Rural Electrification Through Minigrids in Developing Countries: Initial Generation Capacity Effect on Cost-Recovery

Elias Hartvigsson
Division of Electric Power Engineering,
Elias.hartvigsson@chalmers.se

Jimmy Ehnberg
Division of Electric Power Engineering

Erik Ahlgren
Division of Energy Technology,

Sverker Molander
Division Environmental Systems Analysis

Chalmers University of Technology,
Department of Energy and Environment

Abstract

One billion people lack access to electricity around the world. Most of these people live in rural inaccessible areas and improving electricity access them is considered an important goal towards reaching the Millennium Development Goals. Minigrids is one way of improving electricity access for these people. Minigrids have however largely suffered from high costs and low incomes, making it a challenge for them to reach cost-recovery. In this paper we investigate the issue of cost-recovery for minigrid utilities in developing countries. We develop a system dynamics model to investigate the effects of initial capacity generation on cost-recovery, user diffusion and electricity usage. Our results show that it is essential to correctly dimension the capacity of a minigrid and that the effects on cost-recovery from an incorrectly sized minigrid can be delayed up to several years. Furthermore, our results show that in order to evaluate the performance of minigrids it is important to make a comprehensive analysis also looking at growth and absolute number of electricity users and their electricity usage. For future work it is important to endogenously describe the amount of connections the utility can perform and to further investigate the relationship between electricity provision and economic development.

Keywords: rural electrification, cost-recovery, minigrid, developing countries

1. Introduction

As of today one billion people lack access to electricity around the world. Roughly 500 million live in sub-Saharan Africa, and a large majority of them live in rural inaccessible areas (IEA 2013). Improving electricity access for these people is considered an important goal towards reaching the Millennium Development Goals and combating extreme poverty. Even though the causality between access to electricity and social and economical development has not been established, electricity is considered a prerequisite to economic development (Barnes 2007).

The increased electricity access in developing countries has mainly been achieved through grid extension. Grid extension has led to a focus on communities close to the grid or larger urban areas, excluding large parts of the populations that live in rural inaccessible areas. These communities have obtained access through other means, often indirect, limiting their ability to derive more benefits from electricity. If these communities are to gain the benefits of electricity access within the foreseeable future, off-grid solutions are needed. (Díaz, Arias et al. 2010, IEA 2013, Ahlborg and Hammar 2014, Tenenbaum, Greacen et al. 2014, Urpelainen 2014)

Minigrids are small off-grid, independent electricity generation and distribution systems. They have been used in rural electrification in sub-Saharan Africa, developing Asia and Latin America with various levels of success. The strength of minigrids compared to other off-grid electrification solutions is their ability to supply enough electricity for productive uses of electricity. Productive uses of electricity are considered an important link with rural development. One of the major challenges for minigrids has been the utilities inability to reach cost-recovery making them economically unattractive (Barnes and Foley 2004, Kirubi, Jacobson et al. 2009, Levin and Thomas 2014, Schnitzer, Lounsbury S. et al. 2014).

A lack of supporting policies and institutions for minigrid projects has led to a strong focus on grid-extension in rural electrification. In order to make minigrids a noteworthy alternative the issues of cost-recovery needs to be addressed. The difficulties of reaching cost-recovery can partly be explained by poor customers, lack of economic and social development, formation and mismanagement of businesses and operations. Combined with a very dispersed population, adding new customers becomes very expensive making it hard to take advantage of effects of economies of scale.

There is a considerable research literature in variables affecting rural electrification, such as: economic and social development in rural areas, agriculture and non-agriculture markets, optimization of the electric generation and distribution systems, formation of policies and different partnerships structures. For a few examples see (Nouni, Mullick et al. 2009, Haggblade, Hazell et al. 2010). This research has given a good understanding of these individual variables effect on rural electrification. Some of these studies have addressed cost-recovery specifically (Kirubi, Jacobson et al. 2009, Al-Mas 2010, Schmidt, Blum et al. 2013) but they have done so with an analytical atomistic perspective investigating the effects from specific variables.

The drawback of an atomistic approach is that it overlooks the system effects. In rural areas, where the introduction of new technological and social arrangements creates new interfaces between technology, people and their societal and natural surroundings it is important to consider system effects (Ahlborg 2012). Therefore, in order to make a more general analysis we propose a holistic approach using System Dynamics.

A System Dynamics model is created to analyze a techno-economic system in a rural community in a developing country. The model integrates the connection of productive and household users, rural economic development, operation and function of the technical system and analyzes their effects on cost-recovery. Specifically we investigate the effect of initial generation capacity on cost-recovery, user diffusion and electricity usage. Furthermore, the model is also used to identify areas where future work is needed.

The following part of the paper is divided into five sections. First we present a background on past research in the cross-section of System Dynamics, development and rural electrification and then we describe our choice of method. Thirdly we present our dynamic hypothesis followed by results based on simulations and lastly we present conclusions and future work.

2. Background

System Dynamics has been used as a planning tool in the electric power industry for decades (Ford 1997, Teufel, Miller et al. 2013). Models have been used in a wide range of applications ranging from power plant construction times to energy system composition and transformation (Larsen and Bunn 1999, Qudrat-Ullah and Davidsen 2001, Teufel, Miller et al. 2013). For a review of System Dynamics models in energy and electric power systems see Teufel et al. (Teufel, Miller et al. 2013).

The early System Dynamics model where almost exclusively constructed for countries or regions where the current electricity access is very high and where a small share or no people lack access to electricity. This suggests that the electric infrastructure has reached a technological and institutional maturity not found in developing countries.

Since a large majority of people lack access to electricity in developing countries, a vital part of the electric infrastructure does not exist and the main purpose of the national utility is to expand the electric infrastructure. However, national utilities in the developed world currently focus on transformation to more decentralized systems to integrate more renewable energy sources (REN21 2014).

There is a need to construct models specifically aimed at the growth of the electric infrastructure in developing countries due to different purpose of utilities in developed and developing countries. One of the first to develop a System Dynamics models specifically for the electric infrastructure in a developing country was Katherine Steel in 2008 (Steel 2008). Her model analyzed the Kenyan electric power sector and the dynamics between grid and off-grid. Steel concludes that in Kenya the competition between grid and off-grid options is hurting the quality of electricity supply from the grid causing a downward reinforcing feedback loop of power quality. In some scenarios the downward spiral hurt the grid power availability and reliability to the extent that off-grid electricity became the dominant supply of electricity.

The model is based on consumer choice, where consumers can either connect to the grid, to an off-grid supply or change from one to the other. This assumes that there is a choice to be made by the users. However, since a large majority of the current population is living far from the grid receiving a grid connection in the foreseeable future is not likely and therefore no choice between grid and off-grid supply exist.

Steel's model was followed by the work of Rhonda Jordan who analyzed long-term effects of capacity planning in developing countries, focusing on Tanzania, using System Dynamics and Linear Programming (Jordan 2013). The purpose of the modeling was to find the optimal investments strategies in the electric power system based on endogenous behavior. Jordan concluded that it is important to incorporate endogenous electricity demand when either a large part of the population lacks electricity access or when adding new capacity bring improvements in reliability.

In rural electrification System Dynamics have been used to a lesser extent. However, there are more cases of System Dynamics models used in rural energy systems but these models have addressed the energy system and missed the technical representation of electricity (Mashayekhi, Mohammadi et al. 2010, Zhang 2012). A few attempts have recently been made to either address specific technologies in rural electrification or addressing rural electrification on an abstract level and therefore missing technology related dynamics and characteristics (Fernando and Isaac 2014).

In the technologically oriented track of rural electrification research, modeling is relatively common. However, the models used in rural electrification have mostly been modeled the operation and construction of technical system, and often as optimization models trying to find the optimum choice of energy mixes or technology choice (Nfah, Ngundam et al. 2008, Kanase-Patil, Saini et al. 2010, Palma-Behnke, Benavides et al. 2013). As technical models, they are limited to "hard"-variables and exclude variables seen as "soft" and difficult to quantify (Jackson 1985, Checkland 2000, Sterman 2002). This has made the models very good at explaining the technical performance but lacks an integrated connection with rural economic and market growth theory, business administration and electricity usage. Hence they have been unable to endogenously describe the dynamics of cost-recovery.

By creating a System Dynamics model we aim to increase the understanding of the challenges behind cost-recovery, and particularly to analyze the endogenous effects between initial generation capacity of a minigrid and the utility's ability to reach cost-recovery. This will help future minigrid projects to correctly dimension their generation capacity and improve their service to the rural communities while keeping costs and electricity prices down.

3. Method and limitations

Based on data collection in rural Tanzania, literature overview and discussions the model was developed through the iterative process described by John Sterman (Sterman 2000). In total where two field visits done to Tanzania in 2013 and 2014. During the field visits, a number of rural electrification projects were visited. Additionally interviews with customers, operators, government officials and NGOs where held. The interviews were questionnaire-based with complementing qualitative questions.

The income of a utility is directly proportional to the amount of electricity sold. The total amount of electricity sold depends on how much each customer consumes and how many customers the utility has. Therefore, we chose to investigate the effect of initial generation capacity on; income statement, electricity usage and number of customers, we have developed three different initial generation scenarios. The three scenarios are with 50 kW, 100 kW and 200 kW initial generation capacity. The choice of initial generation capacities was done to cover a large range of sizes identified in literature (Schnitzer, Lounsbury S. et al. 2014) and through fieldwork. The model implicitly assumes the usage of fuel independent energy sources, which is a characteristics shared by most renewable energy sources.

In all scenarios the model is run with the same amount of initial users, initial electricity usage and with an initial income for the utility (200 000 USD). If the income statement is decreasing below zero the utility is only allowed to use money for operation (salaries for administrational work in order to continue receive income from electricity produced) and minimum maintenance. Lending of money to maintain these services is done with zero interest or demands on payback time.

The utility's size in terms of personnel is not modeled and considered constant. Without the ability for the utility to hire more personnel the amount of new connection that can be done is fix. Due to pressure from the local community, the utility is also assumed to slightly prefer the connection of households rather than Small and Medium Sized Enterprises (SMEs).

The model is run over a period of 20 years. The technical payback time for electric infrastructure equipment is in the range of 40-50 years in developed countries. Since the risks in building a electric infrastructure in developing countries, and especially in rural areas, is higher than in the developed world there is a need for a shorter payback time. If the utility is not able to reach a positive income statement after 20 years, the chances to payback the system are very limited.

4. Dynamic Hypothesis

Starting with a holistic approach we developed our dynamic hypothesis of cost-recovery to include: operation of a utility, the basic characteristics of electric power system and rural economic growth. The dynamic hypothesis is shown in Figure 1. The diagram shows the central causal loops affecting the utility's income statement, indicated as R1-R4 and B1-B4. The hypothesis is centered on the income and expenditure of a minigrid utility.

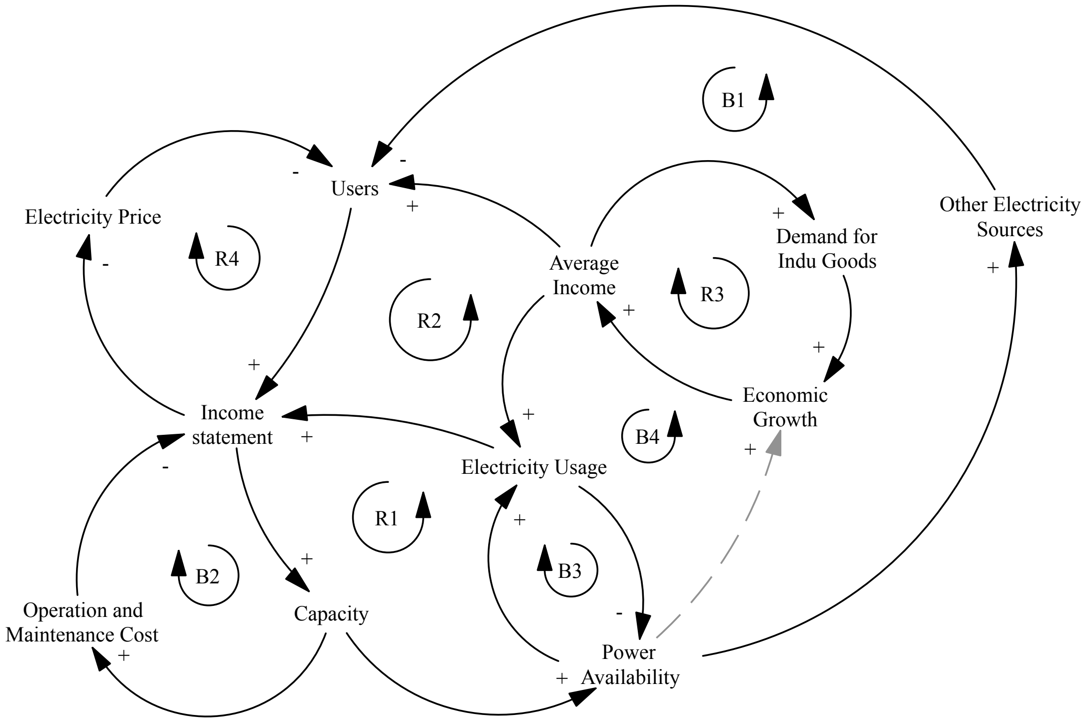

Figure 1. The Causal Loop Diagram describing our Dynamic hypothesis of cost-recovery for a minigrid utility. The dashed arrow between "Power Availability" and "Economic Growth" describes a limiting causality, i.e. "Power Availability" cannot act as a driver for "Economic Growth" but only as a barrier.

The two main variables affecting the utility's income are number of users and the amount of electricity each user consume. Connection of new users is thought to be a diffusion process of relative cost of electricity and perceived risk of connection while electricity usage is linked with income and available power.

If the capacity of the system is large compared to existing electricity usage and number of users it gives room for more users to be connected and for existing users to increase their consumption. However, a larger system also requires larger operation and maintenance (O&M) costs. Even though the share of O&M is decreasing as the size of the system is increasing, the benefit in terms of more sold electricity is not instantaneous.

Users are divided into two groups, households and SMEs. The separation into two groups is due to their differing dependency on and their different ability to pay for electricity. SMEs are assumed to use electricity in their operations and are therefore more sensitive to variations in power availability than households. Furthermore, SMEs are to a larger extent using large loads, such as: welding equipment, electric saws and drills and electric machines, which both consumes more electricity than households appliances and are used during different times of the day. Other services such as bars and restaurants rely on electricity in order to keep their business open after dark.

Economic growth is described by a Cobb-Douglas production function (Cobb and Douglas 1928) and is driven by demand, available capital and labor, described as reinforcing loop R3. Electricity influence production through total factor productivity. Due to different drivers and production characteristics for agriculture goods and non-agriculture goods, production is separated into the two groups (Haggblade, Hazell et al. 2010). Agriculture goods assumed to be produced by local farmers and non-agriculture goods are produced by local SMEs. The production of agriculture goods amongst local farmers is assumed to be mostly subsistence with a limited cash return of 33% of produced value.

Electricity is assumed to be able to work as a direct limiting factor on production but not a direct driver. If demand is lower than production capacity, then power availability will not effect production. However, if demand is larger than production capacity, then lack of power availability will limit production. The dashed grey arrow from Power Availability to Production of Goods describes this relationship.

5. Model Results and Discussion

From our dynamic hypothesis we developed a stock and flow model to investigate the effect of initial capacity generation on income statement. Since the model is still under development and formal validation the results presented below are preliminary.

Figure 2 shows the income statement for the three scenarios. All cases show a very fast decline in the first weeks. This is due to the fact that the utility tries to connect as many new users as possible. Due to the high connection costs in the early stages the utility swiftly depletes its resources.

The decline for the 50kW scenario is too large for the utility to handle and the utility never manages to recover. The 100 kW scenario shows a similar fast decline in returns followed by a slow increase in income and after 10 years starting to make a profit. The 200 kW scenario show very similar behavior that of the 100 kW scenario but as it starts to make a profit after 10 years, the increase is faster than for the 100 kW scenario.

The reduction in the income statement during the first 8 years can be described by a delay in the utility's income, seen in Figure 2. The costs for a single connection compared to the electricity usage for the utility are high. For the utility to start making profit from a connection they need to sell in the same amount of electricity as the connection costs. Which for a household takes roughly 10 years, and for a SME roughly 5 years. Therefore if the electricity consumption in rural areas could be increased, the economic performance for minigrid utilities could improve.

Figure 3 shows the total amount of connections (both households and SMEs). There is a rapid, but small, increase in connections in the beginning for all scenarios followed by a long constant segment. The constant segment is a direct result of the utility's negative income statement. As the utility connects as many users as possible in the early stages, it depletes all its resources and ability to connect more users. The resources remain depleted until the electricity usage has increased enough for the utility to reach a positive income statement.

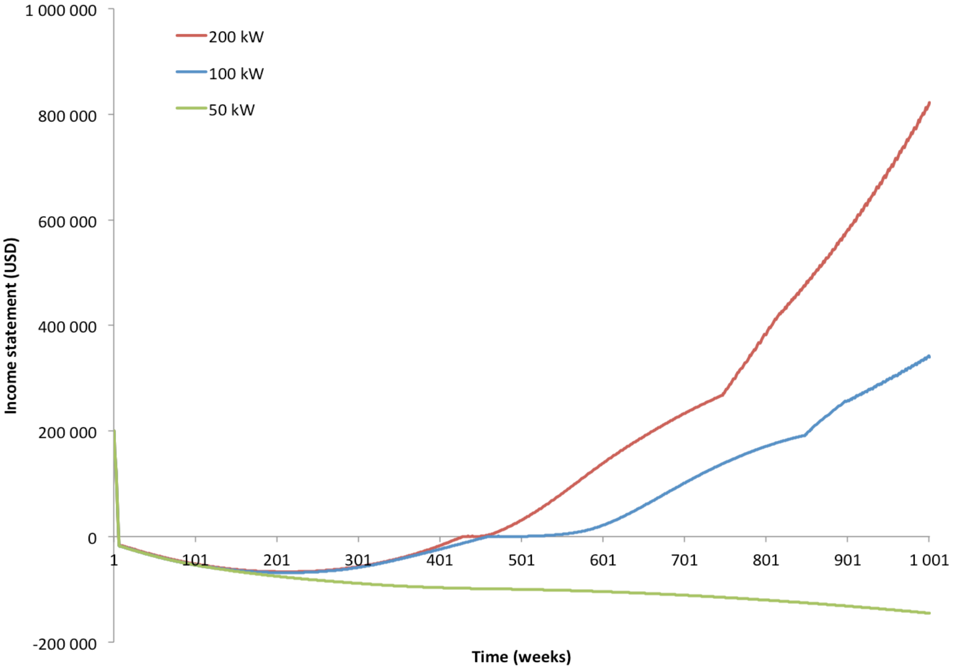

Figure 2. Minigrid utility's income statement over a period of 1000 weeks. The three curves represent an initial capacity of 50 kW (green), 100 kW (blue) and 200 kW (red).

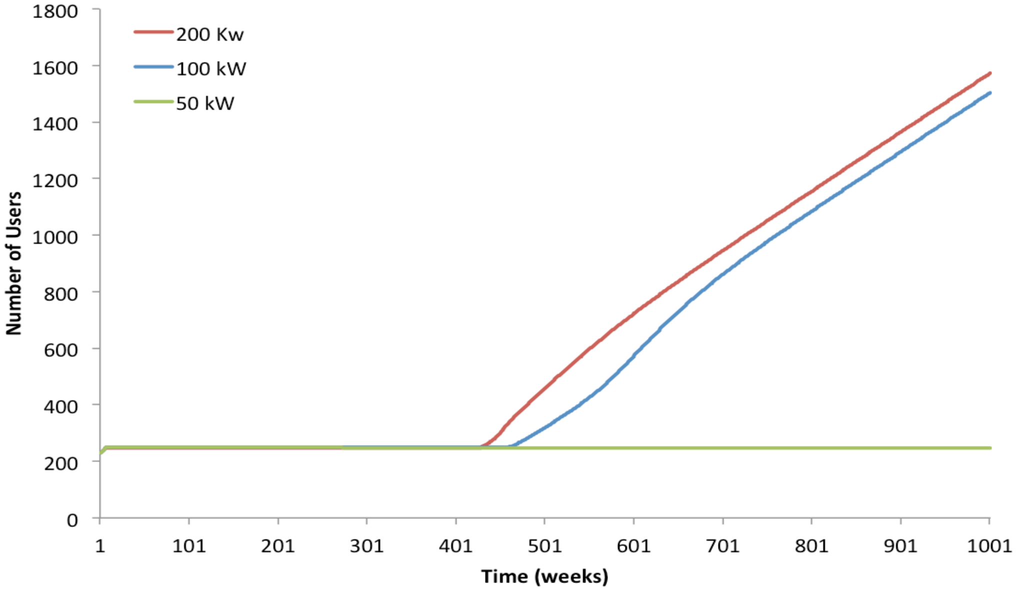

Figure 3. The number of connected household and small and medium sized enterprises users. The three curves represent initial capacity of 50 kW (green), 100 kW (blue) and 200 kW (red).

When the income statement becomes positive the utility can continue connecting users. Since the process of connecting more users takes a considerable time, the local economy (both agriculture and non-agriculture goods) has increased to the extent that the community resident's income does not limit new connections. Due to their increase in income they also perceive the risk as much lower and therefore the limit is rather how many the utility can connect. This explains the relatively linear growth in connections after 10 years.

An endogenous modeling of the utility's workforce, especially regarding the number of technicians that can perform connections would likely result in a very different outcome. In such a case the hiring time, and therefore indirectly the availability of skilled technicians, could possibly have a large impact on the behavior and outcome.

Figure 4 shows the average electricity usage for the three different scenarios. The growth in electricity usage is mostly associated with increase in income. Increased income for households increases their ability to buy new appliances (increase their load) and ability to run their appliances longer.

In all scenarios the electricity usage starts declining at some point in time. The main process driving the reduction in electricity consumption is low power availability. A major issue with decrease in electricity consumption from low power availability is that it creates a downward spiral. As users disconnects or reduce their electricity consumption the income for the utility will decrease resulting in less money to spend on maintenance of the technical system. Without maintenance the system will deteriorate and its capacity reduced even more. This is similar to what Katherine Steel identified in the Kenyan electric power system (Steel 2008).

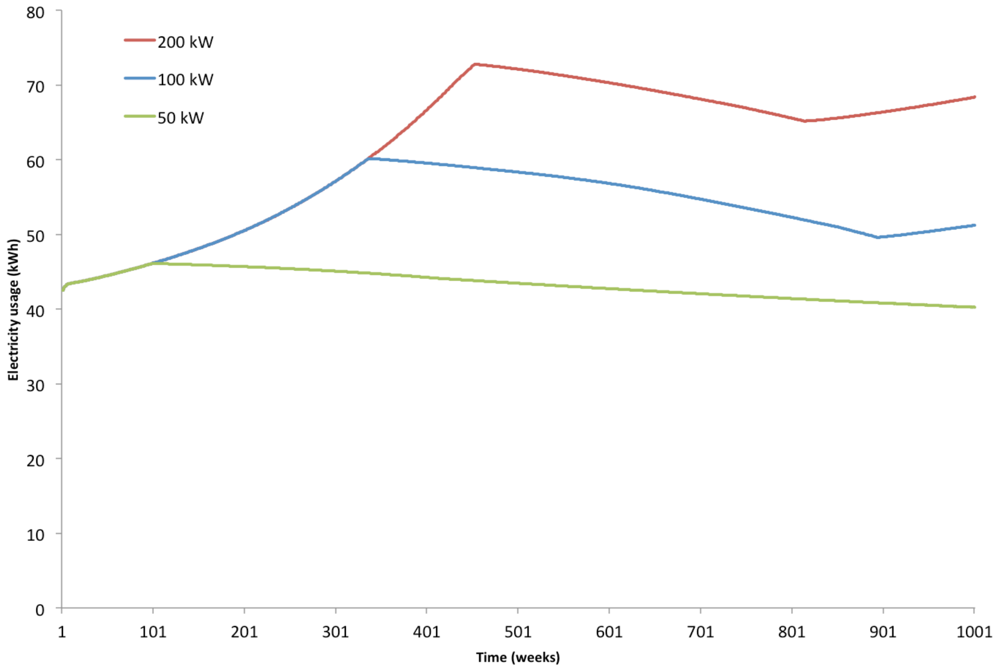

Figure 4. Total electricity usage for both households and SME's in the different scenarios. The main driver for increase in electricity consumption is income and the main barrier is available power. The three curves represent an initial capacity of 50 kW (green), 100 kW (blue) and 200 kW (red).

It is not until the added capacity has caught up with the demand that electricity usage starts increasing, as seen in Figure 4 for the 100 kW and 200 kW scenarios. However, if the utility does not receive enough income it will be unable to increase the demand and hence the electricity usage will fall since generation capacity is decreasing due to wear and tear, as seen in the 50 kW scenario.

As seen in the Figures the scenarios show very different outcomes. However, it should be noted that the simulations are done with the same initial amount of users. Increasing the number of initial users would likely benefit the larger system, and decreasing them would likely benefit the smaller systems. Therefore the results should rather be seen as an indicator that dimensioning is important, not that small-sized minigrids are economically less feasible than larger sized minigrids.

6. Conclusion and Future Work

Our results suggests that correctly dimensioning the generation capacity in a minigrid is essential in order for the utility to achieve cost-recovery. Our findings also indicate that the effects from an incorrectly dimensioned minigrid are delayed and that drawing conclusions on the performance of a minigrid utility by only looking at a small set of variables can result in an inaccurate description. In order to get a better description of the performance, both technical variables, such as power availability and electricity usage, and economical variables such as income statement should be included for in a more comprehensive analysis.

Our results also point to the need to include previous unidentified sectors, such as the utility's ability to connect users. Furthermore, we have identified the importance to in capturing the dynamics between supply, demand and production in rural markets and to better portray their relationship with electricity provision amongst SMEs.

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