.12 to 0.10 USD/kWh (12 to 10 KES/kWh) *(table 3)*. The lifeline electricity consumption block was broadened from a maximum of 10 kWh to 100 kWh. Commercial and industrial categories are presented in the appendix. The Kenyan tariffs, in contrast to the Ethiopian tariffs, also have a pass-through cost for inflation.

6.2 Simulation scenarios

Both Ethiopia and Kenya have set up development strategies in line with the UN SDG:s. The two scenarios chosen for modelling and comparison of the energy sectors in the two countries are one scenario of universal access to electricity by 2030 and one scenario with a much slower expansion of the electricity sector. A slower expansion is expected to lead to a more balanced economy for utilities, as increases in income will compensate for more of the expansion costs. The two scenarios will both be used to for a comparison of the electricity sectors in the two countries and if their efforts to reach universal access to electricity is similar. It can also be used to make a comparison of slow or fast expansion for each country, to see how the different expansion rates will affect the electric power sector in Ethiopia and Kenya respectively.

Both scenarios use historical data up until 2019, and at this year changes are made to fit the scenario. This is done because the system is known up until now so changes prior to this is not possible. To implement changes later or gradually was deemed unnecessarily complex and uncertain for a simplified model and scenario comparison.

6.2.1 Universal access to electricity scenario

The national electrification program of Ethiopia was launched in 2017 and have a national target of universal electricity access by 2025, with the help of temporary off grid solutions (65% grid access and 35% off-grid access). The target for universal grid access is set to the year of 2030 (96% grid access and 4% permanent off-grid solutions for deep urban areas)[8].

The national target for the Kenya Vision 2030 (initiated 2007) aspires to universal electricity access by 2030. However, in 2013 a more ambitious target was set to universal electricity access by 2022. At that point solar home systems and grid connections are proposed to make up for about 25% and 75% of the total number of connections, respectively [7].

In this study the universal access to electricity scenario simulates the future scenario where universal access to electricity is reached by the year 2030, which is the access target for the UN SDG 7 (see background). The main focus for universal access to electricity today is to connect as many people as possible to an electric grid. According to Sida, funding from different aid organisations is today mainly used for connecting people to the centralized electric grid or connecting people to mini grids. In the simulation scenarios it is assumed that all household connections are to the centralised grid with corresponding average grid connection cost. According to actual plans a substantial proportion of the connections may be in the form of solar home systems, especially in Kenya.

Another part of electricity access is the power availability. With more customers and more power demand the power generation needs to expand accordingly. External funding for power production is today often provided to expand renewable and sustainable alternatives. In countries with open markets for power production companies, and where it is possible to make money, independent power producers also contribute to the expansion of power production.

6.2.2 Slow grid expansion scenario

The difference between the scenarios is how quickly new households are added to the grid, the connection rate. The Slow grid expansion scenario have a substantially lower connection rate than the universal access scenario. The slow expansion scenario is used to compare system impacts of a scenario with high connection rate to a scenario with low connection rate. To see both how each of the countries electricity sectors react to different connection rates, but also to compare changes and system behavior between the countries.

6.3 Model description

The *Figure 11* present a simplified conceptual version of the model that is used for simulations of the electric power sectors in Ethiopia and Kenya. The factors marked in red letters *Tariff*, *Maintenance*, *Customers* and *Capacity* are the four important subsystems, along with the factor *Accumulated profit* in bold. This figure displays the relationships between these four subsystems and how they are all related to the economy of the electric power sector. A change in one of the subsystems will lead to changes in the other subsystems, directly or indirectly by affecting the economy. Further down, the figure is divided into smaller parts to focus on each of the subsystems, to present simplified explanations of their internal relationships and system behaviors.

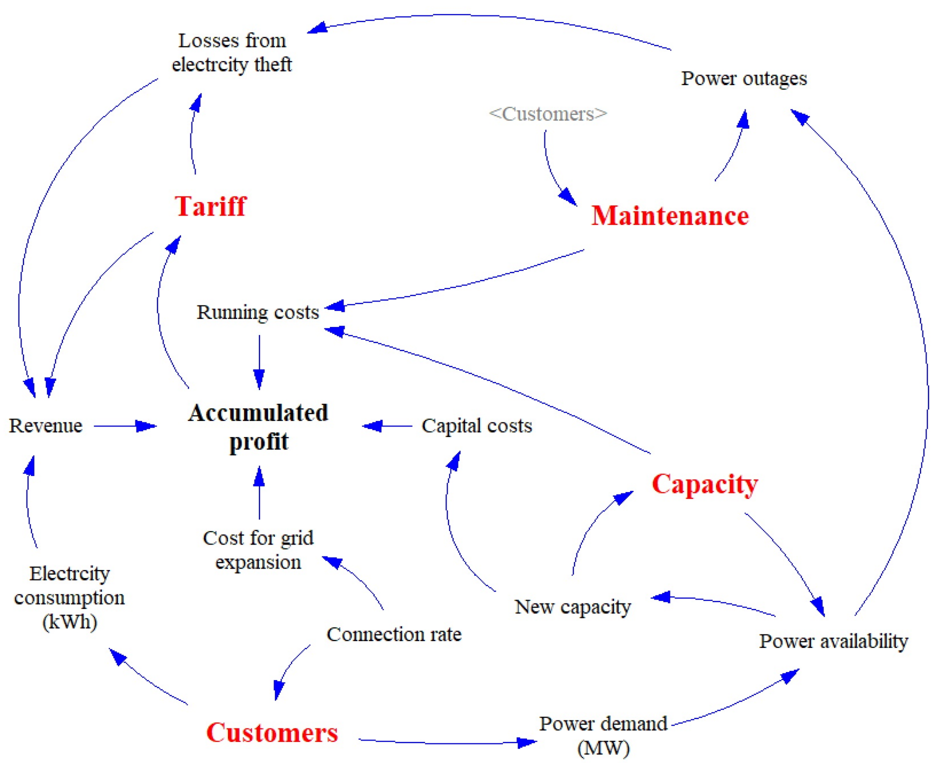

Figure 11: Conceptual causal loop diagram describing the full model.

6.3.1 Customers

The factor *Customers*, visualised in *Figure 12*, is the amount of customers connected to the centralised grid. The amount of customers impact the peak *Power demand* in MW and the total *Electricity consumption* in kWh. The *Connection rate* is the amount of new customers connected to the grid each month and this rate also defines the Grid expansion costs for the system. More customers means more electricity consumption and more *Revenue* followed by more Accumulated profit. But it also means more *Costs for grid expansion* and more *Power demand*.

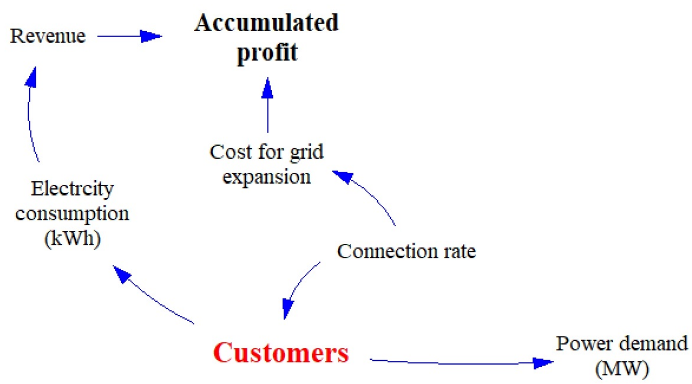

Figure 12: Conceptual causal loop diagram describing the customer part of the model.

6.3.2 Tariff

The *Tariff*, visualised in *Figure 13*, is adjusted according to desired *Profit*. Increased tariffs leads to increased *Revenue*. But increased tariffs will also provide a higher incentive for *Electricity theft* which leads to decreased revenue.

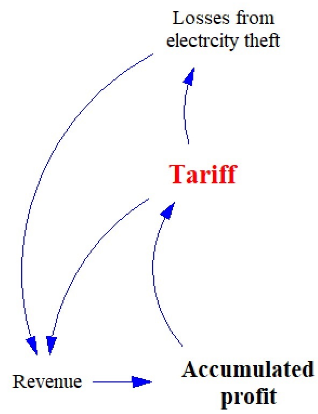

Figure 13: Conceptual causal loop diagram describing the tariff part of the model.

6.3.3 Capacity

The generation *Capacity* is visualised in *Figure 14*. If the power demand is higher than the installed power generation capacity there will be low *Power availability* in the system. To compensate for the low power availability an increased amount of *New capacity* will be installed and the amount of new capacity defines the *Capital costs* for capacity and the amount of capacity defines the *Running costs* for operating and maintaining the already installed capacity. Low *Power availability* will also lead to more *Power outages*, from voltage drops and load shedding.

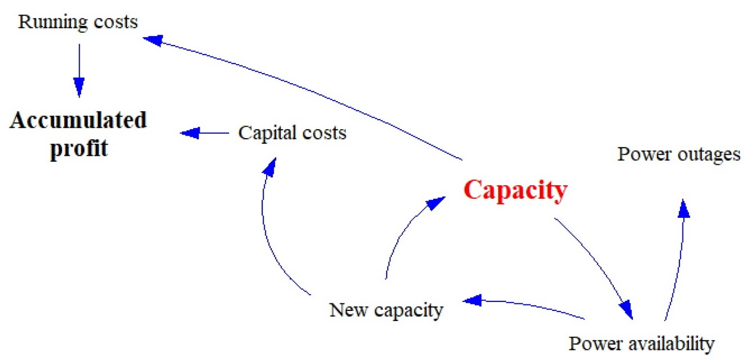

Figure 14: Conceptual causal loop diagram describing the capacity part of the model.

6.3.4 Maintenance

The main function of the grid *Maintenance*, visualised in *Figure 15*, is to decrease the amount of *Power outages* and increase reliability. Less maintenance will lead to more problems in the grid, this creates more power outages and lower reliability. But the amount of maintenance performed will also define the *Running costs* for the grid, and high costs lead to less *Accumulated profit*.

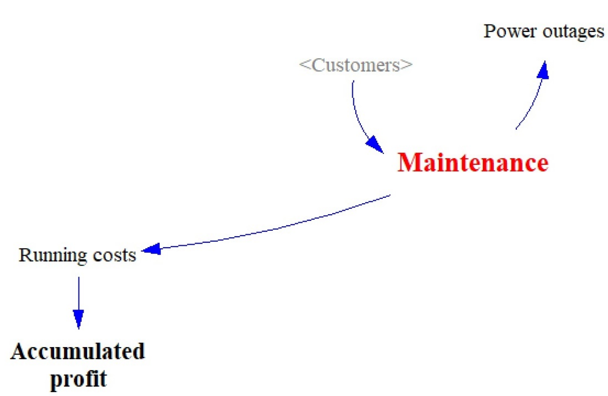

Figure 15: Conceptual causal loop diagram describing the maintenance part of the model.

In the new maintenance model constructed for the quantitative simulations (*Figure 16*) the grid is described as the number of customers or connections in the system and grows according to the Connection rate. Working connections and Broken connections are two parts of the total system. Their sum represents all centralized grid by the number of all current customer connections in the grid. If we have a system with 50% Working connections and 50% Broken connections, then 50% of all customers are without electricity due to grid failures. The Breakdown rate decreases the amount of Working connections and increase the amount of Broken connections. Repair rate does the opposite. The amount of Broken connections divided by the total number of connections (Working connections + Broken connections) gives us the factor of Transmission and distribution system reliability. (see appendix for all system equations)

In *Figure 16* preventive maintenance and repair are combined to a higher degree, since all gathered data only described the sum of these two factors. In both Ethiopia and Kenya these two factors are one and they share budget, staff and equipment. The new factor is called O&M repairs required and is based on historical Repair costs per customer and the current Repair rate.

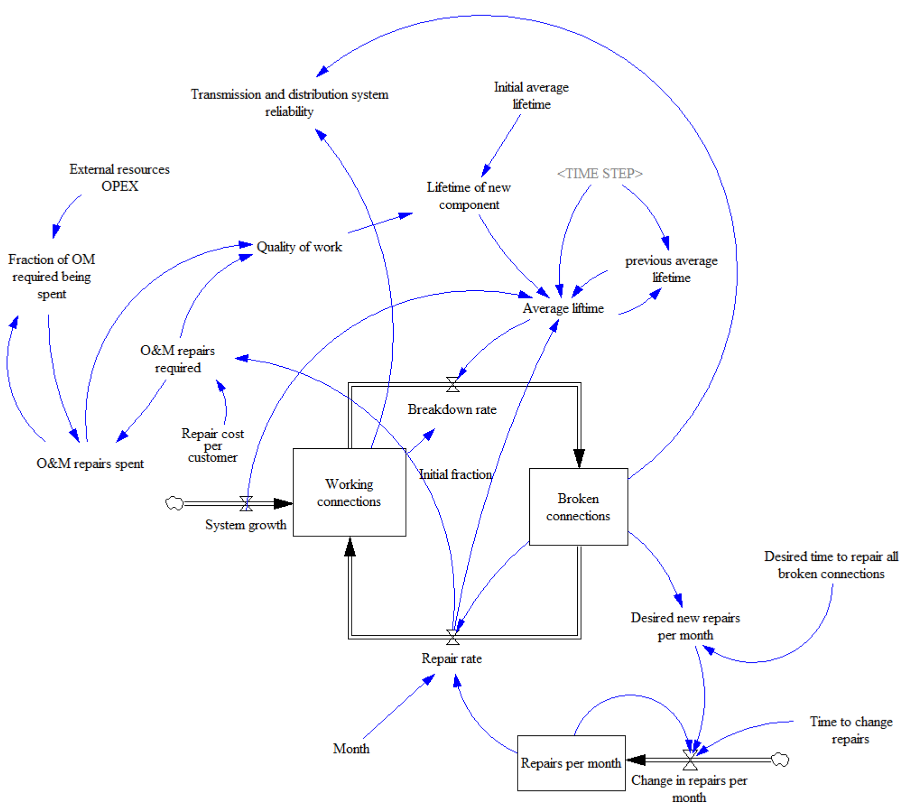

Figure 16: New maintenance model used for simulations.

The different factors in *Figure 9 and 10*, affecting the Quality of work (Such as Salary, Skilled personnel and Parts available) are here all represented in the factor Quality of work, and this factor is calculated as the quotient of O&M repair required divided by the actual O&M repairs spent. Quality of work will then affect the Lifetime of new components and thus affect the system Breakdown rate.

Repair rate changes in relation to the amount of Broken connections. There is also a delay in the change of repair rate represented by the stock and flow of Repairs per month and Change in repairs per month. This delay creates a model behavior similar to historical data, where system maintenance have a hard time to keep up with the system expansion.

The main outputs from the Maintenance part further connecting to the rest of the system model is the O&M repairs spent and Transmission and distribution system reliability. They connect to Reliability which have an impact on Customer satisfaction, Electricity theft and Total losses for the system, as well as OPEX which is the running cost for operation expenses in the system and it affects the Accumulated profit.

A common, simplified model is used for simulating the maintenance work for both Ethiopia and Kenya, even though the interview data initially resulted in two different models (*Figure 9 and 10*). First of all there were not sufficient data on how the harassment of technicians and their retribution would affect the quality of the maintenance work. Therefore this part of the model was left out of the final model. Secondly, the electricity theft that is related to customer satisfaction appears to be non existent in Ethiopia today and most losses are not affected by customer satisfaction. This information was used to calibrate the electricity theft in Ethiopia for the reference model. It is however likely that increased tariffs will increase theft and therefore it was assumed to be a relevant factor for the simulation of the future Ethiopian electric power sector. The full system model including the new maintenance model, can be seen in Appendix.

6.3.5 Equations

Most equations in the model are straightforward, such as *Total electricity consumption = Electricity consumption per customer · Number of customers.* Some other equations are further explained in this section. All equations are listed in Appendix.

Electricity theft (Eq. 1) has a complex behaviour. Both positive and negative feedback with delay interact to create an S-curve and is mathematically represented by a logistic function. This occurs frequently in dynamic systems and have previously been used to model system dynamics of electric reliability [24, 41]. The equation (Eq. 1) contain a scale factor, and in the logistic function there is an exponential with a delay depending on satisfaction and the two factors *k* and *x0*. These two factors are adjusted to calibrate the function.

$$Electricity\ theft = Scale\ factor\ \frac{1}{1 + EXP(-k(\ 100(1 - Delayed\ satisfaction) - x0))} \tag{1}$$

[%]

Increased expenses associated with an expanding electricity sector are in this model balanced by increasing the tariff. Changes in tariff (Eq. 2) depends on the economical balance, the electricity consumption and the system time delay. This time delay is due to many factors such as the political system, acceptances and an economical system inertia due to monthly and yearly budgets and payments. The time delay is calibrated according to historical data.

$$Change\ in\ tariff = \frac{Balance}{Total\ electricity\ consumption} \ /\ Time\ to\ change\ tariff \tag{2}$$

[(USD/kWh)/month]

Balance (Eq. 3) is calculated by revenue, expenses and the desired margin between the two. Revenue and expenses are depending on other factors and change during the expansion, the desired margin is calibrated according to historical data.

$$Balance = Revenue - Expenses \cdot Desired\ margin \tag{3}$$

[USD/month]

The size of the grid is defined as number of customers connected and and use customers as unit. The grid is divided into two parts, working connections and broken connections. The breakdown rate (Eq. 4) is defined as working connections (connections that can break down) divided by average lifetime of grid components. This results in a number of disconnected customers each month.

$$Breakdown\ rate = \frac{Working\ connections}{Average\ lifetime} \tag{4}$$

[Customers/month]

The repair rate (Eq. 5) aims to repair all broken connections per month, but only if it does not exceed maximum capacity for repairs per month. This is calculated and compared for each time step in a minimizing function, where the smallest value of the two is chosen.

$$Repair\ rate = min\left(Repairs\ per\ month, \frac{Broken\ connections}{Month}\right) \tag{5}$$

[Customers/month]

OPEX (operating expenses) (Eq. 6) cover all major running costs in the electricity sector. In this model it is defined as the sum of O&M (operating and maintenance) expenses and running costs for electricity generation. Any external resources or funding covering part of the running costs are subtracted from OPEX.

$$OPEX = \text{âĂİ}O\&M\ repairs\ spent\text{âĂİ} + Required\ generation\ per\ month - External\ resources\ OPEX \tag{6}$$

[USD/month]

CAPEX (capital expenses) (Eq. 7) cover all investments in new capacity (MW) and is defined as new required capacity per month times the cost per new capacity installed. Cost per new capacity is an average cost for current electricity generation projects in each country. A future shift in the electricity generation mix or future price drops for certain technologies are not considered.

$$CAPEX = (New\ Capacity \cdot Cost\ per\ MW) - External\ resources\ CAPEX \tag{7}$$

[USD/month]

The monthly cost for grid expansion (Eq. 8) is based on the averaged historical change rate of customers times the averaged cost for connecting new customers. Outliers are excluded, since the cost of connecting far rural customers vary greatly for each region.

$$Grid\ expansion\ cost = (Connection\ rate \cdot Connection\ cost) - External\ resources\ expansion \tag{8}$$

[USD/month]

Revenue (Eq. 9) is defined as the tariff times the electricity consumption minus system losses. Total losses are defined as the percentage of customers that are without electricity.

$$Revenue = Tariff \cdot Total\ electricity\ consumption\ (1 - Total\ losses) \tag{9}$$

[USD/month]

The profit (Eq. 10) is defined as an accumulation of monetary resources Where the difference between revenue and all system expenses either lead to a positive or a negative accumulation, a system profit or debt, and this can change over time due to system delays, as other factors mange to catch up with the system changes.

$$Accumulated\ profit = Revenue - OPEX - CAPEX - Grid\ expansion\ costs \tag{10}$$

[USD]

The number of working connections (Eq. 11), which is the same as the number of paying customers in the system, depend on the number of new customers connected to the system and customers reconnected minus customers disconnected.

$$Working\ connections = System\ growth + Repair\ rate - Breakdown\ rate \tag{11}$$

[Customers]

The system reliability (Eq. 12) is defined as the % of working connections divided by total number of customers in the system.

$$Reliability = \frac{Working\ connections}{Working\ connections + Broken\ connections} \tag{12}$$

[%]

Before running the model in Vensim® the units were checked so that all variables match with the variable functions. Initial input values were selected from data. When first running the model the behavior of the model was evaluated to see if it behaved reasonably. After this a more thorough calibration of the model was done to fit historical data for several variables. When calibration was completed, the resulting model was chosen as reference model for each country. All historical data used for calibration can be found in Appendix Section 8.1

In the reference models all External resources are set to zero. This does not represent a case where all external finances are cut. But since we do not have data on the amount of external resources for the countries today we have chosen the value zero to represent the current amount of external resources and the model is calibrated according to this. Any change of these factors represents an increase or decrease of external resources compared to historical values.

6.4 Simulation results

Some of the general results are the system behaviors indicated by the final full system model, and how the system tries to balance itself. It can be seen as the sum of the causal loop diagrams in the model with all the included reinforcing and balancing loops.

There are few reinforcing loops in the final system model. Most large systems mainly consist of balancing loops, or else the system would likely have broken down already. But (as mentioned in: system dynamics theory) balancing loops can make it hard to implement changes in a system. Whenever a change is implemented in the model, the balancing loop will try to change it back, and balance the system. This behavior was noticed during simulations. In the figures below simulation results from both scenarios are compared, along with historical data when this is available.

6.4.1 Ethiopia

To reach universal access in Ethiopia by 2030, going from 3 to more than 30 million consumers in about 10 years [10], the connection rate will have to change dramatically from the current value of about 120 000 new customers per year to over 2.4 million new customers per year if a linear growth in connection rate is assumed (*Figure 17*).

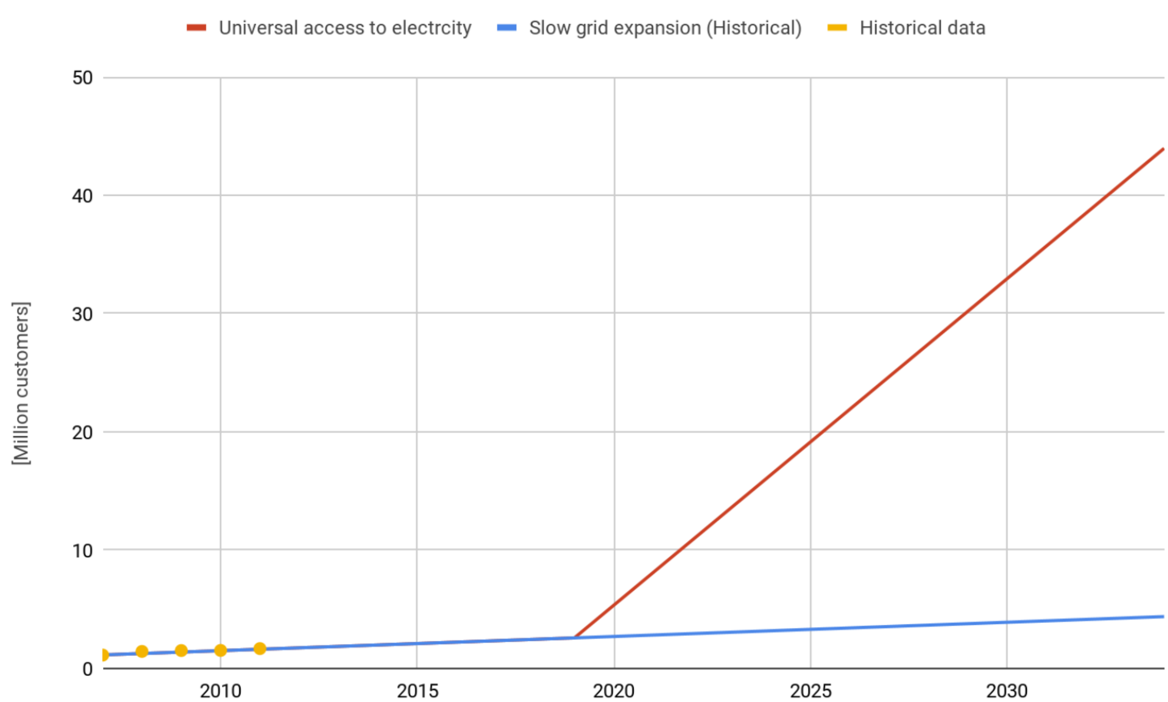

Figure 17: Number of customers connected to the electric power grid in Ethiopia over time.

The increase in connection rate is the main model impact of the Universal Access Scenario for Ethiopia. To reach required connection rate, the external financial support for new grid connections is adjusted in the model. For the Slow Expansion Scenario, the reference model in Ethiopia is used, where system expansion and connection rate is based on historical data.

The nominal values for accumulated profit show the accumulated profit for the modelled parts of the system. It indicates how system changes will impact the accumulated profit and how it will be affected by the different scenarios.

The results from the universal access scenario for Ethiopia, even with full external finance of the increased connection rate still show dramatically increased costs and large negative accumulated profit (*Figure 18*).

The large negative accumulated profit in the universal access scenario occurs both due to the need for increased power generation capacity and for increased system maintenance. (*Figure 19*). Comparing the two scenarios show a large impact on accumulated profit if the connection rate required for universal access is implemented. (*Figure 18*). When the system have adjusted to the rapid increase in connections, the accumulated profit show some signs of leveling out which is observed by a slight direction upwards.

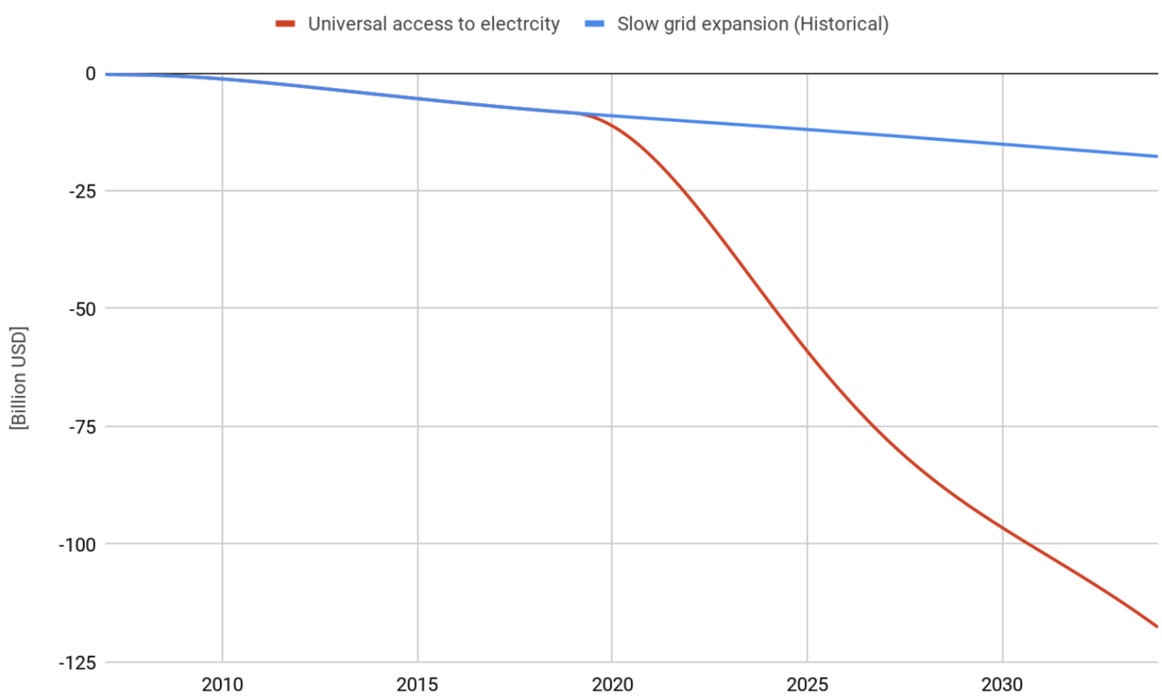

Figure 18: Rough and generalized trend of the accumulated profit for the electricity sector in Ethiopia over time.

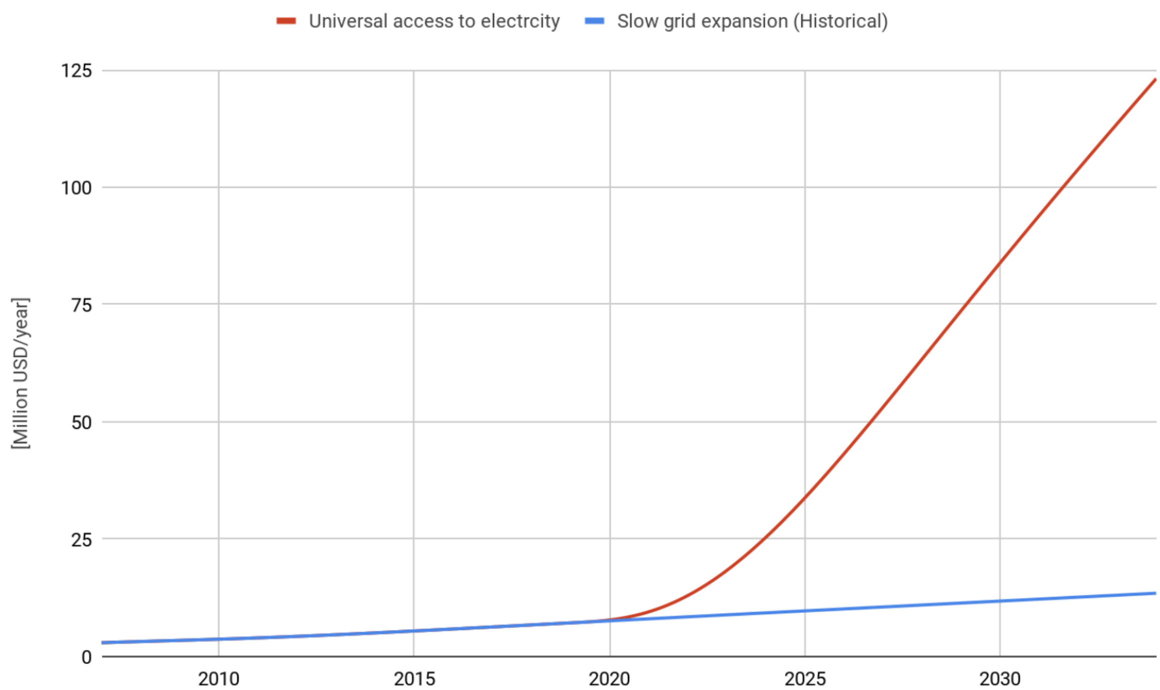

Figure 19: The trend of annual maintenance expenditures for the electric power grid in Ethiopia over time.

Due to political reasons the tariff in Ethiopia have historically been locked in a fixed value that was not even adjusted for inflation. Converting the tariff to USD therefore makes the actual tariff appear to be decreasing. According to the model, more than a doubling of the tariff is required to balance the model, that together with inflation adjustments.

The need to increase tariffs have been acknowledged in Ethiopia and increases have recently been implemented. New tariffs have been set for 2018-2021 (*Figure 2*). In the model the tariffs have manually been kept lower than the model suggest up until the year of 2017, where the historical low tariffs end, to simulate the historical choice to not implement increased tariffs. This may be seen as a political delay in the system (*Figure 20*). In the model, there is a strong behaviour towards increasing tariffs. The Slow Expansion Scenario shows how the tariff, according to the model, reacts to the historical system expansion. The Universal Access Scenario shows in the same way the substantial changes of the tariff needed to facilitate an increased connection rate. This trend is seen even when the cost for all new connections are covered by external resources, due to other increased system costs that follows an expansion. And as can be seen in *Figure 18* even with increased tariffs this system would still be dependent on external resources or other income to balance profit.

If maintenance and other factors contributing to customer satisfaction are not changed, the model predicts an increase in electricity theft. The increase of electricity theft due to increased tariffs in the Universal Access Scenario is very significant. When the tariffs decrease again the theft will follow.

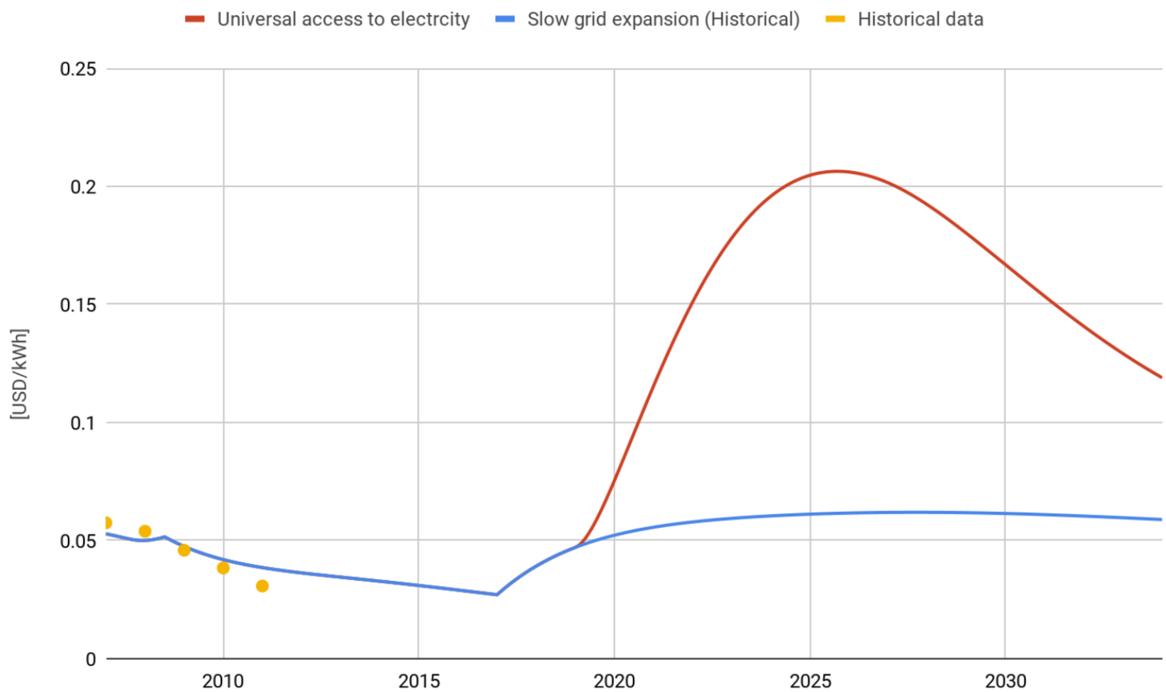

Figure 20: Average tariff for electricity customers in Ethiopia over time.

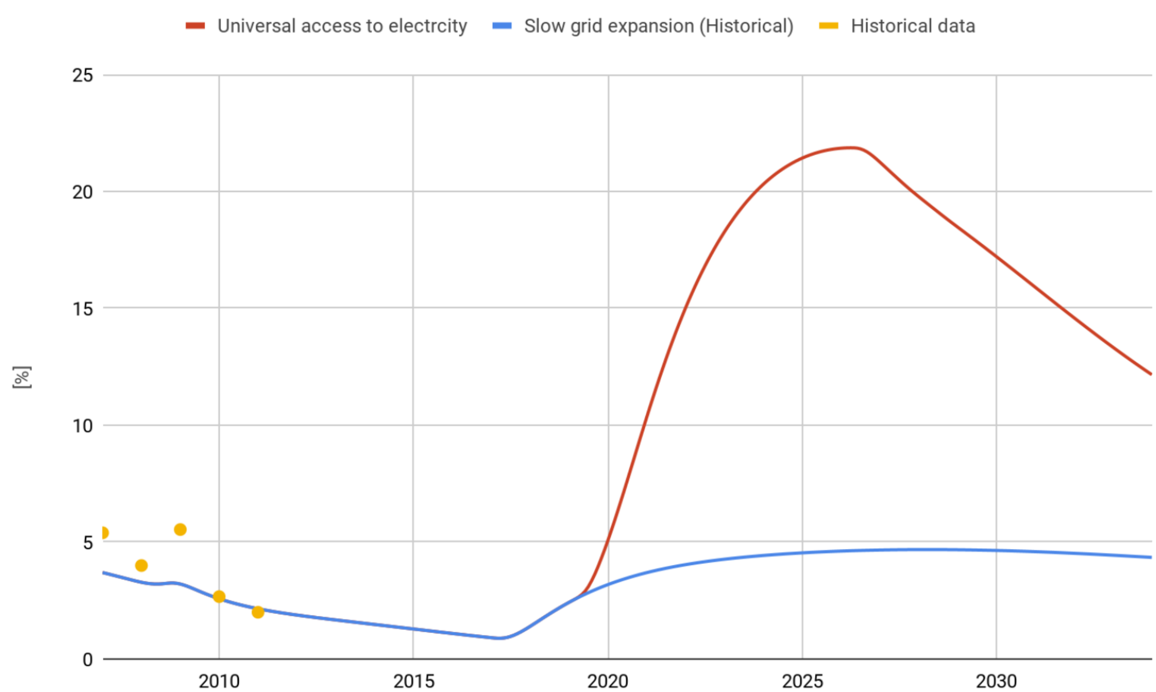

Figure 21: A rough trend of electricity theft in Ethiopia over time.

6.4.2 Kenya

To reach the universal access target in Kenya with close to 15 million connections by 2030, the connection rate actually does not have to increase. Kenya has the last couple of years already implemented an increased connection rate. If the current rate of about 600 000 new customers per year is kept at this level, then Kenya will reach the target of universal access by 2030. And are also close to reaching their own ambitious target of universal access by 2022.

For Kenya the Universal Access Scenario is therefore the scenario continuing the historical connection rate and the Slow Expansion Scenario is the implemented change in the model to compare the high connection rate of today with a possible lower connection rate. (*Figure 22*)

For the Slow Expansion Scenario the Target connection rate is reduced to 120 000 new customers per year. The same connection rate used for the Slow Expansion Scenario for Ethiopia.

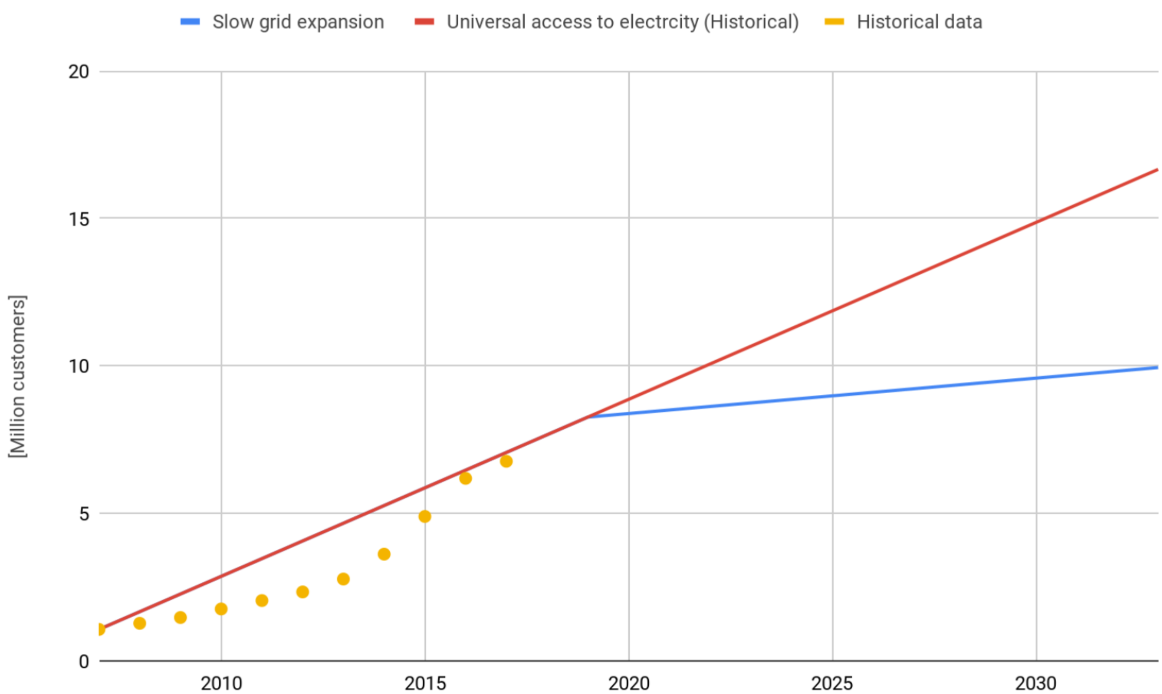

Figure 22: Number of customers connected to the electric power grid in Kenya over time.

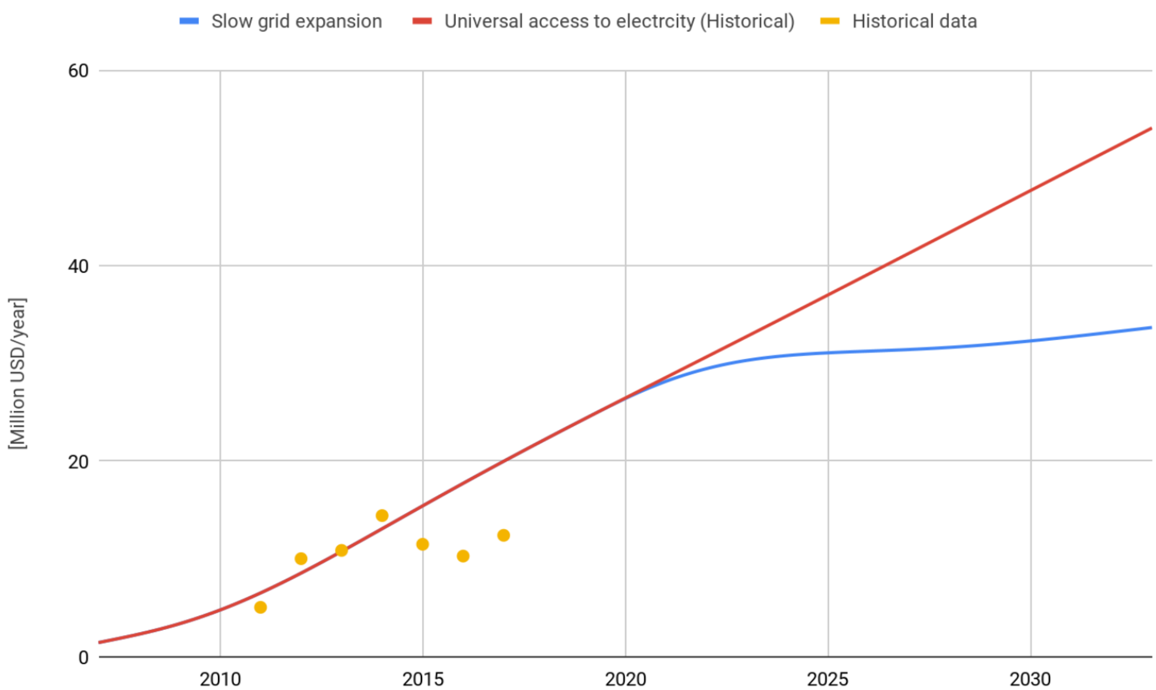

Figure 23: The trend of annual maintenance expenditures for the electric power grid in Kenya over time.

The maintenance costs are high in Kenya and every year they are increasing with the high expansion rate. The trend of maintenance costs closely follow the connection rate and the grid expansion. A lower expansion rate and less costs for maintenance could allow additional investments in preventive maintenance and thereby increase reliability and lower maintenance costs even further in the long run. (*Figure 23*)

The Accumulated profit (*Figure 24*) in the entire electricity sector is negative and the system costs are not recovered. According to the Universal Access Senario, Kenya could turn the negative profit and perhaps even get it positive by slightly raising the tariff (*Figure 24* and *Figure 25*) and keeping it high for some time. By doing this, the system is able to catch up with the costs and balance itself.

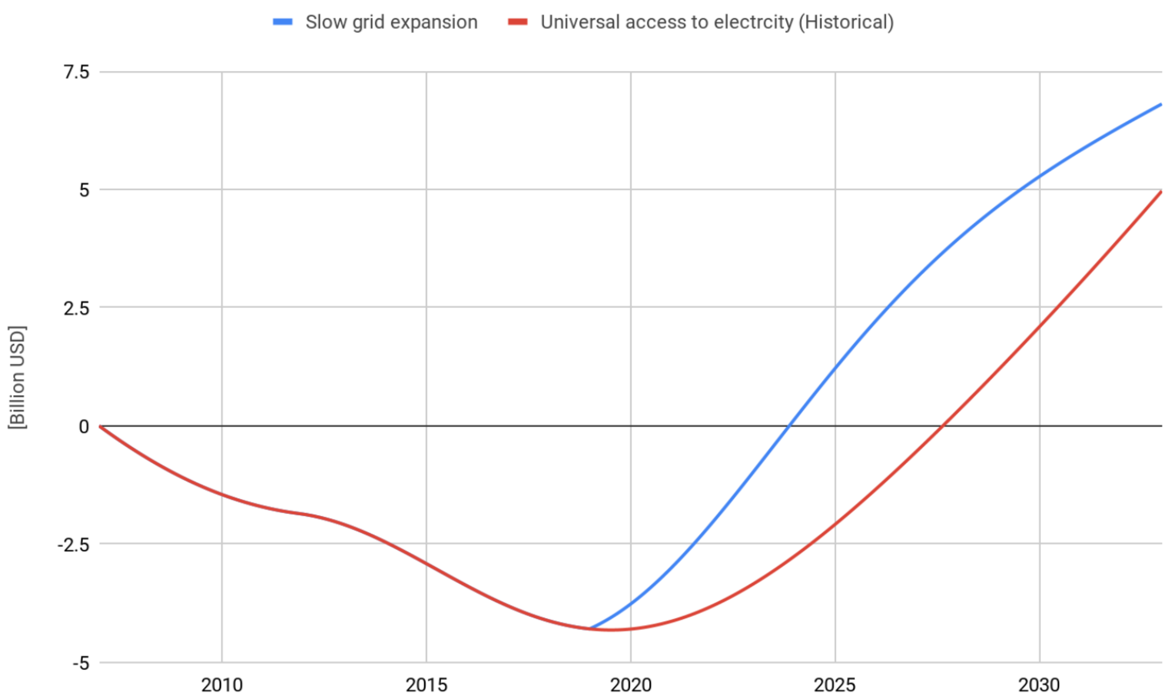

Figure 24: Rough and generalized trend of the accumulated profit for the electricity sector in Kenya over time.

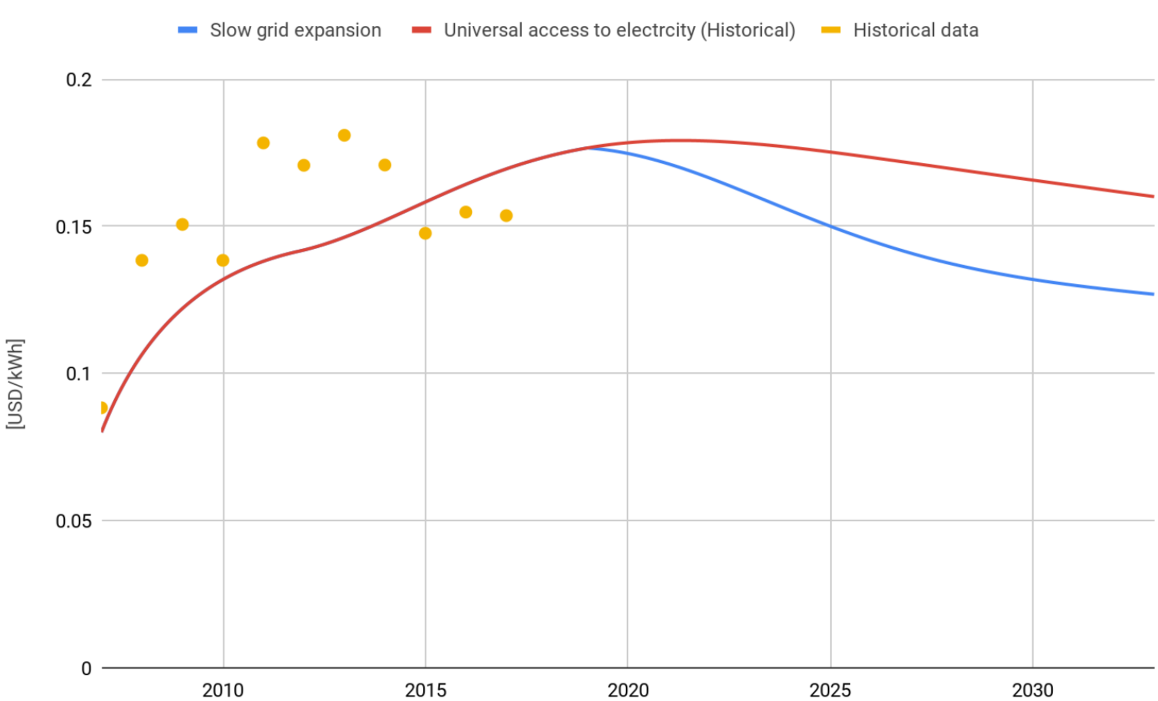

Figure 25: Average tariffs for electricity customers in Kenya over time.

As mentioned in *Section 6.1.2* Kenya is continuously revising tariffs, but KPLC and ERC must take political considerations into account when setting the tariff. It is hard to say anything about the future tariffs in Kenya except that KPLC and ERC are working hard to create a sustainable and stable, cost reflective electricity market [32, 33].

In the Slow Expansion Scenario there is no need for increased tariffs and cost recovery is reached faster. But comparing the two scenarios for Accumulated Profit show that the two curves will cross in the future. Once the system is balanced and cost reflective it is more profitable to have more customers. According to the model, the Universal access Scenario will take longer time to balance but is likely to be more profitable in the long run. That would happen years after 2030 and is not within the modelled scenario time scale.

Electricity theft is high in Kenya creating large economic losses. As long as the expansion rate is high the model predicts theft to remain high as well, but once the system balances it will decrease slightly. As the tariff and the electricity theft is closely related, the Slow Expansion Scenario shows both reduced tariff and electricity theft (*Figure 26*).

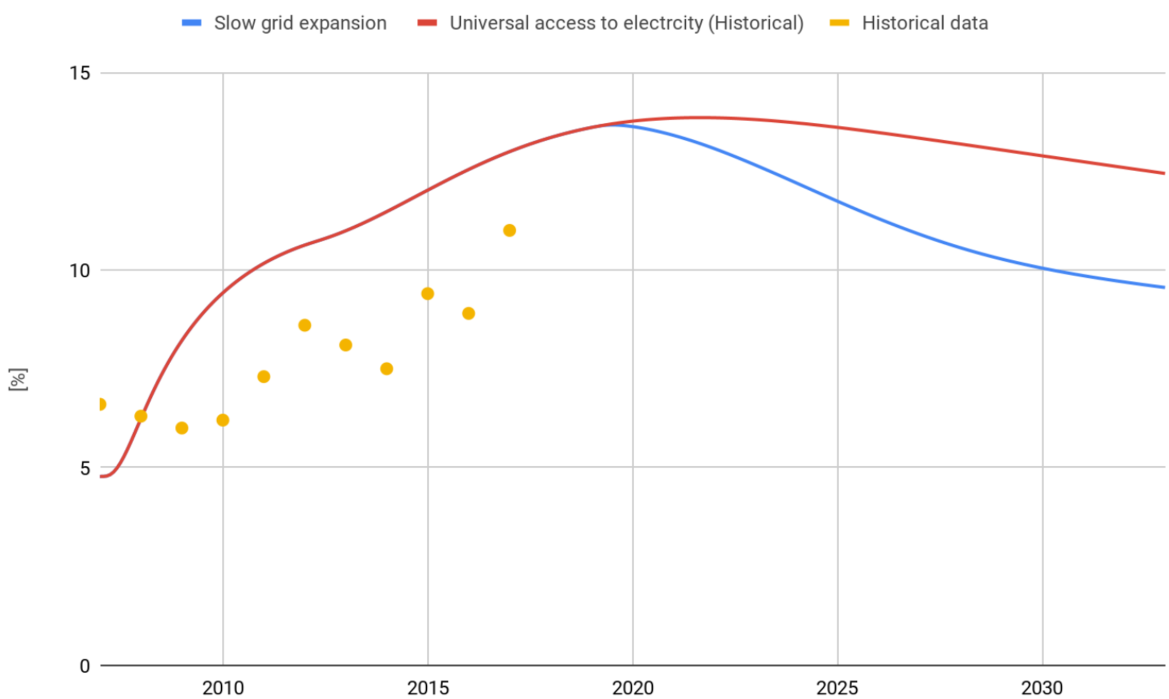

Figure 26: A rough trend of electricity theft in Kenya over time.

6.5 Discussion

Results from simulations in this project should not be used for nominal projections of the electric power system in Ethiopia and Kenya. Rather the results indicate trends, changes, approximate relationships between factors and system behavior. No conclusions can be made regarding the nominal inputs and outputs, but it is possible to see what part of the system reacts to small or large changes and how it does react. Delays, counter reactions, balancing factors and iterations over many years indicate system behavior and trends for long term outcomes. Additional costs that may occur for the last rural connections living far away from the centralised grid are excluded in the scenarios, but a refined model could include some function with increasing connection cost for the last customers to be connected.

6.5.1 Ethiopia

As mentioned in *Section 6.1.1* the number of customers in Ethiopia is today about 3.1 million and this number is believed to double when formalising contracts with customers already connected. But even if a doubling of customers is a great step in the right direction, it won't do much to help reaching the universal access target considering the large population without electricity.

The large negative accumulated profit (*Figure 18*) in the universal access scenario occurs both due to the need for increased power generation capacity and for increased system maintenance (*Figure 19*). The income from the previous year cannot cover the increased costs for the following year. Therefore a negative accumulated profit is created for the system and a larger expansion rate will result in a steeper negative curve. Comparing the two scenarios show a dramatic impact on accumulated profit if the connection rate required for universal access is implemented.

The tariff in Ethiopia has historically been low and will increase according to the model. In the proposed tariffs for the coming years (*Table 2*) the price will more than quadruple in some tariff blocks, this is quite close to what is observed in the Slow Expansion scenario (*Figure 20*). In the Universal Access scenario the required tariff increase is much more substantial and the response from customers under this type of tariff increase is unknown, but it is likely that some would look for alternatives. Further, it is likely that political forces will try to keep the tariff low, even though the tariffs needs to be increased if the system is ever to balance.

This political resistance and delay for increasing the tariff is complex and was not captured by the model. The current tariff is very low and it is quite unlikely that the tariff could be increased so rapidly. Electricity exports are also excluded from the model. Since Ethiopia have big plans for electricity export and their revenue/kWh is much higher for export than for domestic electricity sales, this could perhaps affect the system revenue and accumulated profit.

According to the model, increase in tariff corresponds to increase in electricity theft. However, exactly how quickly the system respond to tariff change and what the electricity theft would amount to in reality is difficult to predict. In the Universal access scenario the theft increase very aggressively as an answer to the increased tariff and the lack of customer satisfaction that could be devastating for the entire electricity sector. It is difficult to accurately predict and model how the theft is related to the rest of the system, but the general trend where high tariffs are followed by theft is reasonable. Both tariff and theft decrease again when the system obtain balance and the accumulated profit will continue down, but it shows signs of levelling out. As the system expands the number of customers and the maintenance needed for the expanding network will continue to increase. This contributes to an increasingly negative Accumulated profit, but the system shows signs of approaching balance.

The plans to increase electricity exports from Ethiopia could possibly be modeled by increasing External resources, but currently the exports are limited and it is unclear what levels of export actually will be achieved in the future. If the revenue from export was more significant it would increase accumulated profit for the total system and possibly the tariff would be in less need of increase. This would in turn limit a future electricity theft. The increased export has previously been the suggested solution from the government to balance the economy of the electricity sector in Ethiopia. But now when the power production in the country is low and at times barely meet the power demand, and investments in increased power generation have been left to the open market, it is unclear what will happen to the power generation capacity and export in the future. One interesting aspect of the situation is that the more power production there is in Ethiopia the more export there is and the more revenue there would be for the producer. This could perhaps lead to large external investments in power generation in the future. But as mentioned it is hard to know the future of this, since the open market is also new and many other factors also influence these investments.

6.5.2 Kenya

In Kenya, tariffs have historically been high compared to Ethiopia and in the model the tariff will further increase and even if it drops slightly in just a few years, it will still remain high for a long time. The Accumulated profit will be negative initially due to high costs for connections, capacity increase and operation during expansion and this is allowed in the model. At a certain point this model catches up with the expansion and the negative profit instead starts pointing upwards, this is what allows the tariff to decrease slightly and this behaviour is even more pronounced in the Slow expansion scenario, since the system have already caught up with that rate of expansion. The system will keep expanding with respect to number of customers and annual maintenance costs, but this increase is close to linear and the system allows for the accumulated profit to turn from dept towards profit (*Figure 24*). In the Slow Expansion scenario the number of customers and the annual maintenance costs is almost constant which puts less stress on the system, and this allows for a steeper increase of Accumulated profit. Since the effect from inflation and changes in currency exchange rates on tariffs are passed on to customers the tariff can be kept comparatively stable.

Electricity theft follows the tariff very closely according to the model. In the Slow Expansion scenario the Accumulated profit that will remain slightly higher than the tariff drop suggests, due to decreased losses elsewhere. But even if electricity theft drops, it remains quite high also for the Slow Expansion Scenario. Lower tariffs is not the only solution that can reduce electricity theft, but the others are less significant and balanced by other factors. Therefore other solutions could be needed first.

When approaching universal access to electricity there will be more grid in rural areas of the country. The connection cost increases with distance to the grid, but in the model an average connection cost is used. Furthermore, the additional cost for maintaining a rural grid is not fully covered in this model since maintenance costs are based on historical data from cities. Together these factors make expansion more expensive for the last connections.

The electric power system in Ethiopia and Kenya are both in a phase of large change, and will be for many years to come. Delays in the system makes it hard for the system to keep up with all the changes and to balance itself, even though the balancing loops exists. The most prominent system change is the system expansion. The expansion rate in number of connections, grid, power production capacity and maintenance for the new larger system will always have to be financed with a smaller income from previous years when the system was smaller. Therefore, during this system expansion, due to system delays, the income from a small system will not only finance capital costs for the system expansion but will also have to finance running costs for a larger system. Since the system expansion will have to go on for many years, the difference between income and cost in the system will either accumulate and create a large debt or have to be funded by external resources or by internal resources by increasing tariffs and creating a very costly system for customers during the system expansion. High tariffs may not directly lead to high income due to unsatisfied customers and resulting electricity theft. The higher expansion rate, the larger difference there will be between last year's income and this yearâĂŹs costs.

A low expansion rate will provide a slow and more economically sustainable system expansion. But a low expansion rate also means that less people will get access to a more efficient, environmentally, economically and socially sustainable energy source. The people without electricity access will still be dependent on less sustainable energy sources, such as kerosene, coal and firewood. This may be seen as a trade off between a high and a low expansion rate. The UN sustainable development target 7.1 aims for universal access to affordable, reliable and modern energy services for all by 2030 [3]. But who will finance the additional costs for an increased electricity access by system expansion? There is a trade off between the benefits of universal access to electricity and the costs and stress from a large system expansion. For some countries it might be preferable with universal access later than 2030. Or else those systems will need massive support in preventive work to prepare their electricity sector for the system expansion. This thesis does not investigate this trade off since it would also involve analysis of none-electric energy sources used today, as well as global politics, global economy and global benefits from electrification adding complexity. This lies outside of the system boundaries for this thesis.

6.5.3 General Discussion

Increasing the tariff as a means of increasing revenue and profit appears to be a combination of a balancing and a reinforcing loop. The electricity theft and the tariff closely follow each other. In order to increase revenue the tariff is increased, but then customer satisfaction will then decrease. This is followed by increased electricity theft which will decrease revenue. This is the balancing loop that is fighting the change. But as other parts of the system require revenue to increase, this will set off the reinforcing part making the tariff to go up further and electricity theft too, and so on. (The same goes for implementing a negative change.) But, according to the model the net effect of increasing tariffs will still be a slightly increased revenue. This together with other delayed factors will make sure this loop balances and does not turn into a reinforcing loop in the long run. As soon as the income is high enough there will be benefits for the system leading to increased customer satisfaction. The electricity theft will then slowly decrease and so will the tariff. The benefits of an increased revenue and profit, such as increased reliability due to more investments, will not show until a few years later. This is due to a delay between revenue, profit, investments and reliability.

The downside of the increased tariff, however, shows immediately. The key factor in this causal loop is the customer satisfaction. Increased tariffs have a negative impact and increased reliability has a positive impact on customer satisfaction. The drop in customer satisfaction could possibly be avoided and income could be a lot higher, if investments in reliability and maintenance are done in advance and the tariffs are increased according to reliability. As mentioned in (Quantitative analysis/quantitative data - Ethiopia), there is a willingness to accept increased tariffs if reliability increases among customers. When customers âĂIJget what they pay forâĂİ without delay, customer satisfaction remains stable. This would enable an increased tariff without the increased electricity theft. It is of course difficult to make investments before revenue is increased, but funding increased reliability would have a double positive effect. First with a higher revenue by enabling higher tariffs, and in the long run lower maintenance costs and thus further increase of revenue.

Increasing the connection rate is done by increasing external resources/financial support for new connections. This is done to study the outcome from such a financial support on the electricity sector, to see if it will help reaching the target. As mentioned development aid have previously been used to fund expansion of the electric grid and increased number of connections, but such an allocation of funds can also have an impact on costs in other parts of the system. In the electric power sector an increase in the number of connections is likely to be followed by increased power demand and a larger electric power grid. This requires additional investments in new generation capacity, power lines and maintenance which can have an adverse impact on the financial situation for utilities.

Using the same system expansion rate in Kenya and Ethiopia for the Slow Expansion Scenario provides a small chance to see the differences between the two countries electricity sectors. When the expansion rate is similar it is possible to see what other factors are similar and different between the countries. It is not really possible to draw any major conclusions from such a comparison, but it does increase the understanding of the different system behaviors.

7 Concluding remarks

A conclusion from this study is that the amount and quality of preventive and reactive maintenance are important factors in the maintenance work in both Ethiopia and Kenya. Most of the maintenance performed in both Ethiopia and Kenya is focused on reactive maintenance, repair, where problems like electricity interruptions are reported and fixed as quickly as possible. Some preventive maintenance is also performed. The amount of preventive maintenance affects the quality of the grid and so does the quality of the maintenance work, both reactive and preventive. The quality of the grid affects the maintenance cost and the amount of power outages, which affects reliability. Low reliability will cause low customer satisfaction and low willingness to pay. The amount of maintenance performed, and especially planned maintenance, is affected by the maintenance budget and documentation of component conditions. Quality of maintenance work is mostly affected by technicians skill and motivation, and also having access to the right components. How investments are allocated for these factors will therefore affect the long term maintenance work and the long term reliability of the grid.

A general upgrade of the grid quality and grid design is currently being implemented in Ethiopia. Some of the factors that require most investments for improved grid quality in Ethiopia are: skill and motivation of technicians, documentation of component conditions and budget for preventive maintenance.

The grid in Kenya have already gone through an upgrade with higher grid quality and a better grid design. This has reduced the number of outages and improved electricity reliability, customer satisfaction and system viability. The amount of planned maintenance and documentation is gradually being increased in Kenya and the results are positive. Some of the factors that require most investments for improved grid quality in Kenya are: access to the right components, skill of technicians and standardized maintenance work.

Electricity theft is another factor of importance in Ethiopia and Kenya. It mostly affect the system as an economical loss, which may prevent important investments. It may also be used as an indicator of dissatisfaction among customers. If electricity theft becomes common and socially accepted in a country it may be difficult to reduce. In Ethiopia electricity theft is low and mostly occur due to bad metering. Part of the electricity theft may therefore be considered as a technical or logistic loss, and this part could possibly be solved by investments in maintenance and technical upgrade. If tariffs increase there is a risk that electricity theft will also increase. In some places in Kenya, the electricity theft does also cause problems in the grid and has therefore a direct negative impact on grid reliability. The electricity theft in Kenya seems to be mainly depending on the tariff. Electricity theft is a complex factor in both countries, but in Kenya especially. It is affected by social, cultural and political factors and it is a very diverse problem. The recent tariff change in Kenya that have reduced costs for low electricity consumption will probably help reducing electricity theft, but is by itself unlikely to be enough to significantly reduce the problem.

The main impact from the universal access to electricity scenario was a high system expansion rate and even with external funding of the expansion itself this expansion would generate many other increased costs. New increased costs that can not be covered by the income from the previous smaller system. The conclusion is that these costs should be either covered by increased tariffs or by external funding as long as the system expansion rate remains high. The tariffs should only be increased to a certain level and lifeline tariffs should remain low to not cause dissatisfaction and increase electricity theft. Therefore the continuous and long-term external funding during a system expansion is deemed important for the financial sustainability. The amount of funding required depends on the expansion rate and the total duration of the expansion. The external funding is also deemed most useful in preventive preparation of the system expansion, since this may allow for higher tariffs.

With proper investments and preparations, power availability and grid maintenance will be sufficient through out the system expansion and reliability may even be improved. Since there is a willingness among customers to pay more for reliable electricity, offering high reliability together with slowly raised tariffs may overcome the negative effects of the increased tariffs, such as electricity theft, and instead allow for high customer satisfaction. Sufficient tariffs together with low losses is important for the financial sustainability of the electricity sector. If this is archived and remain for some time it will even allow for decreased tariffs in the future. Well performed preventive maintenance work and an electricity sector that is prepared for system expansion will reduce costs in the long run, improve cost recovery and financial viability for the electricity sector.

In Ethiopia this preventive work has started but the conclusion is that the system is not yet ready for universal access to electricity by 2030 and that it would have a severe impact on the financial sustainability of the electricity sector. The only way it would be possible would be by a substantial amount of external funding from government or other financiers. The conclusion is that further preventive work should be implemented before increasing the system expansion to allow for financial sustainability and a future universal access to electricity.

In Kenya some preventive work have already been implemented and this work is continuously increasing. The system expansion have been increased to required levels for universal access to electricity by 2030. The conclusion from this study is that with sufficient preventive work, high tariffs and external funding, Kenya may reach universal access to electricity by 2030 without substantially weakening the financial sustainability of the electricity sector.

The conclusion is further that more data and simulations are required in this field of research in order to better understand the behavior of large grid expansions.

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8 APPENDIX

8.1 Data used for model calibration

Year -	Month -	Customers -	Total electricity consumption [kWh/month]	Total losses [%]	Capacity* [MW]	Tariff [USD/kWh]	Revenue [USD/month]	O&M repairs spent [USD/month]
2004	0	766041	156166667	-	2318	0.06005	9376969	-
2005	12	889661	174916667	-	2318	0.06049	10581680	-
2006	24	-	-	-	2318	0.05966	-	-
2007	36	1111358	220333333	20.39	2275	0.05745	12657831	-
2008	48	1421333	269000000	18.99	2324	0.05388	14493218	-
2009	60	1495895	245083333	20.53	2214	0.04583	11231193	-
2010	72	1506248	273916667	17.66	2155	0.03834	10501739	-
2011	84	1662255	344416667	16.99	2310	0.03069	10569365	-

Data from Infrastructure Africa Database
*Capacity data from UN Database

Table 4: Historical data for Ethiopia used for calibration of Vensim® model.

Year -	Month -	Customers -	Total electricity consumption [kWh/month]	Total losses [%]	Capacity [MW]	Tariff [USD/kWh]	Revenue [USD/month]	O&M repairs spent [USD/month]
2007	0	1060383	443500000	16.6	1216	0.0883	37400953	-
2008	12	1267198	452666667	16.3	1268	0.1384	59774485	-
2009	24	1463639	468666667	16.0	1314	0.1506	67069561	-
2010	36	1753348	510250000	16.2	1418	0.1384	67057853	-
2011	48	2038625	528416667	17.3	1540	0.1783	89005916	420349
2012	60	2330962	548416667	18.6	1611	0.1707	87976075	835165
2013	72	2767983	603666667	18.1	1723	0.1809	102354595	905675
2014	84	3611904	637916667	17.5	2094	0.1708	101512140	1202254
2015	96	4890373	659333333	19.4	2263	0.1476	90825614	957773
2016	108	6182282	689333333	18.9	2254	0.1548	99565652	857240
2017	120	6761090	704916667	21.0	2270	0.1536	101163205	1034135

Data from KPLC Annual reports and finacial statements

Table 5: Historical data for Kenya used for calibration of Vensim® model.

8.2 Full Vensim® model

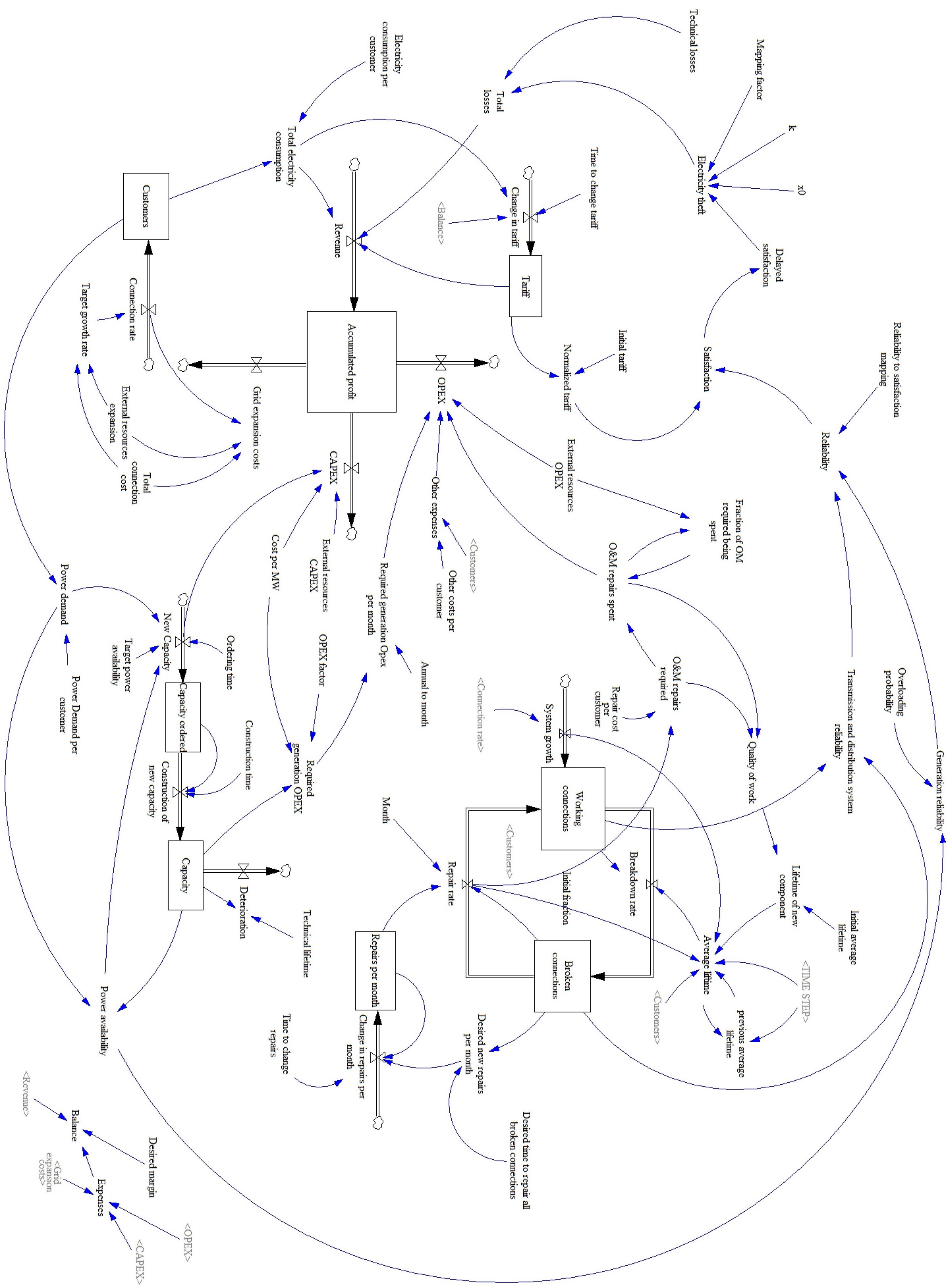


Figure 27: The full Vensim® model used in the simulations.

8.3 List of Vensim® equations

(01) Accumulated profit= INTEG (Revenue-CAPEX-Grid expansion costs-OPEX, 100000) Units: USD
(02) Annual to month= 12 Units: month
(03) Average liftime= (System growth*Lifetime of new component*TIME STEP+Customers*previous average lifetime +Repair rate*Lifetime of new component *TIME STEP)/(System growth*TIME STEP+Customers+Repair rate*TIME STEP) Units: month
(04) Balance= Revenue-Expenses*Desired margin Units: USD
(05) Breakdown rate= Working connections/Average liftime Units: customer/month
(06) Broken connections= INTEG (Breakdown rate-Repair rate, Customers*Initial fraction) Units: customer
(07) Capacity= INTEG (Construction of new capacity-Deterioration, 2318) Units: MW
(08) Capacity ordered= INTEG (New Capacity-Construction of new capacity, 0) Units: MW
(09) CAPEX= (New Capacity*Cost per MW)-External resources CAPEX Units: USD/month
(10) Change in repairs per month= (Desired new repairs per month-Repairs per month)/Time to change repairs Units: customer/month/month
(11) Change in tariff= (-Balance/(Total electricity consumption))/Time to change tariff Units: (USD/kwh)/month
(12) Connection rate= Target growth rate Units: customer/month
(13) Construction of new capacity= Capacity ordered/Construction time Units: MW/month
(14) Construction time= 36 Units: month
(15) Cost per MW= 2e+06 Units: USD/MW
(16) Delayed satisfaction= SMOOTH3(Satisfaction , 6) Units: dmnl
(17) *Ethiopia*: Desired margin= IF THEN ELSE(Time<95 :AND: Time>52 , 0.1 , 0.4) *Kenya*: Desired margin= 1.1 Units: dmnl
(18) Desired new repairs per month= DELAY1(Broken connections/Desired time to repair all broken connections , 1) Units: customer/month
(19) *Ethiopia*: Desired time to repair all broken connections= 36 *Kenya*: Desired time to repair all broken connections= 24 Units: month
(20) Deterioration= Capacity/Technical lifetime Units: MW/month
(21) Expenses= CAPEX+Grid expansion costs+OPEX Units: USD/month
(22) External resources expansion= 0 Units: USD/customer Universal access: STEP(2.2e+08,180)
(23) External resources OPEX= 0 Units: USD/month
(24) FINAL TIME = 360 Units: month The final time for the simulation.
(25) Fraction of OM required being spent= 0.8*(1+0.5*External resources OPEX/"OM repairs spent") Units: **undefined**
(26) Grid expansion costs= (Connection rate*Total connection cost)-External resources expansion Units: USD/month
(27) *Ethiopia*: Initial fraction= 0.1 *Kenya*: Initial fraction= 0.05 Units: dmnl
(28) *Ethiopia*: Initial tariff= 0.06005 *Kenya*: Initial tariff= 0.08 Units: USD/kwh
(29) INITIAL TIME = 0 Units: month The initial time for the simulation.
(30) "OM repairs spent"= DELAY FIXED ("OM repairs required"*Fraction of OM required being spent , 12, "OM repairs required" *0.8) Units: USD/month
(31) Customers= INTEG (Connection rate, 766041) Units: customer

(32) Electricity consumption per customer= 194 Units: kwh/customer/month Per month
(33) Electricity theft= Electricity theft scale factor*1/(1+EXP(-k*(100*(1-Delayed satisfaction) -x0))) Units: dmnl
(34) Electricity theft scale factor= 0.5 Units: dmnl
(35) External resources CAPEX= 0 Units: USD/month
(36) Generation reliability= Overloading probability(min(1/(Power availability)/1.3,1)) Units: dmnl
(37) Initial average lifetime= 12*40 Units: month
(38) *Ethiopia*: k= 0.03897 *Kenya*: k= 0.04205 Units: dmnl Value is calibrated from data (use 0.1 as initial value)
(39) Lifetime of new component= Quality of work*Initial average lifetime Units: month
(40) Month= 1 Units: month
(41) New Capacity= max(Power demand*(Target power availability-Power availability) /Ordering time,0) Units: MW/month
(42) Normalized tariff= (Initial tariff/Tariff)ˆ(1) Units: dmnl
(43) "OM repairs required"= Repair cost per customer*Repair rate Units: USD/month
(44) OPEX= "OM repairs spent"+Required generation Opex per month+Other expenses-External resources OPEX Units: USD/month
(45) OPEX factor= 0.02 Units: dmnl
(46) Ordering time= 24 Units: month
(47) Other costs per customer= 0 Units: **undefined**
(48) Other expenses= Other costs per customer*Customers Units: **undefined**
(49) Overloading probability ([(0,0)-(1.4,1)],(0,1),(0.5,0.99),(0.6,0.98), (0.687373,0.97),(0.750509,0.96),(0.80
(0.854379,0.9),(0.906314,0.85),(0.958248,0.78), (1,0.71),(1.4,0)) Units: dmnl
(50) Power availability= Capacity/Power demand Units: dmnl
(51) Power demand= Customers*Power Demand per customer Units: MW
(52) Power Demand per customer= 0.0015 Units: MW/customer
(53) previous average lifetime= DELAY FIXED(Average liftime , TIME STEP , 12*40) Units: month
(54) Quality of work= ("OM repairs spent"/"OM repairs required") Units: dmnl
(55) Reliability= sqrt(Generation reliability*Transmission and distribution system reliability)*Reliability to satisfaction mapping Units: dmnl
(56) *Ethiopia*: Reliability to satisfaction mapping= 0.867326 *Kenya*: Reliability to satisfaction mapping= 0.8 Units: dmnl
(57) Repair cost per customer= 300 Units: USD/customer
(58) Repair rate= min(Repairs per month,Broken connections/Month) Units: customer/month
(59) Repairs per month= INTEG (Change in repairs per month, 1000) Units: customer/month
(60) Required generation OPEX= Capacity*(Cost per MW*OPEX factor) Units: USD Brukar ligga pÃĕ 2-4
(61) Required generation Opex per month= Required generation OPEX/Annual to month Units: USD/month
(62) Revenue= Tariff*Total electricity consumption*(1-Total losses/100) Units: USD/month
(63) Satisfaction= Satisfaction mapping factor*sqrt((Normalized tariff*Reliability)) Units: dmnl

(64) Satisfaction mapping factor= 0.75 Units: dmnl
(65) SAVEPER = TIME STEP Units: month The frequency with which output is stored.
(66) System growth= Connection rate Units: customer/month
(67) ("STEP" function used for change of connection rate) *Ethiopia*: Target growth rate= (10000)*(1+(External resources expansion/Total connection cost)/10000) *Kenya*: Target growth rate= (50000)*(1+(External resources expansion/Total connection cost)/10000) Units: customer/month
(68) *Ethiopia*: Target power availability= 1.2 Units: dmnl
(69) Tariff= INTEG (Change in tariff,Initial tariff) Units: USD/kwh
(70) Technical lifetime= 50*12 Units: month
(71) *Ethiopia*: Technical losses= 0.15 *Kenya*: Technical losses= 0.8 Units: dmnl Not affected by customer satisfaction
(72) TIME STEP = 0.0625 Units: month The time step for the simulation.
(73) Time to change repairs= 24 Units: month
(74) *Ethiopia*: Time to change tariff= 36 *Kenya*: Time to change tariff= 24 Units: month
(75) Total connection cost= 1000 Units: USD/customer
(76) Total electricity consumption= Electricity consumption per customer*Customers Units: kwh/month
(77) Total losses= (Electricity theft+Technical losses)*100 Units: dmnl
(78) Transmission and distribution system reliability= 1-(Broken connections/(Working connections+Broken connections)) Units: dmnl
(79) Working connections= INTEG (Repair rate+System growth-Breakdown rate, Customers*(1-Initial fraction)) Units: customer
(80) *Ethiopia*: x0= 93.23 *Kenya*: x0= 70 Units: dmnl Value calibrated according to data (use 28 as initial value)

8.4 Ethiopian IPP:s

246 MW

በመግአ እንዲያዙ በመግአ ቦርድ ተቀባይነት ያገኙ የኃይል ፕሮጀክቶች ዝርዝር።

ተ.ቁ	የፕሮጀክቱ ስም	አቅም ርዝመት	የሚሰራበት ክልል ልዩ ቦታ ስርጭት	የፕሮጀክቱ ወጪ ግምት (በሚሊዮን ዶላር)	መግለጫ
1	Hydro Power Genale Dawa 6	469MW	ገናሌ	793	
2	Hydro Power Genale Dawa 5	100MW	ገናሌ	387	
3	Hydro Power Chemoga-Yeda I & II	280MW	አማራ	729	
4	Hydro Power Halele Warabessa	424MW	ኦሮሚያ	1.2	
5	Hydro Power Dabus	798MW	ኦሮሚያ	984	
6	Scaling Solar IPP Gad - Phase 1	125MW	ሶማሌ	150	
7	Scaling Solar IPP Dicheto - Phase 1	125MW	አፋር	150	
8	Mekele Solar	100MW	ትግራይ	120	
9	Humera Solar	100MW	ትግራይ	120	
10	Welenchetti Solar PV project	150 MW	ኦሮሚያ ክልል	165	
11	Weranso Solar PV Project	150 MW	አፋር ክልል	165	
12	Metema Solar PV Project	125 MW	አማራ ክልል	150	
13	Hurso Solar PV Project	125.0 MW	ድሬዳዋ	150	
14	Transmission and substation project	-	-	-	18 ዝርዝር ፕሮጀክት ሎቶች ያሉት ሲሆን ከዚህ ቀደም ከቻይና ስቴት ግሪ ጋር የተጀመረው ድርድር እስካልጠናቀ ድረስ በመግአ እንዲያዝ የተወሰነ።

የገንዘብና የኢኮኖሚ ትብብር ሚኒስቴር
የሪከርድ አስተዳደር አገልግሎት
5

Table 6: Cost of planned Ethiopian IPP:s

8.5 EEU tariffs

Energy Tariff amendment study according to consumers class

Tariff amendment		As of Dec. 18 onward	As of Dec. 19 onward	As of Dec. 20 onward	As of Dec. 21 onward
Tariff Category	kwh/month	Birr/kwh	Birr/kwh	Birr/kwh	Birr/kwh
1.Residential tariff block					
1.1 1st block	Up to 50 kwh	0.2730	0.2730	0.2730	0.2730
1.2 2nd block	Up to 100 kwh	0.4591	0.5617	0.6644	0.7670
1.3 3rd block	Up to 200 kwh	0.7807	1.0622	1.3436	1.6250
1.4 4th block	Up to 300 kwh	0.9125	1.2750	1.6375	2.0000
1.5 5th block	Up to 400 kwh	0.9750	1.3833	1.7917	2.2000
1.6 6th block	Up to 500 kwh	1.0423	1.4965	1.9508	2.4050
1.7 7th block	Above 500 kwh	1.1410	1.5877	2.0343	2.4810
2. General Tariff					
2.1 Flat Rate		1.0352	1.3982	1.7611	2.1240
3. Low Voltage Industry Tariff					
3.1 Flat Rate		0.8161	1.0544	1.2927	1.5310
3.2 Demand Charge rate		50.0000	100.00	150.0000	200.0000
4. Medium Voltage Industry Tariff. 15kv & 33kv					
4.1 Flat Rate		0.6047	0.8008	0.9969	1.1930
4.2 Demand Charge rate		36.8850	73.7700	110.6550	147.5400
5. High Voltage Industry Tariff. Above 66kv					
5.1 Flat Rate		0.5174	0.6540	0.7911	0.9280
5.2 Demand Charge rate		21.9100	43.8200	65.7300	87.6400
6. Street Light Tariff					
6.1 Flat Rate		1.0352	1.3982	1.7611	2.1240
7. Bulk Supply Tariff					
7.1 Demand Charge rate per kw		39.2908	78.5815	117.8723	157.1600
7.2 Generation Tariff. Monthly per kwh		0.2218	0.4435	0.6653	0.8870

Table 7: Electricity tariffs in Ethiopia according to consumer class

Service Charge rates amendment study for four years, starting 2018 GC	
Tariff Class	Service Charge (in Birr)
1. Domestic	
1.1 Post paid	
Up to 50kwh	10.00
Above 50 kwh	42.00
1.2 Prepaid	
Up to 50kwh	3.50
Above 50 kwh	14.70
2. General Tariff	
2.1 Post paid	54.00
2.2 Prepaid	18.90
3. Any Industry Tariff	
3.1 Three Phase	54.00

Table 8: Electricity tariffs in Ethiopia, service charges

8.6 KPLC tariffs

Energy Regulatory Commission

Annex 1: *Approved Energy Non Fuel Electricity Retail Tariffs for Tariff Control Period (2018/19)*

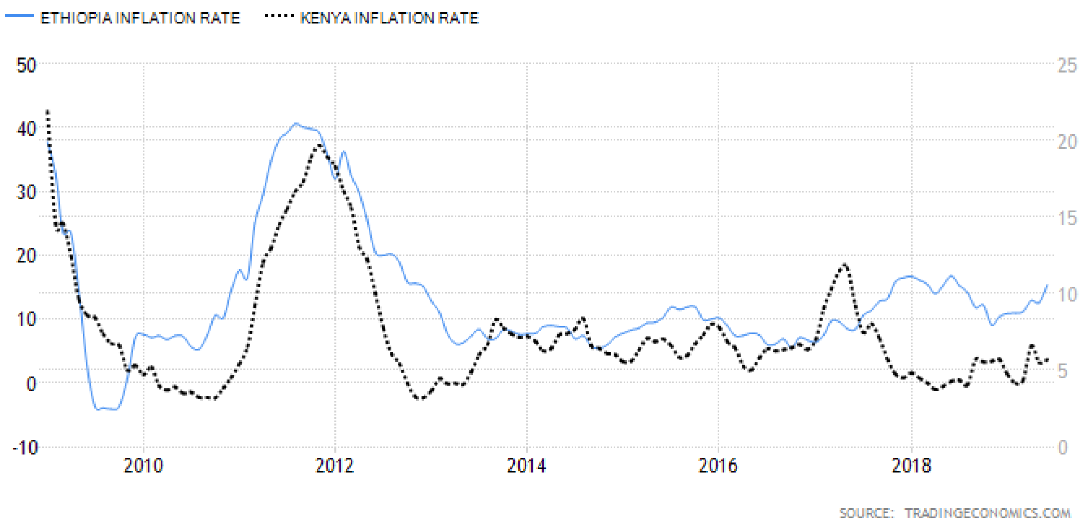
Code	Customer Type(Code Name)	Energy Limit kWh/month	Charge Method	Number of Customers	Unit	1st July 2018	1st Nov 2018
DC	Domestic		Fixed		KShs/month	0	0
DC1	Domestic Consumer 1	0-10	Energy	5,734,815	KShs/ kWh	12.00	10
DC1	Domestic Consumer 1	11-100	Energy		KShs/kWh	15.80	10
DC2	Domestic Consumer 2	>100	Energy	516,977	KShs/ kWh	15.80	15.8
SC1	Small Commercial 1	0-100	Energy	177,089	KShs/ kWh	15.60	10.00
SC2	Small Commercial 2	>100-15000	Energy	86,027	KShs/kWh	15.60	15.60
CI1	Comm./industrial	>15,000	Fixed		KShs/month	0	0
			Energy	3,096	KShs/ kWh	12.00	12.00
			Demand		KShs/ kVA	800	800
CI2	Comm./industrial	No Limit	Fixed		KShs/month	0	0
			Energy	381	KShs/ kWh	10.90	10.90
			Demand		KShs/ kVA	520	520
CI3	Comm./industrial	No Limit	Fixed		KShs/month	0	0
			Energy	53	KShs/ kWh	10.50	10.50
			Demand		KShs/ kVA	270	270
CI4						0	0
CI4	Comm./industrial	No Limit	Fixed		KShs/month		
			Energy	38	KShs/ kWh	10.30	10.30
			Demand		KShs/ kVA	220	220
CI5	Comm./industrial	No Limit	Fixed		KShs/month	0	0
			Energy	32	KShs/ kWh	10.10	10.10
			Demand		KShs/kVA	220	220
SL	Street Lighting	No Limit	Fixed		KShs/month	0	0
			Energy	8,478	KShs/kWh	7.50	7.50

Together We Succeed

Table 9: Electricity tariffs in Kenya

8.7 Inflation rate in Ethiopia and Kenya 2009-2019

Figure 28: Inflation rate in Ethiopia and Kenya 2009-2019 [2]



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