THESIS FOR THE DEGREE OF DOCTOR OF PHILOSOPHY

To be or not to be

On system dynamics and the viability of mini-grids in rural electrification

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Gothenburg, Sweden 2018

Cover:

"The pursuit of peace and progress cannot end in a few years in either victory or defeat. The pursuit of peace and progress, with its trials and its errors, its successes and its setbacks, can never be relaxed and never abandoned."

Dag Hammarskjöld
United Nations Bulletin Vol. XVI, February 15, 1954

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Abstract

One to two billion people are expected to receive electricity access in developing countries in the coming decades. Many of these people will live in rural areas in developing countries where the existing grid will not be able to reach. These people will therefore rely on off-grid technologies to gain electricity access. One off-grid technology that is expected to grow significant is mini-grids. In addition, the number of mini-grids in developing countries are expected to growth significantly. Furthermore, renewable energy sources are increasingly used in mini-grids, putting larger emphasises on dimensioning and management of the technical system. However, previous experiences with mini-grids in rural electrification have been mixed, and many systems have failed or been abandoned prematurely. The many interactions between technical, operational and social elements make it difficult to attribute the failures to specific causes.

The main purpose of this thesis is to investigate why mini-grids in rural electrification fail. The investigation focuses on reliability of electricity and how it is impacted by and impacts operation of mini-grids, the technical system and the community. The investigation is made through the implementation of system dynamics and load assessment.

Rural electrification consists of many actors with different goals, it concerns the behaviour of people and is affected by technology. As, such, formulating relevant problems in rural electrification is difficult. As shown in Paper II, qualitative system dynamics can aid the process of tackling this complexity and therefore also in formulating problems. Results from Paper IV show that initial dimensioning of mini-grids is important for long-term viability. However, the dimensioning is dependent on estimations of electricity usage or electricity usage in similar areas, which are often done through collection of data through interviews. As shown in Paper III, interview-based load profiles might not be an accurate estimation of measured load profiles. Thus, estimates from interview-based load profiles might provide misleading estimations resulting in non-optimal sizing. Results from Paper I show that long-term reliability in mini-grids is affected by operational practices and community behaviour. Even though poor reliability is associated with the failure of specific components in the technical system, they are subject to operational practices and are thus influenced by the overall functioning of a mini-grid. As such, long-term reliability in mini-grids needs to be considered from a system perspective.

Keywords: system dynamics, rural electrification, mini-grids, complexity, reliability, load assessment

Acknowledgements

List of publications

The thesis is based on the work in the following publications (listed as I-V).

I.   Hartvigsson, E., Ehnberg, J., Ahlgren, E. et al., Using system dynamics to understand deteriorating electricity reliability in mini-grids. *Manuscript*

II. Hartvigsson E., Ahlgren E., Molander S., Tackling complexity and problem formulation in rural electrification through conceptual modelling and system dynamics. *Submitted to an international scientific journal*

III. Hartvigsson E., Ahlgren E. (2018), Comparison of load profiles in a mini-grid: assessment of performance metrics using measured and interview-based data. *Energy for Sustainable Development*. 43 pp. 186-195

IV. Hartvigsson, E., Stadler, M., Cardoso, G. (2018), Rural electrification and capacity expansion with an integrated modeling approach. *Renewable Energy*. 115 pp. 509-520.

V.   Riva F., Ahlborg H., Hartvigsson E., et al. (2018) Electricity access and rural development nexus: review of complex socio-economic dynamics and causal diagrams for more appropriate energy modelling. *Energy for Sustainable Development*. 43 pp. 203-223

Additional publications during the PhD project not included in the thesis.

VII. Ehnberg J., Ahlborg H., Hartvigsson E., Method for flexible distribution and transformation design in rural electrification. *Manuscript in preparation*

VIII. Hartvigsson E., Ehnberg J., Socio-technical aspects of dimensioning and operation of mini-grids in rural electrification. *Manuscript in preparation*

IX.   Hartvigsson E., Riva F., Colombo E., Ehnberg J., The merry-go-round of electrification programs: potential pitfalls of only using electricity access as an indicator for electrification. *Submitted to the International Conference of System Dynamics*

X.   Cardoso, G., Stadler, M., Mashayekh, S., Hartvigsson E. (2017), The impact of ancillary services in optimal DER investment decisions. *Energy*. 130 pp. 99-112.

XI.   Ehnberg, J., Ahlborg, H., Hartvigsson, E. (2016), Flexible distribution design in microgrids for dynamic power demand in low-income communities, IEEE PES PowerAfrica Conference,

XII.   Hartvigsson, E., Ehnberg, J., Ahlgren, E. et al. (2016), Using system dynamics for long term bottom-up electric load modeling in rural electrification, International System Dynamics Conference.

XIII.   Hartvigsson, E., Ehnberg, J., Ahlgren, E. et al. (2015), Assessment of Load Profiles in Minigrids: A Case in Tanzania, 50th International Universities Power Engineering Conference (UPEC).

XIV.   Hartvigsson, E., Ahlgren, E., Ehnberg, J. et al. (2015), Rural Electrification Through Minigrids in Developing Countries: Initial Generation Capacity Effect on Cost-Recovery, International Conference of the System Dynamics Society.

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Chapter 1 Introduction

1.1 - Background

The first recorded central electric power station providing electricity to the public (and thus the first public mini-grid) was built in 1881 in Godalming, UK. Before 1881, the streets in Godalming were lit by gas through an agreement with a local gas company. When the agreement expired in September 1881, and the town and the gas company failed to find a new agreement, electricity was suggested as an alternative. Using a local waterwheel as a power source, 47 lights were built on the town streets. Since a network was needed to install the street lights, it was announced that people who wanted electricity could have a wire connected to their house and enjoy the benefits of electric lights, compared to their old gas lights. After 6 months, only 8-10 people had accepted the offer and the system only supplied a total of 57 lights. In 1884 the project was considered a failure, the town abandoned electricity and reverted to gas lighting (McNeil, 1990).

So, what caused the system to fail? Why did only a few people accept the offer of having electric lights in their homes? As stated by McNeil, it was likely due to many factors. Around 1880s, gas lighting was a common technology and thus generally well accepted while electricity was new and considered with a certain level of suspicion and scepticism, to the extent that incidents of vandalism occurred (Tanner, 1954). Furthermore, due to technical limitations, reliability in the system was poor, causing problems of low voltage and therefore poor illumination. Thus, reducing the apparent benefits of electric lighting. This led the project to re-think their initial technical solution and abandon the original waterwheel and install a generator inside the town. The new generator partly solved the issues of low voltage and poor reliability. Nevertheless, the project failed and it took Godalming an additional 23 years before receiving lasting electricity access in 1904.

Around the same time as the experiment in Godalming was conducted, electric power systems across the world emerged. One year after Godalming, in 1882, Pearl street station in New York began operation, and unlike Godalming was considered a success. The growth of regional electric power systems in the western world during the 1920s has largely been attributed to co-developments in entrepreneurship, management, organizational theory, technology and politics (Hughes, 1993). The success at Pearl street station was followed by many other successful examples and resulted in largely centralized and large scale electric power systems. These developments allowed for electric power systems to evolve into efficient and viable systems, able to withstand technical, social, political and economic changes.

Since one billion more people are estimated to receive access to electricity in the coming decade the question why the experiment in Godalming failed becomes relevant. Furthermore, a majority of these people live in rural areas, and will rely on off-grid systems in order to receive electricity access (IEA, 2017; The World Bank, 2017a). Previous efforts to increase electricity access have to a large extent relied on extending the large national grids. The focus of centralized electricity production has led to a focus on fossil fuel based energy sources (IEA, 2017), which has had significant negative environmental consequences (Alstone et al., 2015; Wamukonya, 2003). Furthermore, the rise of cheap small off-grid solutions has in some instances led to competition between grid and off-grid systems, which has affected the economy and technical reliability of large operators in developing countries (Steel, 2008).

The geographical position and low demand of rural areas makes the traditional method of extending the existing large-scale grids inefficient and costly. In addition, abundance of renewable energy resources (small scale hydropower, solar PV, wind power and biomass) in many areas, the inaccessibility by roads during certain times suggests that off-grid solutions are advisable. One of the most successful rural electrification off-grid options has been Solar Home Systems (SHSs). SHSs are small solar PV and battery systems that supply electricity for a few low consuming household appliances. Their affordability and availability has resulted in fast dissemination in many developing countries, even with limited intervention or subsidies from government or aid-programs (Ondraczek, 2013).

However, SHSs (and similar sized technologies) are beneficial when it comes to certain impacts from electricity (Azimoh et al., 2016), but their size makes them unable to supply electricity to many productive uses of electricity, which means the application of electricity directly or indirectly increases value or production (Cabraal et al., 2005). This means that both direct and indirect applications are considered. Direct applications include processes such as changing a diesel engine to an electric machine for milling; increasing opening hours through electric lights; or selling cold drinks. Indirect applications are improved health due to better healthcare associated with electricity access and modern equipment, increased study time due to electric lights and improved productivity due to increased lighting. As such, productive use of electricity is considered to be an important link between electricity access and rural development (Cook, 2011, 2013).

However, many of the productive use activities require high levels of power and energy. Thus, in order to supply electricity for productive uses, larger systems, such as mini-grids, are needed. Unlike SHSs, mini-grids have enough capacity to supply a wide range of productive uses, and thus, should improve the realization of the benefits associated with electricity access. In addition, mini-grid size also simplifies the integration of renewable energy sources while maintaining high technical and economic performance (E. Hartvigsson & Ahlgren, 2018). As such, mini-grids will probably be an essential technology in order to reach current goals of electricity access in rural areas (Tenenbaum et al., 2014; United Nations, 2015).

1.2 - Mini-grids and rural electrification

Mini-grids are referred to extensively in the scientific, grey and engineering literature, and as such various working definitions exist regarding: size, energy source, availability of a grid-connection and management structure. In this thesis: *Mini-grids are independent generation and distribution electric power systems situated in rural areas of developing countries supplying a few hundreds to a few thousand customers that includes a local organization conducting operation and management*. The above definition is actively chosen to have a certain level of ambiguity while also being limited. A strict definition, even though technically useful, lacks relevance for the varied and changing conditions found in rural electrification. Access to electricity can change existing social, economic and environmental structures (Ahlborg, 2015). It changes and creates new relations of power that impacts the management and distribution of electricity, which has implications on the topology and functioning of the electric power system (Ahlborg & Sjöstedt, 2015; Ehnberg et al., 2016; Riva, Ahlborg, et al., 2018). In addition, the sizes of communities supplied with mini-grids and the expected growth of electricity demand in many developing countries suggests that the technical size of mini-grids can vary greatly in both space and time. Thus making a definition based on a strict size unusable when considering long time-frames. In addition, changes in regulations, which are likely to change when considering long time-frames, might alter the legal definition of a mini-grid.

The independency of mini-grids in terms of power and energy and their inaccessibility means that they have an opportunity and challenge to utilize local renewable energy sources rather than fossil fuels. Using local renewable energy sources puts emphasis on the technical sizing and operation of the systems. Over-use or improper usage of some renewable energy sources can have negative impacts on the local environment, poorly sized mini-grids can result in reliability issues or lack of economic viability (Okure et al., 2018). In addition, many renewable energy sources are (as of 2018) characterized by a large initial investment cost and a low operational cost, making changes in the generating capacity difficult if access to appropriate financial resources is limited. With a current lack of formal financial institutions willing to lend money to increase the capacity of min-grids, the initial sizing becomes increasingly important. Thus, it becomes increasingly important to understand the dynamics of electricity usage when considering capacity expansion of mini-grids.

Electric power systems both influence and are influenced by society, economy, politics and technology (Hughes, 1993). Thus, when considering long-run impacts of electricity on the functioning of electric utilities, it is important to consider feedback effects (Salman et al., 2016). The operational practices of an operator impact electricity reliability through the allocation of resources. Large scale dissatisfaction can cause social unrest (Aklin et al., 2016) with potential large implications for an operator. The creation of social-norms, and

trust between the community and operator directly influence electricity theft (Never, 2015), and lack of response to community dissatisfaction can cause conflicts between the operator and the community (Elias Hartvigsson, Ahlgren, & Molander, 2018).

Therefore, when considering the long-term performance of mini-grids, the technical functioning of the system cannot be separated from feedback effects between the community, the operator and their environment. This thesis, therefore is based on a system understanding of a mini-grid and is shown in Figure 1. The description is based on the understanding that a mini-grid consists of three sub-systems: a technical sub-system consisting of the physical infrastructure; an operator sub-system that describes the managerial and operational practices; and a community sub-system consisting of customers of the mini-grid and other community members. These sub-systems interact with each other and the surroundings. The interaction of these sub-systems, both between them and their surroundings suggests that systems methods are appropriate for analysing its dynamic behaviour.
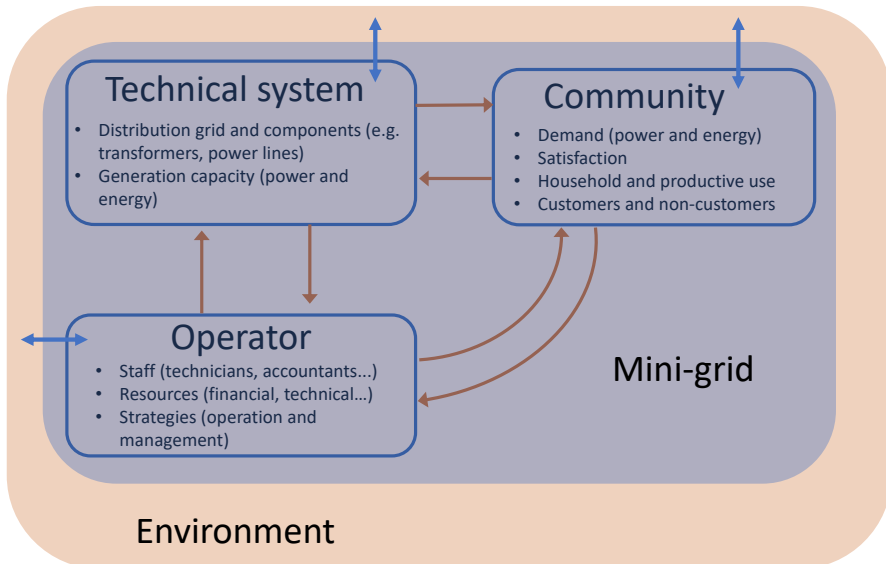
Figure 1 Conceptual diagram showing the boundary of a mini-grid and its three sub-systems.

The diagram in Figure 1 shows interconnections between both the various sub-systems and with the environment. The connections that the diagrams describes between the various elements suggests that the individual sub-systems cannot be analysed separately, e.g. using reductionism, but that an analysis of mini-grids needs to take into account how the various sub-systems affect each other and what the impacts from the feedbacks are. The variables that are included in the mini-grid boundary are endogenous. Endogenous variables both affect and are affected by other variables within the mini-grid, such as reliability and electricity demand. Variables in the environment are exogenous. Exogenous variables affect

variables in the mini-grid but are not affected by variables in the mini-grid and include access to financial institutions and fraction of income used for paying a connection fee. The influence of both "soft" and "hard" factors on mini-grids suggests that a qualitative and quantitative approach is advisable. In addition, the large number of endogenous variables suggests that systems methods are advisable. One systems approach that allows for both a qualitative and quantitative analysis of systems is system dynamics. Specifically, system dynamics focus on formulating models for analysing and proposing solutions to problems arising from feedbacks in societal problems.

1.3 – Viability, system dynamics and mini-grids

The experiences of mini-grids in rural electrification have so far been mixed. Successful cases of mini-grids have amongst others been found in Kenya (Kirubi et al., 2009), Tanzania (Ahlborg & Sjöstedt, 2015), Bangladesh (Yadoo & Cruickshank, 2010) and Nepal (Palit & Chaurey, 2011). Even though NGO and development aid-led mini-grid projects have played a crucial role and will play a significant role in the future, it is agreed that private actors are also needed (Tenenbaum et al., 2014). Interest from private actors in mini-grids has recently surged. In east-Africa, a large number of private or semi-private actors have emerged and either have ongoing projects or a considerable number of projects in their pipelines. For NGOs, development aid and private led mini-grid initiatives to be successful and to continue investing resources in mini-grids, individual mini-grids need to be successful.

However, the overall track-record when it comes to long-term success rates of mini-grids is low (Dutt & MacGill, 2013; Rahman et al., 2013). Findings from analysis of a large number of mini-grids suggests as many as 30-50% fail within a 5-20 year time-period (Goldemberg et al., 2004; Greacen, 2004; Maier, 2006). The causes for failure of mini-grids can be related to technical, economic, social and political factors. Poorly constructed mini-grids or lack of repair and/or maintenance can lead to failure and collapse of the technical system (Greacen, 2004). Lack of sufficient income, inappropriate tariff schemes or high and unexpected expenses can cause the operator of the mini-grid to abandon the project (Taele et al., 2012). Lack of understanding of the social context can lead to lost outcomes (Matinga & Annegarn, 2013), social unrest (Aklin et al., 2016), conflicts and conflicting interests (Foley, 1992; Elias Hartvigsson, Ahlgren, & Molander, 2018) and lack of trust of the operator (Rawn & Louie, 2017). In addition, excessive focus on technical and economic viability reduces focus from other important aspects, causing otherwise technical and economic viable systems to fail (Cust et al., 2007).

Even though analysis of factors can improve the understanding of these individual processes, it is difficult to attribute their impact on a system level, and more importantly how they impact each other. This becomes relevant since most factors are connected. For example; lack of trust or conflicts with the operator can increase electricity theft, causing

economic and technical damage; in order to improve economic viability, increased utilization of the electric systems, which rely on a load mix that includes productive use of electricity and is therefore linked with socio-economic outcomes of the community, is needed. Furthermore, if the studied time-span is sufficiently long, the connections between factors can alter their impacts. Thus, it is problematic to attribute the failure of mini-grids to individual factors without knowledge about their relationships, and thus it is relevant to consider the influence from systems effects.

A more appropriate description when considering longer time-spans should therefore relate to mini-grid overall viability. A mini-grid viability refers to its ability to survive and therefore include both the impact of individual factors and the impacts that arise due factors relationships. Since mini-grid viability is dependent on the relationships between factors or sub-systems, viability can be described as hierarchical and thus a viable system has to consists of viable sub-systems (Beer, 1979). Considering the conceptual description in Figure 1, a viable mini-grid therefore consists of viable technical, operator and community sub-systems, and it is not sufficient if only one or two of these sub-systems are viable. This explain why mini-grids that have been economically viable still reportedly failed (Cust et al., 2007).

The main relationship between the three sub-systems in Figure 1 is through electricity and its associated characteristics. The main task of the operator is to be a link between the electric power system and the community. The operator makes sure that the technical system is functioning adequately, given constraints from the community. The community interacts with the technical system by consuming electricity. Based on the consumption the community establishes a relationship with the operator and the electric power system. The functioning is dependent on the management, operation and allocation of resources of the operator. Through the usage of electricity and demand for electric power, the consumption of electricity directly influences the functioning of the electric power system. The lack of a functioning electricity supply can give rise to conflicts with the community (Elias Hartvigsson, Ahlgren, Ehnberg, et al., 2018; Elias Hartvigsson, Ahlgren, & Molander, 2018). Therefore, the functioning of the electric power system forms the central relationship when considering the viability of mini-grids.

Problems can have two origins, either they are outside the control of the mini-grid (i.e. exogenous) or they arise due to the relationships and feedback between factors and relationships (i.e. endogenous). Exogenous impacts include storms and lightning destroying equipment or changes in laws and regulations, while endogenous impacts include misuse of equipment, malicious practices or conflicts. Even though the cause of exogenous problems are not specifically linked to a mini-grid, their ability to handle exogenous issues is due to their abilities. In order for a mini-grid to be viable, it needs to be able to handle impacts that are both exogenous and endogenous. With the right resources, tools and knowledge an operator should therefore be able to handle problems that are either endogenous or exogenous. Thus, in order for a mini-grid to be viable the operator needs to have a sufficient

set of tools, knowledge and resources for handling problems. This includes setting aside resources for capacity expansion, be informed of political events and their implications on its operator and have long-term plans regarding operational goals. The lack of viability can therefore be described as an endogenous problem of mini-grids.

One method to analyse endogenous problems is system dynamics. System dynamics is a systems modelling method focused specifically on describing and tackling endogenous problems. In system dynamics, this is achieved by describing problems as a set of factors that are each connected through causal relationships. Since all factors are dependent on each other, a system dynamics description consists of closed feedback loops. This becomes beneficial as it allows for linking a systems structure with a specific problem. The endogenous description in system dynamics evidently reduces the scope of problems that can be tackled. However, the endogenous limitations are likely suitable when tackling problems relating to mini-grids. As technical systems, mini-grids are independent, and thus technical issues arise from endogenous dynamics. In addition, most mini-grids are located or are expected to be located far from the grid, at locations that are inaccessible. Local economics are often based on and around agriculture with additional supportive activities. It is therefore reasonable that most mini-grids operate with a high degree of socio-economic independency.

In addition, system dynamics allow for both a qualitative and quantitative modelling approach. As such, it is possible to both include the issues relating to the electric power systems and problems related to "*soft*" factors. "*Soft*" factors are factors that for various reasons are difficult to quantify, such as satisfaction and expectations, but that still have an impact on the outcome. Furthermore, system dynamics concern the behaviour of systems and are therefore appropriate when considering the long time-frames important for mini-grids.

1.4 - Aim

Using viability and system dynamics as a starting point, the aim of this thesis is to address the issue of *"why do mini-grids in rural electrification fail?"* The question is investigated departing from a system dynamics approach and specifically focusing on the influence of reliability on the viability of mini-grids. Moreover, the issue is tackled through the following four research questions.

Question 1: *Can the failure of mini-grids be explained by endogenous dynamics?*

Question 2*: What role can electricity usage and reliability have on the viability of mini-grids?*

Question 3*: Can the investigation of reliability in mini-grids be useful for tackling reliability issues at the local and national level?*

Question 4: *What interventions could improve the viability of mini-grids?*

1.5 - Thesis Outline

The thesis is outlined in the following way. **Chapter 2** provides a background to reliability of electricity in developing countries. This is followed by **Chapter 3** that presents the main theoretical approaches used and their connection to rural electrification: systems thinking and complexity and problem formulation. Related research is presented in **Chapter 4** while **Chapter 5** gives an overview of the research approach that has been employed throughout the thesis: system dynamics and load assessments. **Chapter 6** briefly presents data collection and case study work. **Chapter 7** presents the main findings from the work. Finally, the thesis ends with conclusions and future work in **Chapter 8**.

Chapter 2 Reliability of electricity and developing countries

2.1 - Reliability

Reliability is a feature of a technical system and describes its ability to function given certain environmental or operational conditions (Rausand & Arnljot, 2004). In electric power systems, the basic function is to satisfy the system load within reasonable economic and quality margins (Billinton & Allan, 1990). Reliability can therefore be considered as a proxy for the viability of the technical system in a mini-grid. Specifically focusing on reliability of electric systems, the European Network of Transmission System Operators for Electricity (ENTSO-E) defines reliability in terms of two aspects: adequacy and security (ENTSO-E, 2015). Adequacy is defined as an electric power systems ability to supply the aggregated electrical demand of its customers at all times. Security is defined as the system's ability to withstand sudden disturbances. Disturbances are generally described as technical (loss of system elements, e.g. components or electric short-circuits). Low reliability thus refers to reduced ability to either: supply electricity to customers or to handle disruptions.

A major part of reliability analysis is causal analysis (Rausand & Arnljot, 2004). Often, causal analysis includes the technical processes that can lead to failure, however, the causal events leading to failure can also be caused by mismanagement, lack of repairs and poor managerial practices. As such, the original cause of failure might not necessarily be technical. Similarly, reducing operational practices regarding technical maintenance, repairs and quality of components can impact both a systems adequacy and security, and thus have large implications on system's overall reliability (Pless & Fell, 2017).

In order to perform analysis, comparisons and effective maintenance of electric power systems, in terms of reliability, and issues of adequacy and security are divided into the electric power systems main sub-systems. These consists of three Hierarchical levels (HL) with associated reliability indices: generation (HL I), transmission (HL II) and distribution (HL III) (Billinton & Allan, 1990). Thus, these reliability indices either concern generation, transmission or distribution. On an HL I level indices concern the probability of the generation system not satisfying demand, either regarding energy LOEE (Loss of Energy Expectation) or power LOLE (Loss of Load Expectation). Reliability models at the HL I level include modelling of the load, generation and a risk of overloading. Since mini-grids

are energy and power independent, this means that HL I reliability is directly influenced by initial sizing and understanding of load dynamics. This becomes especially important since increasing generation capacity during a mini-grid's lifetime can be problematic (Elias Hartvigsson, Stadler, et al., 2018).

In large electric power systems, transmission is considered one of the most essential parts and is often constructed with a number of redundancies. In mini-grids, the transmission system is generally small and is mostly constructed during the initial development phase. This suggests that they are mostly influenced by the initial project scope and access to funds, rather than the operation of a mini-grid. Furthermore, during an initial phase, if a project has been funded, resources are likely to be allocated to construct a well-functioning transmission system. As such, reliability issues for mini-grids at HL II are likely rare. When considering reliability analysis at HL II, modelling approaches are used that are similar to those for HL I levels. This means that the main reliability issue is related to capacity of the transmission system.

At a distributional level (HL III) reliability is often measured in terms of blackouts, either in frequency or duration. Common indices for measuring distribution system reliability are System Average Interruption Duration Index (SAIDI) and System Average Interruption Frequency Index SAIFI. SAIDI indicates average downtime per customer (e.g. time when electricity could not be supplied) while SAIFI indicates average number of interruptions per customer (without regard to their duration). Due to system expansion and connection of new customers, the construction of the distribution system continues during the operational time of a mini-grid. It is therefore likely to be affected by faulty practices arising from social or economic pressure. Due to the status and/or benefits that electricity access can bring, pressure can arise from the community to reduce otherwise strict demands on components. Furthermore, as the construction of distribution lines is expensive, there might be economical pressure from the operator itself to reduce costs associated with new connections.

During the thesis reliability is defined from a customer perspective, e.g. interruptions experienced by a customer regardless of the cause. As such it includes disruptions (occurrence and duration) in generation, transmission and distribution (Roos, 2005). While reliability in this way is similar to HL III indices, it includes failures on all HL levels. This is considered important since experienced electricity reliability is one of the major factors in determining customer satisfaction in developing countries (Aklin et al., 2016). Furthermore, using traditional reliability indices in developing countries is difficult. Generally, quantitative data with sufficient quality is often missing (Taneja), making it difficult to calculate reliability indices with sufficient accuracy.

2.2 Current situation

Even though difficult to measure with sufficient quality, reliability of electric power systems in developing countries is, and has been a concern in research (Eberhard et al.,

2008). Furthermore, reliability is not equally poor in all developing countries and there are large variations between countries. Figure 2 shows power outages in hours per year for businesses with electricity access for a number of sub-Saharan African countries. According to Figure 2, power outages (SAIDI) range from a few hours for Namibia and South Africa to over 2500 for Central African Republic (The World Bank, 2017b). This can be compared to the 2016 SAIDI value in Sweden, which was 78 minutes (Tapper, 2017).
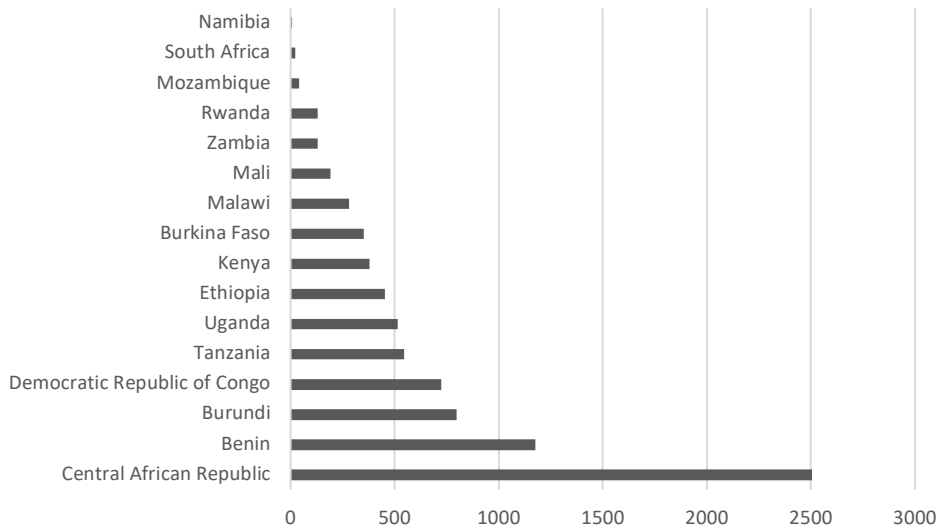
Figure 2 SAIDI values for firms with access to electricity. Data from the World Bank Enterprise survey.

The reliability of electricity in developing countries has likely deteriorated. Figure 3 show losses in the electric power systems in the poorest countries. As seen in the figure, losses substantially increased between the early 70s until 2013. Even though losses are not directly included in most reliability indices, it indicates the functionality of an electric power system. High losses can either be due to a poorly constructed technical systems, or due to misuse of the system.
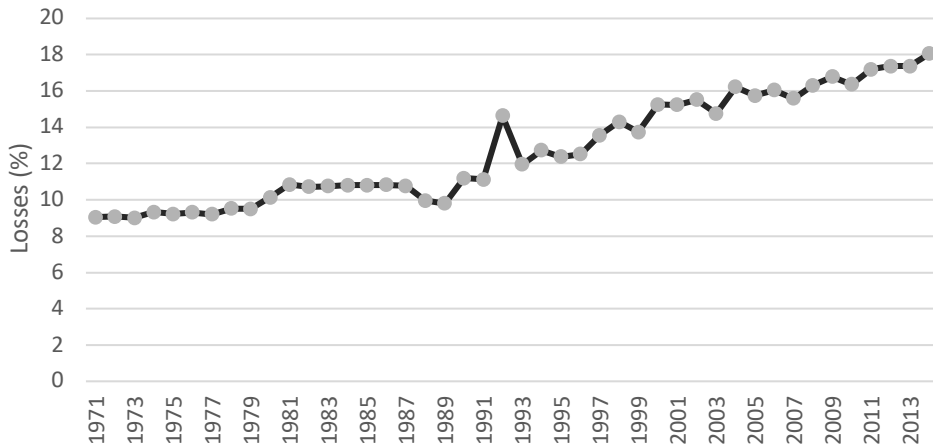
Figure 3 Losses in the electric power system for the poorest countries in the world. Data from The World Bank Doing Business survey.

None-technical-losses are a major issue for electric utilities in many developing countries (Depuru et al., 2011; Jamil, 2013; Smith, 2004). The largest contributor to non-technical-losses is electricity theft, and cause losses of up to 17% in some countries (Lewis, 2015). In limited areas non-technical losses can be substantially higher. Districts in India have reported losses of up to 50% (Min & Golden, 2014). Electricity theft can be divided into two categories; customers not paying their bills or having managed to rewire their connection in order to avoid metering; and customers who obtain an illegal connection and are thus never integrated into the financial system of a utility. Electricity theft can reduce the technical performance of the electric power system by the usage of poor-wiring and connection quality, which has a higher probability of failure, thus causing increase number of faults. It also has indirect implications since it reduces operator income while still forcing generation to remain high. Thereby reducing repair and maintenance resources (Steel, 2008).

The usage of lower quality components can also be due to pressure to reduce costs in order to increase number of connections. Constructing distribution systems is generally very expensive due to the components needed. In addition, populations in rural areas is often dispersed, making the cost for each individual connection high. Figure 4 shows an example of the usage of poor-quality components (left) and high-quality expensive components (right). The acceptance of poor-quality components, bribes, corruption and lack of transparency has significant impacts on overall reliability. In developing countries, the origin of power system failures, and thus low reliability, is not necessarily technical (Pless & Fell, 2017).

Figure 4 Examples of cases with poor-quality equipment (left) and good-quality equipment (right).

2.3 Impacts from low reliability

The low reliability of electricity supply in developing countries reduces benefits of electricity and impacts economic and social development. Low reliability has two direct major consequences on business relying on electricity; it forces them to make investments in their own generation equipment (Dollar et al., 2005); or they lose production and/or operation capabilities during blackouts. Running and owning a generator unit is a considerable cost and cannot be afforded by some businesses. As such, poor reliability has had a significant impact on sub-Saharan African growth (Andersen & Dalgaard, 2013). The reliability also disproportionally impacts small companies that might lack the resources to invest in backup systems. The total estimated economic loss from emergency power in sub-Saharan Africa is in the order of 3-4% of their GDP (Eberhard et al., 2008). The World Bank Enterprise Survey collects data on issues that enterprises in sub-Saharan Africa face and they rank unreliable electricity services as one of three major obstacles. Similar conclusions were drawn by Dollar et al. (2005) and Sanghvi (1991).

Improving reliability has positive impacts outside the economic performance of businesses. Low reliability cause a large dissatisfaction amongst households (Aklin et al., 2016). Improving reliability for households with a poor supply has larger impacts on

satisfaction than supplying unreliable electricity to a previously un-electrified household. Improving electricity reliability can have a positive impact on electrification rates (Khandker et al., 2012; Taale & Kyeremeh, 2016). In order to highlight the importance of reliability and to improve collection of data, The World Bank developed the Multi-Tier framework (ESMAP, 2015). The Multi-Tier framework consists of 5 Tiers and 7 attributes to describe electricity access in a wider spectrum. The 5 Tiers represents different levels of access, with Tier 1 representing the most basic access and Tier 5 the most advanced access. The 7 attributes are: peak capacity, availability (duration), reliability (number of disruptions), quality (voltage stability), affordability, legality (bill is paid to the utility) and health and safety (absence of accidents and perception of high risk in the future). However, high quality data is often missing.

Chapter 3 Systems and complexity in rural electrification

3.1 – Systems and systems thinking

A system is described as a collection of elements that interacts and where the collection of elements shows behaviour not found in the single elements (Robert L Flood & Carson, 1993). An element is a representation of a phenomena, either from the natural or social world. Furthermore, it is assumed that the collective behaviour exists in such a way that the system exhibits a specific function, or purpose (P. Checkland, 1999). A purpose could be to maintain its own existence and reproduce or to deliver a specific outcome (in the case of electrification to improve the indicator used for electricity access). In addition, the system can be subject to inputs and can generate outputs. Given that an input affects the system, a system has a certain level of control and thus an ability to regulate itself, either due to external inputs or due to changes within its boundary. This description of systems does not limit itself to any specific subject and systems can be used in a wide range of disciplines. Systems thinking can therefore be considered as an approach used to discuss aother subjects and can be considered a meta-discipline (P. Checkland, 1999). This description of a system can be conceptualized as shown in Figure 5.
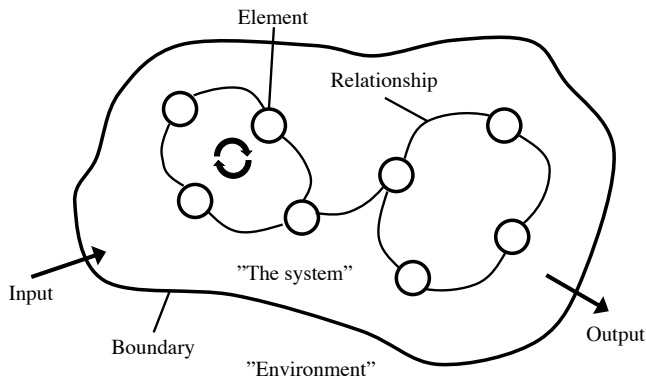
Figure 5 Conceptualization of a system.

In systems analysis the interest is not in the detailed workings of each individual element but rather in their interactions and the resulting behaviour. The behaviour of a system is the change of its state variables over time. Thus, systems analysis differs in the

method of inquiry from reductionism that relies on dividing complexities into separate parts, each of which can be analysed separately. One of the most important steps in system analysis if that of boundary selection. The boundary defines what is included and with which level of detail in the analysis.

Systems thinking can be divided into "hard" and "soft" systems thinking. According to P. Checkland (1999), the separation can be described in the following way; in a "hard" systems approach, systems are taken to exist in the world and are subject to analysis and intervention in order to make them "better" (such as systems engineering); in the "soft" systems thinking approach the focus is on the process of understanding of the world, e.g. how can we make sense out of the complexity that we observe. A limited separation of "hard" and "soft" systems thinking in terms of applications is that "hard" systems approaches are appropriate in well-defined problem situations, while "soft" systems approaches are appropriate in ill-defined and fuzzy problem situations. Societal problems are often perceived to be ill-defined and thus a "soft" systems approach would be advisable.

System dynamics is often described as being part of the "hard" systems thinking approach. It requires well-defined problems and assumes that systems exist and can be formulated as elements interaction through causal relationships (Mashayekhi & Ghili, 2012; John D Sterman, 2000). In addition, an important aspect of system dynamics is that it considers problems and the purpose in system dynamics modelling is often to find solutions to these problems. System dynamics thus considers that systems can be engineered and consequently be improved. Due to the application of system dynamics on complex societal problems, the issue of handling ill-defined problems has been tackled (Vennix, 1999). Within the system dynamics community, "soft" systems dynamics is often related to the use of soft variables (variables that are difficult or not possible to quantify) and thus considers qualitative modelling, while "hard" system dynamics relates to the quantitative modelling, and therefore assumes that variables can be quantified.

3.2 - Complexity and problem formulation

Complexity is a commonly used concept in a wide range of areas, and a consensus on the definition of complexity is lacking (Törnberg, 2017). Complexity is closely related to systems thinking, and complexity is therefore considered based on the work on complexity from systems theory, specifically from the work of Robert L Flood and Carson (1993) and Weaver (1948). Weavers original classification of complexity consisted of: organized simplicity, disorganized complexity and organized complexity. Organized simplicity refers to systems that are deterministic and that allow for simplified assumptions, such as an electrical circuit. Disorganized complexity are systems that consists of a very large number of random variables. Systems of organized complexity are systems with a large number of countable elements, but which are too few to allow them being analysed using statistical analysis. Most systems found in social science are characterized by organized complexity.

In addition, according to Flood and Jackson, problems found in systems can be separated into either difficult or complex. Difficult problems can be perceived as superficially complex (e.g. containing a large number of variables interacting in many ways). What prohibits them from being complex is that they are operated according to well-defined laws (e.g. technical systems). Lastly, complexity is influenced by people's capabilities (Robert L Flood & Carson, 1993). This suggests that by improving our knowledge about a complex system, its complexity can be reduced.

Access to electricity is not only influenced by technical factors but also includes social, economic and environmental factors. The perceived quality of life improvements and status of electricity is an important driver for electrification (Matinga & Annegarn, 2013; Paula Borges da Silveira et al., 2017); the associated costs with electricity creates barriers for access for some people (Ahlborg & Hammar, 2014); local environmental resources impacts peoples livelihood (Scoones, 2009) and generation of electricity (Elias Hartvigsson, Stadler, et al., 2018); and access to technology can reduce some barriers and emphasize others. In addition, factors in these fields impact each other. It is therefore not possible to sufficiently separate the impact from specific factors. Rural electrification can therefore be described as being part of an organized complex system.

Systems of organized complexity and their manifested problems cannot be solved using reductionist or statistical methods but require systems thinking. However, much of global development efforts are still based on a reductionist approach (Ramalingam et al., 2008). A reductionist approach assumes linear cause-effect chains, and thus often fails to fully realise the implications of interventions when dealing with systems. This has likely had negative effect on outcomes of development aid. International development efforts are often based on maximizing a specific impact, and often rely on those impacts being quantifiable. This becomes problematic when the overall desired outcome cannot be agreed on or is not quantifiable.

Much of global development efforts originates from the policies of the donating countries. Strategies and goals are formulated and implemented from a top-down perspective, with limited knowledge about the desires and contextual conditions of the recipients. As such they are formulated largely based on perceived linear cause-effect chains. In complex systems, linear cause-effect cannot explain or anticipate the outcomes of decisions. An alternative is bottom-up approaches. In bottom-up approaches, needs and goals are formulated by the recipients and strategies are formulated in order to realize those goals. Realistically, those goals will not be easily measured since they represent the desires of the recipients. Consequently, they would not be limited to single sectors but be multi-faceted. In order for the strategies to efficiently realize these goals they need to consider the contextual complexity and therefore have to be holistic. In rural electrification, mini-grids can represent such a bottom-up approach.

Research focused at the complexity in the contexts of energy and electricity systems in developing countries has so far been relatively unexplored by scholars. Awuzie and

McDermott (2013) investigated complexity in energy infrastructure projects in developing countries and found that in order to understand the complexity, a systems thinking approach is needed. Urban et al. (2007) made a characterization of energy modelling in developing countries and found that most energy system models are based on assumption that work well in western contexts but that new requirements are needed for developing country contexts.

Rural electrification can be considered as part of the overall development agenda, which amongst other things also includes development in health, education, democracy, infrastructure and economics. However, rather than considering these efforts as separate entities they are highly interconnected. Health has positive impacts on education; education is one the most influential factors determining electricity access (Kemmler, 2007); infrastructure impacts both electricity access to economic opportunities (Lenz et al., 2017); level of democracy impacts electrification rates (Trotter, 2016). As such, it is not possible to tackle a problem in one of these sectors without both influencing problems in other sectors, and being influenced by the changes in other sectors. This suggest that development (and rural electrification) is a 'messy' problem (Ackoff, 1997). A 'messy' problem is collection of complex problems that are interdependent, making it difficult to single out and tackle one specific problem. Figure 6 shows a conceptual graph of a 'messy' problem. As is seen, it is very similar to the description of systems, but with the elements representing complex problems. These individual complex problems interact and share important factors. The high use of wood and charcoal has considerable implications on deforestation rates. Access and use of electricity can reduce or limit this usage and thus the problems of deforestation and electrification are highly dependent on each other.
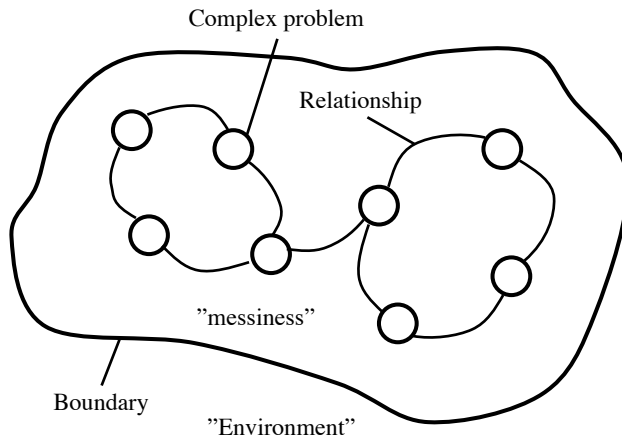
Figure 6 Shows a 'messy' problem conceptualised as a number of complex problems that are interconnected.

In addition to being complex, rural electrification is also a highly political process and politics have direct influence on the functioning of electric power systems (Min & Golden, 2014). On global levels, the agenda is highly influenced by large multilateral aid

organisations and their members countries. On national levels, ministries and governments are key actors in the formulation of and implementation of policies but are also influenced and part of bilateral aid programs. On local and regional levels, politicians engage to influence specific projects outcomes. The political nature of electricity provision makes the problem 'wicked'. 'Wicked' problems are problems that cannot be formulated without specifying their solution (Rittel & Webber, 1973). Wickedness is a common characteristic of problems found in society as societal problems often involve divergent and changing perspectives and worldviews. Similar to 'messy' problems, they are difficult to formulate. The complexity, 'messiness' and 'wickedness' of rural electrification make formulating well-defined problems difficult. This creates a barrier for the implementation of some systems methods since they rely on well-defined problems (such as system dynamics). Thus, considering rural electrification from a "hard" system perspective, they are systems which we can identify, analyse and improve. However, due to their "messiness" and "wickedness", identifying them is problematic. If the systems cannot be sufficiently well identified, restructuring them in order to improve specific outcomes becomes problematic. Thus, any attempt that aims at improving the outcome of rural electrification and be relevant needs to consider its complexity, messiness and wickedness.

Chapter 4 Related research

4.1 - Long and short-term electricity usage and modelling

Rural electrification research is a highly interdisciplinary field but most of the research has been technology focused (Mandelli, Barbieri, et al., 2016; Schillebeeckx et al., 2012). One of the key technological and economic challenges in rural electrification is matching generation capacities with electric load (Manning et al., 2015). As such it has been widely covered in the rural electrification literature (see (Azimoh et al., 2016; Bhattacharyya, 2015; Castellanos et al., 2015; Fadaeenejad et al., 2014; Kenfack et al., 2009; Mandelli, Brivio, et al., 2016b; Nfah & Ngundam, 2009; Olatomiwa et al., 2015; Ramchandran et al., 2016; Sen & Bhattacharyya, 2014) for a few examples). Rohit Sen et. al (Sen & Bhattacharyya, 2014) used HOMER to identify the most economical energy supply option for a rural area in India. Their system was based on synthesized load profiles for two customer groups (households and local businesses) and had a peak load of 68 kW. In addition, they conducted a sensitivity analysis of their system by allowing the future load to increase or decrease, and thereby creating a link between their solution and future load developments. Lanre et al. (Olatomiwa et al., 2015) used HOMER to study the most economical energy mix of energy sources for six different rural regions in Nigeria. In order to improve the accuracy, they used two groups of load profiles: social infrastructure and households.

Developing countries are generally characterised by poorly functioning electric utilities, economic barriers, weak institutions prevalence of poverty and inequality and an anticipated large-scale energy transition. These characteristics makes long-term models developed for western context an inappropriate choice for considering the long-term dynamics of electricity and energy in the developed world (Bhattacharyya & Timilsina, 2010; Urban et al., 2007).

Due to the large uncertainties both in short-term (daily load profiles) and long-term electricity usage, the dimensioning of mini-grids is not a straight forward process and is more difficult than for large national grids (Boait et al., 2015). Daily load profiles, simulated peak power demand and daily energy consumption, have significant impacts on the dimensioning of mini-grids. The impact on dimensioning is increased when considering renewable based mini-grids while maintaining a high reliability (Ehnberg, 2007). As found by (Mandelli, Brivio, et al., 2016a), the uncertainty in the formulation of load profiles have a significant impact on the dimensioning of solar PV based mini-grids. However, if the

reliability requirements are reduced, the matching of demands with generation becomes easier (Ehnberg, 2007), but with significant implications on systems viability.

In addition, long-term trends in electricity usage are important. Even though it is possible to increase a mini-grid's capacity during its lifetime, it is generally difficult due to various factors. Amongst other things, generation capacity influences system operation and economy of the operator. Investigating mini-grids in 16 villages in Argentina, Díaz et al. (2010) it was found that electricity usage increased with between 25% - 100% during a 7 year period. Focusing on two poor villages in Brazil, Obermaier et al. (2012) found that during a 3 year period, average electricity usage increased in both villages. However, they also found that increase in electricity usage mostly occurred for a smaller part of the population, suggesting an increase in electricity inequality. Similarly, (Pereira et al., 2010) analysed 23 000 households in rural Brazil between 2000 and 2004 and found an increase of 34% in electricity usage. Even though there are only few empirical studies on the long-term behaviour of electricity usage in rural electrification, there is a relative large body of literature on long-term modelling of energy and electricity.

Most long-term models targeting developing countries are focused on the national level and do not contain details regarding local dynamics. In addition, many models that include details of long-term dynamics at the rural levels often focus on overall energy (Riva, Tognollo, et al., 2018). Even though relevant in the perspective of energy transitions, it adds considerable model complexity, and thus uncertainty, if electricity usage is the object of study. Focusing on various energy use functions, van Ruijven et al. (2011) developed a bottom-up rural model for household energy (including electricity) consumption. They found that access to data, and data quality on electricity usage were important barriers for understanding energy trends. Dividing factors affecting household energy use into exogenous and endogenous, (Kowsari & Zerriffi, 2011) developed a conceptual framework for assessing household energy use. Howells et al. (2005) developed an extension to the MARKAL model to include household energy use in rural South Africa. Amongst their conclusions was that the type of electricity supply system had large implications on electricity use when environmental factors were taken into account. However, none of the studies have specifically included or studied productive use of electricity. Since productive use of electricity often takes place during different times of the day as compared to household use, they can have significant impact on the electricity and power demand.

However, there is a general lack of short-term and long-term data on electricity usage in rural electrification (Bhattacharyya & Timilsina, 2010; Cross & Gaunt, 2003; Nfah et al., 2008; van Ruijven et al., 2011). The lack of access to data generates problem for creating accurate models (Cross & Gaunt, 2003), formulating efficient policies (Wijaya & Tezuka, 2013) and to make appropriate investments (Terrado et al., 2008) and thus impacts the reliability of electric power systems (Karki et al., 2010). According to Riva, Tognollo, et al. (2018) two main approaches to long-term energy modelling are found in the literature: econometric (top-down) and end-use (bottom-up). As reported by (Bhattacharyya &

Timilsina, 2010), end-use approaches produce more realistic results, however, they suffer from lack of data in developing countries.

In terms of load profiles, the lack of electricity usage data has caused most research to rely on synthesising methods, often using data collected from interviews (Sen & Bhattacharyya, 2014). Using synthesised load profiles can be a resource efficient method in order to make load assessments. However, due to the lack of data, there have been few comparisons between synthesised load profiles and measurements. Mandelli, Merlo, et al. (2016) developed a method for generating load profiles from interview data and verified the method with measurements for a rural, grid connected college in Cameroon.

The extensive use of survey-based data in load profiles is highlighted in Table 1. It shows publications in rural electrification and off-grid classified according to the type of data used. An initial selection was done in Scopus using the search terms "rural electrification" and "load profile", which resulted in 41 publications. Out of these 41 publications, 3 were removed since they were written by the author. An additional 10 were removed since they either did not consider off-grid systems or a developing country context. The remaining 28 are shown in Table 1. As shown by the table, a vast majority only consider survey data with low resolution. Few are concerned with high resolution survey based data and using measured data. The limited usage of measured data suggests that synthesized load profiles are rarely verified with measurements and therefore have a level of uncertainty. This lack of short-term data in rural electrification has led to a range of assumptions regarding the use of electricity and its impacts on the dimensioning of electric power systems. The table also shows an increase in recent years in publication, indicating that the interest of load profiles impacts in rural electrification is growing.

Table 1 Publications identified in Scopus containing the search terms "rural electrification" and "load profile". The publications are listed according to the type of data used to generate their load profiles.

Publication	Survey data		Measured data	Source not specified
	High Res (<1h)	Low Res (>1h)		
(Ajayi & Ohijeagbon, 2017)		x		
(Akinyele, 2017)		x		
(Benavente-Araoz et al., 2017)		x		
(Blodgett et al., 2017)		x		
(Brivio et al., 2017)	x			
(Heeten et al., 2017)			x	
(Jing et al., 2017)	x			
(Kaur & Segal, 2017)		x		
(Rajbongshi et al., 2017)		x		
(Uddin et al., 2017)		x		
(Win et al., 2017)		x		
(Kadri & Hadj Abdallah, 2016)			x	
(Louie & Dauenhauer, 2016)			x	
(Mandelli, Brivio, et al., 2016a)	x		x	
(Mandelli, Merlo, et al., 2016)	x		x	
(Mehra et al., 2016)			x	
(Moghavvemi et al., 2016)				x
(Ustun, 2016)		x		
(Rajanna & Saini, 2016a)		x		
(Rajanna & Saini, 2016b)		x		
(Buchana & Ustun, 2015)		x		
(Chauhan & Saini, 2015)		x		
(Murenzi & Ustun, 2015)		x		
(Bilal et al., 2013)		x		
(Kanase-Patil et al., 2011)		x		
(Nfah & Ngundam, 2009)		x		
(Nfah et al., 2008)		x		
(Tatiétsé et al., 2002)		x		

Amongst the load -profile studies in off-grid systems, there is a large focus on very small systems. Figure 7 shows the results from the Scopus search classified according to the reported peak load. As can be seen, a vast majority focus on system sizes smaller than 50kW. This has significant implications on the dynamics of the load. Small systems have a limited capacity to supply electricity to productive use (e.g. milling, workshop, welding and

processing), which have a significant impact on the load profile, operator income and rural development. This has likely had a large impact on the assumption that the load-profile of rural areas can be characterised by a high evening peak and low day load, and consequently a low load factor.
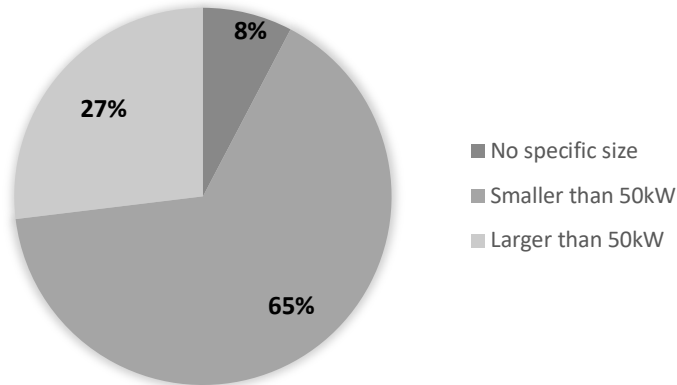
Figure 7 Publications from Table 1 classified according to reported peak demand.

Current generation capacity matching studies have not taken into account the feedback and delays from key driving processes, which are important when considering long-run impacts (Salman et al., 2016). For example, increased electricity consumption can lead to increased income levels (Bridge et al., 2016); customer acquisition costs decrease as system sizes increase; and unreliable electricity supply can negatively impact the use of electricity and decreases operator's economic performance (Chakravorty et al., 2014; Steel, 2008); and customer satisfaction can influence willingness to pay (Winther, 2012) and therefore the operation and management of the mini-grid. One method that considers feedback and delays is system dynamics.

4.2 - Complexity and rural electrification

Even though not explored explicitly in rural electrification, complexity is often mentioned by scholars. Without specifying, Brent et al. (Brent & Rogers, 2010) has described the environment that mini-grids operate in as complex. Similarly, Nicola Blum et al. (Blum et al., 2015) described mini-grids as complex due to the use of electricity and maintenance of the technology (generation and distribution of electricity) at the local level. Their description is similar to the description Liu et al. (Liu et al., 2007), who identified coupled human-natural systems in Kenya to be complex. Focusing on the impacts of electricity, Matinga and Annegarn (2013) found paradoxical impacts from electricity and attributed it to the complexity of the social settings in which electricity acts. Even though complexity is not mentioned by some scholars, the environment in rural electrification is

often described to contain a large number of factors, many of which are unknown and which are characterized with a large number of interactions. This description is very similar to the description of Flood and Jackson's description of complexity (Robert L. Flood & Jackson, 1991). However, none of the research mentioned has clarified what complexity implies and has not explicitly tackled complexity as an issue in rural electrification.

Even though the detailed causal relationship between electricity access and usage and its environment is debated, there is a general consensus that access to electricity impacts and is impacted by several factors in rural communities. Under the right circumstances, access to electricity may improve education, healthcare, ability to create new businesses and use of other energy sources. However, findings report that access to electricity has not had the expected benefits (Kooijman-van Dijk & Clancy, 2010; Neelsen & Peters, 2011). The uncertainty in the outcomes can be attributed to the complexity of the electricity-development nexus (Matinga & Annegarn, 2013; Riva, Ahlborg, et al., 2018). As such, access to electricity needs to be considered in relation to its environment, thus requiring a system perspective (Ramalingam et al., 2008).

4.3 - System dynamics and electric power systems and markets

Applications of system dynamics on electric power systems and markets in the developing countries and emerging economies are limited. Notable contributions have been done by Isaac Dyner in Colombia (Castaneda et al., 2017; Dyner et al., 1995; Fernando & Isaac, 2014; Redondo et al., 2018), Hassan Qudrat-Ullah in Pakistan (Hassan Qudrat-Ullah, 2005; H. Qudrat-Ullah & Davidsen, 2001; Hassan Qudrat-Ullah & Karakul, 2007), Katherine Steel in Kenya (Steel, 2008) and Rhonda Jordan in Tanzania (Jordan, 2013). In addition, even though not specifically targeting electric power systems and markets, the Threshold 21 model is an integrated development model for developing countries from the Millennium Institute and includes an energy specific sector (Millennium Institute, 2013). Continuing on the Threshold 21 model but specifically focusing on the sustainable development goals, the Integrated Sustainable Development Goals Model[1] was developed in order to aid the formulation of strategies and policies to improve the realisations of the sustainable development goals.

The work of Isaac Dyner in Colombia has mainly analysed the behaviour of the electricity market and utilities. Amongst others, Castaneda et al. (2017) reported that the diffusion of small scale solar on household level could be a significant threat for utilities, with the possibility that the utility would enter the "death spiral". The diffusion would initially impact generation but also have significant long-term impacts on distribution companies. Hassan Qudrat-Ullah used system dynamics to investigate Pakistan's electricity policies impacts. Amongst other, he reported issues with Pakistan's policy independent power producers. In order to tackle an increase in demand, Pakistan opened up for private

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[1] https://www.millennium-institute.org/isdg

sector investments and implemented policies including government guaranteed purchase of electricity. The result was a large increase in independent power producers with a risk aversion attitude and short-term perspective, resulting in a large increase in gas-based electricity while hydropower-based generation was left unused (H. Qudrat-Ullah & Davidsen, 2001). Deregulation of the market in developing countries in order to increase the private sector involvement and number of independent power producers is often considered to be an important part of improving electrification (Tenenbaum et al., 2014).

Steel (2008) developed a system dynamics model focusing on the reliability of electricity and its relationship to the competition between grid and off-grid systems Similarly to the "death spiral" identified by in Colombia, Steel found that during certain conditions, low reliability resulted in a vicious loop of reduced reliability and economic resources. Steel's work highlights the dynamics that the availability of off-grid systems has on large national power systems, which could be further strengthened by reduced costs for some technologies, such as SHS. Continuing on the work of Steel, Jordan (2013) investigated the issues of capacity expansion in Tanzanian. Jordan integrated optimisation techniques and system dynamics into capacity planning methods, thus considering demand as an internal factor in the capacity planning process. Amongst her findings was that it is important to consider demand endogenously in capacity planning if either a large part of the population lack access to electricity, or if there are improvements in reliability due to capacity expansion being large. Even though mini-grids often fall in at least one of these categories, capacity expansion is often not considered endogenously.

Chapter 5 Research approach and modelling

5.1 - Overview of research approach

In order to tackle the viability of mini-grids, a modelling-based systems approach is implemented. This includes the development of both qualitative and quantitative models. As described in Chapter 3, mini-grids are part of complex systems. As such, in order to analyse the origin of different outcomes for mini-grids, it is necessary to analyse mini-grids using systems based methods. One method is to analyse the relationship between system structures and their corresponding behaviour is system dynamics. Due to the large amount of feedback between various factors, and due to the relative self-reliance of mini-grids, system dynamics is considered an appropriate method for inquiry.

An important characteristic of complex systems is that it is not possible to attribute outcomes to changes in specific factors without having sufficient knowledge about the system structure (Homer & Oliva, 2001). However, without knowledge it is difficult to define a boundary, and therefore to define the investigated problem, which is a precondition in system dynamics (Mashayekhi & Ghili, 2012). This creates a catch-22 situation for the development of systems models. Thus, based on Gigch (1991, pp. 119-136), knowledge acquisition is explained from a modelling perspective by successive inquiring system models of increasing level of abstraction. Gigch's approach is then applied to the system dynamics modelling methods of John D Sterman (2000) and R. G. Coyle (1996) in order to developed qualitative and quantitative models. In order for models to be relevant they need to be associated with processes and concepts that exist in the "*real world*". The process of developing relevant models and interventions in the "*real world*" therefore require an inquiring system and a decision making cycle (Gigch, 1991). The modelling process can then be described by increased knowledge acquisition using system dynamics and is conceptualised in Figure 8.
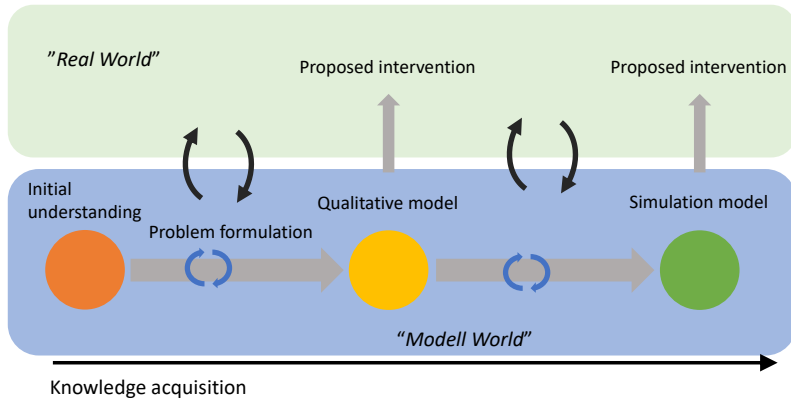
Figure 8 Conceptualization of the knowledge acquisition and modelling process.

System dynamics can be described as a problem-solving modelling approach and thus requires well-defined problems. The outcome of a system dynamics modelling process is therefore often a proposed intervention or suggestion as to how the investigated problem can either be solved, or its undesired impacts reduced. This step requires the modelling result to be interpreted and linked to the studied issue, which presumably exists in "the real world". The knowledge gained through the modelling process can be used to formulate interventions and interpret the model and its result. As such, proposed interventions and suggestions in "the real world" are outcomes of the increased knowledge when applied to the developed models.

However, and as discussed in Chapter 3, problem formulation concerning mini-grids in rural electrification is difficult and presents a barrier for system dynamics. The issue of problem formulation in rural electrification is tackled in Paper II, which also presents a method for using qualitative models to aid in the problem formulation process. Thus, in order to develop system dynamics models of a mini-grid it is necessary to have sufficient knowledge about each of a mini-grids sub-system. Due to the ability of systems dynamics to describe organisational and social structures it is considered an appropriate method to analyse the operator and community sub-system. However, system dynamics is not an appropriate method of inquiry to understand the functioning of a technical system. The functioning of electric power systems is the main focus of electric engineering in general and reliability analysis in particular. Thus, in order to understand and model the relevant technical processes in the functioning and their impact on the operator and community, a technical analysis needs to be carried out. The relationship and boundary of the system dynamics and technical model respectively is described by Figure 9.
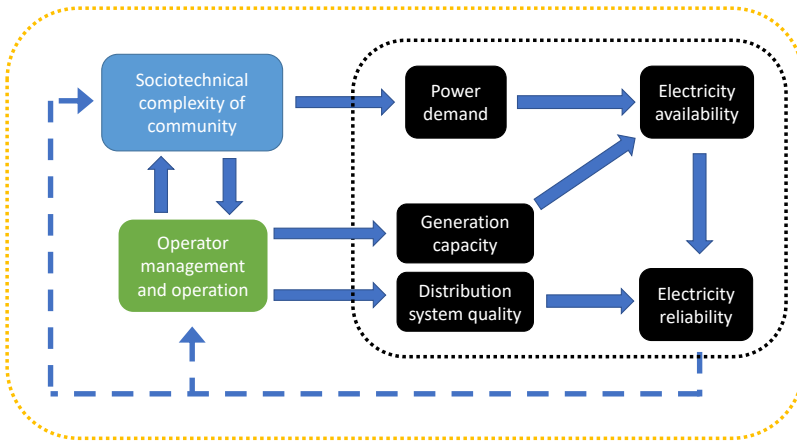
Figure 9 Overview of the integration of the system dynamics models with the technical models in order to consider reliability of electricity endogenously.

The Figure considers the overall model of mini-grids, which consists of three sets. The technical model described with its associated factors in the black boxes; the green box that describes the operation and management strategies and policies of the operator; and the blue box that described the socio-technical complexity of the local community. One important characteristic of technical systems is that they can be separated from their environment in laboratories and studied with minimal influence from their surroundings. This has implications on the generalizability of results. The technical phenomena of an electric power system are the same regardless of place and its time. However, all relevant applications of technology always include interactions with a changing environment that is mostly influenced by humans and their decisions. In order to understand the functioning of technology, it is therefore necessary to take into account the relevant socio-technical environment.

5.2 - System dynamics

System dynamics has been implemented throughout the thesis, both as a modelling method and as an approach to systems thinking. This section describes the origin, theory and application of system dynamics on interdisciplinary problems, with a specific focus on the challenges found in rural electrification. System dynamics evolved as a tool in order to analyse dynamic complex societal problems. Specifically, system dynamics targets a set of problems that can be described endogenously. An endogenous problem is defined as a problem that mainly arises due to internal dynamics, e.g. without any external influences. A key characteristic of endogenous problems is that they are defined as systems of interrelated closed information feedback loops (Forrester, 1961).

These types of problems are often found in a wide range of environments. However, similar to these environments is that they all to some extent include human decision making

and interactions. A core part in successful human decision making is our ability to predict the impact of our decisions. In order to foresee the impact of a decision, we use simplified models of how we perceive the cause-effect chain to be. These mental models are based on our experiences, education and values (Senge, 2006). However, in societal problems, the number of factors that would be needed to take into account are too many and integrated in complex structures that result in counterintuitive behaviour of these systems (Forrester, 1971). The intuitive behaviour and expected responses of such systems become more difficult since the cognitive capacity of the human mind is largely limited. It is estimated that short term working memory is limited to 7 (plus minus 2) "*chunks*" of information (Miller, 1956). Drawing legitimate conclusions in systems with a large number of factors is therefore not possible. Even when using our cognitive capacity optimally, it would result in considerable limitations in our ability to foresee the impacts of our decisions (Diehl & Sterman, 1995). However, our cognitive capacity is rarely used optimally. Focus is often placed on information that is believed to be certain and that conforms with our values and beliefs (Tversky & Kahneman, 1974). Thus, our mental models are often not correct, resulting in poor decisions. In addition, due to our inaccurate understanding of cause and effect in complex systems, we often believe the decisions are successful and attribute desired outcomes to decisions (Kahneman & Tversky, 1981; John D Sterman, 2000). With an inability to perceive the failure of our mental models and decisions, implementing policies that cause the desired impacts become difficult.

These limitations make it difficult to foresee the impact of decisions, or the dynamics behaviour of systems. In order to better understand both the effects and side effects of decisions and system structures, system methods are needed. System dynamics evolved as a method to aid in the understanding of systems that are primary based on information-feedback structures. An information feedback system is a system mainly governed by closed causal loops focused around the exchange of information or materials. The purpose of system dynamics is to describe these systemic structures in order to improve understanding about them, their behaviour and the development of appropriate interventions.

Initially, system dynamics was developed as a method for solving problems in societal and organisational systems (Forrester, 1961). As such, system dynamics relies on well-defined problems and problem formulation is the most important step for achieving a successful modelling process (Mashayekhi & Ghili, 2012). However, many problems found in society are not easily defined and are considered 'messy' (Ackoff, 1997). The 'messy' nature of societal problems makes the application of problem solving methods difficult. In order to aid in the problem formulation process a number of systems methods have been proposed, e.g. group model building (Vennix, 1999), soft systems methodology (P. B. Checkland, 1989) and strategic options development and analysis (Eden, 1995).

5.2.1 - Principles of system dynamics

One of the core concepts in system dynamics is that the investigated problem can be described endogenously. An endogenous description of a problem relies on the assumption that problems are caused by internal dynamics rather than external factors. In order to describe a behaviour endogenously, system dynamics mainly relies on two concepts: feedbacks and delays. Rather than describing events being part of linear cause-effect chains, they are described as part of closed feedback loops. This causes system behaviour to arise due to the comparative strength of the associated feedback loops. Their comparative strength is in turn linked with their associated responses, e.g. delays. The description of a problem as closed causal loops and delays gives rise to a problematic structure, and the purpose of a system dynamics modelling process can therefore be described as linking a system structure to a behaviour (Davidsen, 1992).

In order to analyse a problem endogenously, system dynamics relies on two modelling techniques: conceptual models and simulation models. Conceptual models are used for describing, communicating and qualitatively analysing system structures (R. G. Coyle, 1996; Morecroft, 1982). There is a wide range of conceptual models available in system dynamics (e.g. flow diagrams, subsystem diagrams, policy diagrams and influence diagrams). The work throughout this thesis has used causal loop diagrams as a main conceptualizing tool, and thus is the focus.

The purpose of causal loop diagrams is to sketch the main feedback mechanisms of a perceived problem (Randers, 1980) and is therefore a first step in a simulation modelling process (Robinson, 2008b). Causal loop diagrams are described as a set of closed causal loops (see Figure 10). A causal loop diagram describes a model's structure through a set of variables that are linked through casual relationships. Causal relationships in system dynamics are assumed to be unidirectional, e.g. they only act in one direction. The direction of causal relationships in system dynamics are indicated by an arrow and its influence with either a '+' or a'-', see Figure 10. The influence of a causal relationship is described as the direction of influence the affecting variable has on the affected variable (Lane, 2008). A '+' means that a change in the affecting variable will result in a similar change in the affected variable. Analogously, a '-' means that a change in the affecting variable will result in an opposing change in the affected variable.
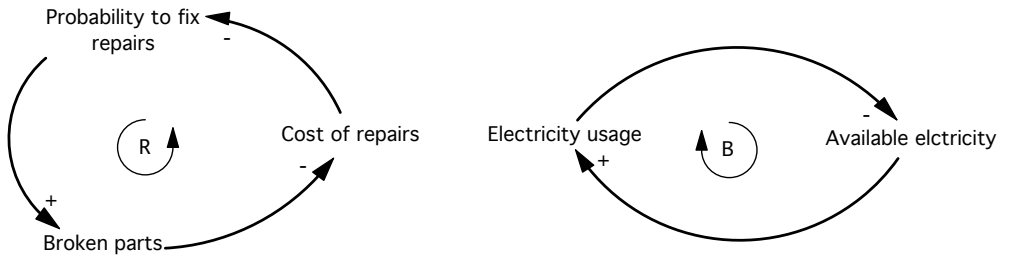
Figure 10 Two causal loop diagrams. The left diagram describes a self-reinforcing (R) feedback loop and the right diagram describes a self-balancing (B) feedback loop.

Depending on the influence of the causal relationships in a feedback loop, it can either be self-reinforcing or self-balancing. In a self-reinforcing causal loop, a change in a variable results in a new change in the same variable in the same direction. In a self-balancing causal loop, a change in a variable results in a new change in the same variable in the opposite direction.

It is the mix of self-reinforcing and self-balancing loops, their relative strengths and delays that generates a system's behaviour. However, a qualitative analysis cannot attribute systems structure and behaviour without the aid of simulation. In order to develop simulation models from conceptual models, system dynamics use stock and flow models. Stock and flow models include mathematical representations of the conceptual models. As such, a stock-and-flow model developed from a causal loop diagram includes at least the feedback loops found in the conceptual model. Stock-and-flow models model system behaviour through the use of stocks (system state variables) and flows (changes to system state variables). Figure 11 shows a simple stock and flow model. The box represents a stock, and the incoming and outgoing arrows represent its associated flows.
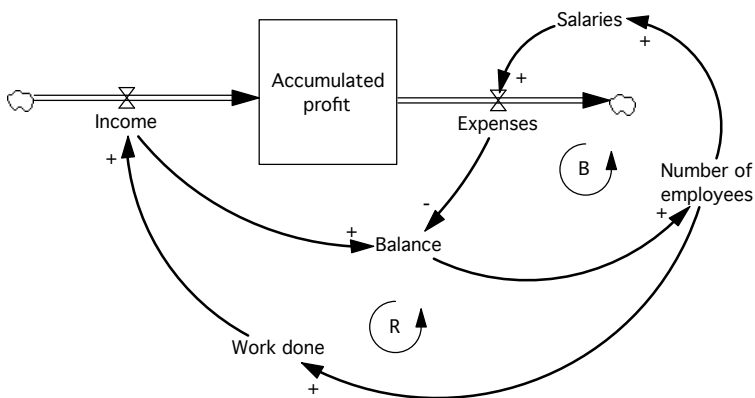
Figure 11 A graphic representation of a simple stock and flow model. Box indicate stocks, double arrows represents flows and single arrows causal relationships.

5.2.2 - System dynamics as a simulation tool

The most common application of system dynamics is as a problem-solving method focusing on simulation. One of the key parts of a system dynamics modelling process thus involves the development, implementation and analysis of simulation models (John D Sterman, 2000). Two arguments are presented as to why simulation models are necessary. First, in order to link system behaviour with structure simulation is necessary. Even though system structure can be qualitatively described, it is not possible to attribute behaviour to structure without simulation. Our ability to attribute behaviour to even the most simple diagrams is poor (John D Sterman, 1994). Secondly, and derived from the first argument, the impact of interventions, such as policies, cannot be analysed without a simulation model.

Simulation in system dynamics refers to the development and quantitative analysis of stock and flow models, e.g. mathematical representations of the conceptual understanding that is described through the use of diagrams. However, since system dynamics models often are applied to problems found in social environments, they often deal with the use of soft variables. Soft variables, are variables that for various reasons cannot easily be measured or quantified. Such as satisfaction, quality of life and status. By including such variables in a simulation model, the modeller adds a level of uncertainty. However, from a system dynamics simulation perspective, it is argued that even though the quantification of such variables is difficult, and likely done with a level of error, the error would be larger if completely omitted, since they are known to have an influence (Forrester, 1961).

By developing robust and relevant simulation models, apart from linking a system behaviour to a system structure, gives the modeller the ability to test the systemic impacts of interventions. This can have profound impacts on the developments and implementations of interventions in system due to the limitations of mental models. Furthermore, it also allows a modeller to investigate the sensitivity of model assumptions, thus improving the robustness of the model.

However, the development of simulation models from qualitative models is not without issues. Since simulation models almost exclusively contains more detailed information, their development requires additional resources and data. In some cases numerical data might not exist for certain variables and/or relationships. In order to aid the development of simulation models, a number of tools have been developed (e.g. see John D Sterman (2000), Forrester (1961) or Pruyt (2013)). These tools allow the modeller to reduce uncertainties in simulation models to assumptions, without reducing the model's boundary and thus relevance to the tackled problem. Partly due to the uncertainty on quantification, the system dynamics community have developed a large set of tools for building confidence in their models, and thus in their results (for an overview of confidence building tools in system dynamics see Barlas (1989), Senge and Forrester (1980) and John D. Sterman (1984)).

System dynamics simulation was used in Paper I and IV. However, the conceptual implementation is slightly different in the two papers. Paper I uses system dynamics simulation in order to link a system structure with behaviour in the case of deteriorating electricity reliability. This is done through developing a causal loop diagram and an associated simulation model. Thus, the implementation representing a typical (John D Sterman, 2000) system dynamics simulation process. In Paper IV, system dynamics was used to investigate the impact of feedbacks in capacity expansion. Capacity expansion involves the process of matching generation with demand, both long-term (increase in total electricity usage) and short-term (occurrence and size of peak load). Thus, a system dynamics model was linked with a capacity planning model (DER-CAM[2]) and a bottom-up load model. The purpose of the system dynamics model in Paper IV is to model the feedback between electricity availability and the operator's ability to increase generation capacity and between growth in electricity usage and electricity availability. As such, system dynamics represents a part of the modelling approach.

An observation regarding the perception of (dynamic) simulation and forecasting in simulation work has been found. Many system dynamics simulation models (including those developed and presented in this work) models the behaviour of a system over time. And the considered time almost exclusively includes the future. However, the author argues that there is a distinct difference, both conceptually and theoretically between forecasting and simulating the behaviour of a system over time that includes the future. System dynamics involves the behaviour of systems on an aggregated scale. The output of a system dynamics model is therefore a quantification of a specific system structure. Thus, the output is only a description (and often not the only one) of a system structure, and states nothing about whether that specific structure will hold in the future. The simulation results thus only describe whether the current system structure cause a specific behaviour. Due to the pragmatic nature of system dynamics, this involves a dynamic problem, and thus the output links a problematic structure to a behaviour. The output of such models, should unless stated, not be perceived as forecasts but rather as quantitative descriptions of systems structures. In order to conduct forecasts (the question of whether forecasts can be done is a different discussion and is left out), a very different analysis has to be done and should include an analysis of the future uncertainty of the system structure.

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[2] DER-CAM (Distributed Energy Resource and Customer Adoption Model) is a model for assessing the optimal allocation and distribution of distributed energy resources developed at the Lawrence Berkeley National Laboratory, California. It is formulated as a Mixed-Integer Linear Program in GAMS and has been used extensively in the mini- and micro-grid market in the United States.

5.2.3 - System dynamics as a tool for system description and qualitative analysis

The formalization of conceptual system dynamics models into simulation models require a considerable amount of resources. In addition, it is argued by some authors that the results generated from a simulation model can be misleading (G. Coyle, 2000), and thus that a qualitative analysis of the systems structure can be enough for system intervention. The motivation is that system description and qualitative analysis can generate sufficient systems insights in order to formulate interventions, and in some cases remove the need to formulate computer models (R. G. Coyle, 1996; Wolstenholme & Coyle, 1983). This has led to a debate on the relevance of qualitative and quantitative modelling within the system dynamics community (e.g. see G. Coyle (2000) and the response from Homer and Oliva (2001)).

The most commonly used conceptual model in system dynamics is causal loop diagrams. Causal loop diagrams are diagrams representing a number of variables that are connected through causal relationships, which are interconnected with each other through feedback loops. Thus, in a causal loop diagram all relevant variables are dependent on another variable. A causal loop diagram can therefore be seen as a representation of a system structure. Since the focus is on causation and description, causal loop diagrams can be considered somewhere in the realm of descriptive and explanatory models, and thus represents a level of knowledge acquisition (Gigch, 1991).

Even though a simulation model can be used to link structure with behaviour, it does not provide insights to why the investigated structure exists. Thus, a model per se cannot generate insights in order to prevent the same issue of reoccurring in similar situations. However, the process of developing a system model improve understanding of the system and its boundary, and thus also its origin. According to Robinson (2008a) qualitative models represents a step towards the development of simulation models and therefore also a partial understanding (as compared to simulation model). Depending on the problem at hand, this partial understanding might be sufficient to understand why the investigated problem occurs. This issue becomes strictly relevant when considering work on mini-grids in rural electrification. A problematic behaviour can be identified, simulated and analysed in a single case and thus propose solutions to reduce the negative outcomes. However, unless the nature of the identified problem is understood, it cannot be efficiently avoided in other mini-grids, thus limiting the impact of the initial modelling work.

Paper II and V solely relied on a qualitative description and analysis. In Paper II, conceptual modelling is presented as a tool to tackle the complexity in rural electrification. The construction of good and relevant conceptual models is time consuming and to some extent difficult. An initial modelling attempt requires a certain level of knowledge (Allison & Hobbs, 2006). Specifically, when considering systems modelling, a certain level systems knowledge is needed. It is shown in Paper II that conceptual modelling (causal diagrams in this case) can aid in the identification of relevant factors and relationships in systems.

Furthermore, the identification of variables and processes in a systemic way can aid in identifying undesired and desired feedback loops. Thus, even without the additional aid of simulation, some suggestions can be made in order to improve mini-grid viability.

The application of system dynamics as a tool for system description and qualitative modelling in Paper V was a bit different. The paper's purpose is to identify feedback loops in the energy-development nexus for more appropriate modelling. By describing the energy-development nexus in terms of feedback processes, the complexity of the nexus is highlighted. Since complex systems are interconnected elements, it is often not possibly to attribute a change in behaviour to a specific change in a factor without sufficient knowledge about the system and thus system boundaries. The description of the nexus as a complex system consisting of feedbacks thus aids in understanding why the outcomes of electrification (and development) efforts differ in various cases. Describing the energy-development nexus as consisting of feedback processes thus has implications in terms of energy and/or development modelling.

5.3 - Load assessment

In order to conduct the aggregated system dynamics modelling described in the previous section, in depth knowledge of load behaviour and its impacts is needed. This is relevant, since one of the main interactions between the technical infrastructure and the operator is through the functioning of the technical system. Thus, it is important to have sufficient knowledge of relevant processes in mini-grid operation, load behaviour and the impacts of the load in terms of operation and functioning of a mini-grid. This is achieved through load assessment.

Load assessment refers to the process of knowledge acquisition through collection and analysis of load data. Including both data collection and analysis is considered relevant due to the difficulty to obtain sufficient and relevant data on electricity usage in rural electrification. There is a general lack of data regarding long and short-term electricity usage in rural electrification (Cross & Gaunt, 2003; Nfah et al., 2008). The lack of data presents a major barrier for studying electricity usage in rural electrification (Wijaya & Tezuka, 2013) and is necessary in order to make appropriate technology investment decisions (Terrado et al., 2008). The lack of, and difficulty in obtaining data, means that methods for assessing loads need to take into account both the data collection and analysis process.

Load assessment is divided into two areas, assessment of power and assessment of energy. Assessment of power refers to fast changing behaviour of electric loads. As such it has direct implications on the sizing of a mini-grid and its corresponding components. Components needs to be appropriately sized to handle peak power demand with an acceptable margin. Thus, the main object of data collection and analysis is the generation and analysis of load profiles. In order to make appropriate analysis of load profiles and to

identify key technical parameters, such as peak demand, load factor and daily energy consumption, high resolution data is needed. High resolution data is considered to be data with enough resolution to with an acceptable certainty identify relevant technical parameters. What is considered acceptable certainty will be dependent on the load behaviour (fast and more irregular changes in load behaviour requires higher resolution) and what the measured parameters will be used for. In many cases this means that data collection needs to be done using data-logging equipment rather that collection of interview and appliance data.

Since components are distributed in the mini-grid, high resolution data needs to be collected at different levels and for customers with different energy and power demands. Collecting high resolution data for an entire mini-grids shows overall power demand dynamics and is relevant for the generation sizing. High resolution data on customer levels are important in order to link customer groups (e.g. households, businesses and public institutions) with the entire mini-grid load profile and to understand the dynamics of coincidence loads between customers and customer groups. Since it is not practical to conduct high resolution data on each single customer, appropriate selection of customers is needed. Preferably, the selection should reflect the diversity of customers in the mini-grid and thus include customers from each major customer group.

Assessment of energy refers to the long-term dynamics in electricity usage. It has direct implications on mini-grid operation. Depending on the tariff scheme used, electricity usage is dependent on the electricity tariff, and they therefore need to be considered together. In addition, electricity usage and tariff directly correlate with operator income. Thus, an increase in electricity usage is followed by an increase in operator income. In addition, trends in electricity usage can indicate changes in behaviour and consumption of electricity usage, thus acting as a link between customers realisation of electricity benefits and the operator. Since the focus is on long-term trends, data collection needs to automated for practical purposes. Depending on the tariff scheme used, both electricity usage and electricity expenditures are often collected and kept by the operator. However, as data on electricity usage and expenditure collected by operators can lack sufficient quality and consistency. A mini-grid consist of hundreds to a few thousand customers, which are often part of different customer groups. It is therefore difficult to identify trends. An important aspect of energy assessment is thus the identification of trends from electricity usage and expenditure data.

Due to its aggregated form, assessment of energy also has implications on the development and validation of system dynamics models in rural electrification. Since electricity usage is a major element in mini-grids and rural electrification, having knowledge about its dynamics is essential in order to form reference modes in system dynamics models. References are hypothetical behaviours of a system and used during the initial system dynamics modelling phase. In addition, due to the general lack of long-term

high quality and quantitative data in rural electrification, electricity usage and expenditure trends have an important role in the statistical model validation.

Chapter 6 Case work

Even though systems theory and models can result in important realisations, the underlying issue of access to electricity, its implications and complexity suggests that empirical evidence are important. Apart from supporting model development and aiding in keeping modelling efforts relevant, case work helps to establish an understanding of processes relevant to rural electrification and development. An outcome of the complexity, messiness and wickedness in rural electrification is that it is difficult to agree on a problem definition. As described by P. Checkland (1999), "*worldviews*" are an important aspect of problem identification. Case work can help identify the "*worldviews*" of relevant actors. Without case work, the relevant "*worldviews*" of actors might not be sufficiently known, and thus the tackled problem might not be relevant in an actual rural electrification context.

The work presented has therefore, in addition to literature, relied on in-depth case studies of mini-grids and an overview of the current mini-grid atmosphere in Tanzania. To the knowledge of the author, there are currently no databases with qualitative and qualitative data on rural electrification. Even if data would be accessible through databases, the importance of contextual factors makes it difficult to store and transfer relevant information. An issue in rural electrification is therefore the dependency on case studies to collect data. In this regard, there are two different pathways. Either highly detailed and descriptive data is collected from a few cases or more general but less descriptive data is collected from many cases. In-depth case work allows to collect descriptive data and include collection of indirect data (e.g. data not initially considered). Thus, case work can reveal important system structures and relationships. Due to the scope, case-work can include a range of information collecting methods, such as open-ended interviews, questionnaires, workshops etc. The collection of large scale data involves a large number of observations but were the details regarding those observation is often lost through methodological inquiries. Thus, the collection of large scale data can increase the scope of problems. This can be considered from a scale perspective, were a focus on highly detailed data represent a microscale perspective and a focus on highly aggregated data represents a macroscale perspective.

The focus of this work has been on a mesoscale perspective of rural electrification, which sits between a microscale and macroscale perspective. On microscale, rural electrification studies describe and analyse specific issues or processes with a very high level of detail. Microscale studies focus on building theories to explain why certain events

happen and are thus very rich in descriptions. In addition, a microscale perspective contains large share of context dependent information, making conclusions limited in terms of generalizations. On macroscale, rural electrification studies generally analyse large data-sets of highly aggregated observations. Macroscale studies are good to identify and analyse trends amongst these variables. This includes econometric studies, or studies using statistical methods, such as correlation or granger causality, to identify patterns. In addition, they rely to a higher degree on large quantities of data but where each data point contains less information. A source for macroscale studies is national censuses or data collected by large multilateral organisations such as the IEA and The World Bank. Their main advantage is that they can often describe overall trends well, but due to the lack of detail in the data, the fail to offer explanation to why trends occur. This has been highlighted in applications of Granger causality[3] were analysis of time series have resulted in absurd results (Granger, 2004).

On a mesoscale level, there is a focus to explain the reason to why trends occur. Thus, it requires an appropriate level of knowledge about the main processes responsible for the behaviour. Identifying these processes requires both a certain level of detailed information from cases and knowledge about overall trend behaviour. In order to collect detailed, but context specific data, two mini-grid projects have been followed during 5 years. These two projects have allowed for the collection of detailed information regarding relevant processes. In addition, to collect data on trends interviews were conducted with project managers for an additional 5 organisations or companies running or projecting mini-grids in Tanzania.

6.1 Case studies

Two mini-grids were chosen for in-depth analysis. Both are situated in the highlands of south-western Tanzania. The area has a relatively high number of mini-grids operated by either NGOs, the Tanzanian government or Church organisations. Out of the two mini-grids, one was developed by an Italian NGO (ACRA) together with local partners, the second mini-grid was developed through a Church organisation with international support. The two mini-grids were chosen since they represent two different outcomes. The first mini-grid have so far been successful in terms of viability and has managed to tackle issues that has risen. The second mini-grid has shown a number of problems regarding electricity reliability.

During the length of the project three visits were done, in 2013, 2014 and 2017. Each visit included interviews with operator officials and customers of the mini-grids. In addition, measurements were done on electricity usage to identify dynamics in electricity usage and reliability. This was supplemented with additional official data and records

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[3] Granger causality is a method for extracting the causal relationship between two time-series. This is achieved to studying if one time-series can be used to predict the other time-series with sufficient accuracy.

concerning the operation and growth of the mini-grids. By making several visit during the length of the research project, it was possible to identify trends in each of the mini-grids. Interviews targeted towards the customers were done using questionnaires with complementary questions. Interviews done with the operator staff were semi-structured and recorded (with the interviewees approval) for later analysis.

The ACRA mini-grid is a newly established mini-grid. It was constructed by the Italian NGO ACRA with support from local organisations and international funds but is operated by a local community-based organisation (LUMAMA). It consists of a 300kW hydropower plant and as of January 2017 supplied 1491 customers distributed in six villages. The structure consists of an operator with staff responsible for the operation of the mini-grid. The operator is managed by an organisation consisting of representatives from each village that is supplied by the mini-grid. From the beginning, the project was developed to be a community operated mini-grid and thus ACRA helped to set up and train staff. The people in the supplied area mainly engage in subsistence farming. Their cash income is thus seasonal, which has implications on the overall economy of the villages. It also contains a number of business and smaller industries which has both a high social and economic impact on the community, and on the operation of the mini-grid. This includes, welding, milling (mainly maize) and workshops. In addition, the area has a number of small shops selling a variety of goods (including electric appliances) and restaurants using electricity in their businesses. Even though a number of challenges has occurred during its lifetime, the mini-grid has overall been successful.

The second mini-grid is also hydropower based but is smaller and has a smaller outreach (both in terms of number of customers and area). The power plant has a maximum capacity of 100kW and supplied as of January 2017, 452 customers. The hydropower plant was initially constructed for the local hospital and was opened for the public around 2001. Similarly, to the first mini-grid, the population is mainly involved in subsistence farming with an additional number of productive activities such as: welding, milling (mainly maize) and workshops. In addition, the area has a number of small shops selling a variety of goods (including electric appliances) and restaurants using electricity in their businesses.

The mini-grid is operated by the local hospital with staff allocated to the operation of the mini-grid. This staff consists of one technician, one engineer and administrative support staff. The mini-grid use a flat energy payment scheme which is based on estimated power demand. Thus, the electricity consumption of customers has no direct impact on operator income. And there is no incentive for customers to reduce their consumption. Recently, the mini-grid has faced a number of issues that has deteriorated its electricity reliability. The reduced reliability has had implications on both the customers and the operator.

Chapter 7 Conclusions and Discussion

This chapter presents the main findings of the thesis. The findings are presented in terms of discussions relating to the research questions presented in Chapter 1. At the end of the Chapter, a synopsis relating to the overall research question of "*why do mini-grids fail?*" is presented.

7.1 - Conclusions

> **Question 1:** *Can the failure of mini-grids be explained by endogenous dynamics?*

The models presented in the appended publications shows that the failure of mini-grids can be described by endogenous dynamics and that this has implications on the development and operation of mini-grids. Paper I and IV showed that using system dynamics, endogenous representations of reliability can describe the technical and economic failure of mini-grids. In Paper I, a system dynamics model was developed with the focus on explaining deteriorating electricity reliability endogenously. The paper presented both a general qualitative (causal loop diagram) and a stock-and-flow (simulation) model using data from a case. Describing reliability as part of a feedback process rather than as a linear cause-effect chain has impacts on the understanding and formulation of interventions. Using knowledge obtained through the modelling process, a number of possible interventions to improve reliability were formulated. Simulations showed that without any intervention, or with the wrong type of intervention, reliability kept deteriorating causing system collapse.

In Paper IV system dynamics was used to link electricity reliability (but only considering impacts from generation capacity on reliability) when considering capacity expansion strategies. Depending on how the dynamics of electricity use develop and based on the initial generation capacity, the need for capacity expansion will differ. However, in cases when there is considerably growth in electricity use as compared to initial generation capacity and when considering long time-frames, there are benefits to consider reliability endogenously. This becomes especially important when access to financial institutions is limited making it difficult for the operator to obtain the resources to expand generation

capacity. Lack of access to appropriate financial institutions is often the case in many developing countries.

Paper II consider mini-grids using a wider system boundary and focus on a qualitative endogenous description. As such, it does not provide a definitive answer to the aforementioned research question, but provides an advancement towards improving the understanding of viability as an endogenous issue. The system structure presented in paper II was based on literature and case work in Tanzania. The system description through closed causal loops showcase the interconnectedness of factors in rural electrification. The interconnectedness emphasizes the need to use systems methods when tackling problems in rural electrification, which has been lacking in the development agenda (Ramalingam et al., 2008). The presented qualitative model contains a number of what initially might be classified as desired or undesired feedback loops. However, since it is not possible to link systems structure with its behaviour without simulation, describing feedback loops as desirable can be problematic. This becomes apparent since growth (and thus their associated processes) is often only desirable within certain limits. The identification of undesired feedback loops is less problematic since they can be identified as driving processes for undesirable variables. In Paper II, this includes the feedback loops associated with changes in conflicts based in the response of either increased tariffs, reduced reliability or increased inequality. The existence of this specific feedback loop has implications on how to understand and formulate relevant interventions regarding conflicts, tariffs and reliability.

Question 2: *What role can electricity usage and reliability have on the viability of mini-grids?*

The low electricity usage amongst customers in rural electrification is generally seen as problematic, and an issue for reaching financial viability of mini-grids. Thus, the general understanding is that "*more electricity usage is better*". However, as shown in Paper I, II, IV and V the relationship is considerably more complex and increased electricity usage has both positive and negative impacts on the operator, the technical system and the community. Positive impacts include; ability to improve the socio-economic situation, which during the right circumstances could potentially feedback to electricity usage; and increased income for the operator. Negative impacts are associated with reduced electricity reliability and the link between electricity usage and reliability.

From a technical standpoint electricity usage has three major characteristics: power demand, energy demand and occurrence of demand. Depending on the tariff scheme and generation technology used, it might be more desirable for the operator to increase power demand during certain parts of the day, increase individual customer's power demand, or increase electricity usage without affecting peak demand. Previous research has identified typical load profiles for mini-grids and rural areas to consist of a low night and day use

followed by a high evening spike, which is very different from the measured load profiles presented in Paper III. This can be explained by two factors; the low productive use in the considered mini-grids, thus considerably underestimating the daily demand; and the usage of interview-based load profiles with insufficient information.

Promoting activities that increase electricity usage is often positive, but in order to reduce undesired outcomes should be done in accordance with the utilized tariff schemes and technical limitations. If electricity, and consequently power demand, is growing it can cause damage on the electric power system. In order for damages to be reduced, power demand needs to be limited. However, constraining power demand without undesired feedback effects is difficult. As shown in Paper I and IV, high power demand can cause reliability issues with negative long-term effects on viability and potential system collapse. High power demand compared to capacity increase wearing of equipment and can cause blackout if demand is higher than capacity. Increased wearing of equipment leads to more frequent failure and increased need for repairs, putting additional strain on the operator. Similarly, blackouts can cause direct negative economic losses and reduced satisfaction.

An initially reasonable activity for an operator is to promote increase in electricity usage in order to improve income. If the increase in electricity usage is due to implemented policies and practices, it might be socially difficult to change these policies without resistance. For example, as was seen in Paper I increases in tariffs have direct consequences on the community and increase electricity theft, which reduced the initial desired impact. It is therefore important to consider electricity and power demand dynamics and how this can feedback on the outcome of policies. In addition, it is important that the operator is aware of the technical limitations of the mini-grid and have appropriate plans to how to tackle them.

Question 3: *Can the investigation of reliability in mini-grids be useful for tackling reliability issues at the local and national level?*

In this thesis the focus has been on tackling the processes and factors affecting viability of mini-grids. Partly due to the nature of the methods used, and due to the functioning of electric power systems, some results regarding electricity usage and systems structure could be relevant in the context of national electric power systems. The technical functioning of electric power systems is universal, however the management of them change between organisations and environmental constraints depends on the geographic location. However, as qualitative models are more general than qualitative models, it is possible that they could provide knowledge that is also relevant in wider contexts.

It is possible that future scenarios of electric power systems in developing countries includes that mini-grids will become connected to the larger, national electric power systems. If this occur, mini-grids can become a type of technical and economic entity, which can be independent when the conditions in the national grid is not favourable. For

example, if there are local reliability issues or lack of generation capacity, the mini-grid can disconnect and operate in an island mode. This would allow the mini-grid to reduce the negative impacts that can be associated with national grids in developing countries. These forms of constellations of mini-grids are already being implemented in Europe and the US, and suggest that it can both benefit the mini-grid and the national grid (Cardoso et al., 2017). However, the low reliability in developing countries can both act as a barrier and driver for such constellations. If the reliability in the national grid is lower than that of the mini-grid, or if the economic incentives for selling services to the national utilities are low, the mini-grid might not find it desirable to become connected to the national grid. If the incentives are beneficial, it could instead improve the markets for mini-grids as it could improve their income.

Even though a large part of rural electrification is likely to be done through mini-grids, grid extension will still be a viable solution for many areas. The decisions of where to utilize grid-extension and where to deploy mini-grids is ambiguous and depends on the method. The areas of interest for grid extension in rural electrification could therefore include areas with a similar demographic and socio-economic characteristics to the community's subject to mini-grids. The load assessment presented in Paper III could therefore be relevant for utility scale operators. Sizing of grid extension in rural electrification is often rough and fixed around a specific power rating per connected household and not taking into account productive uses of electricity, nor dynamics in the demand. The reliance of simplified and overgeneralized load profiles can lead to inappropriate sizing. This can have important implications on the grid reliability or leading to an inefficiently used grid. Load assessment of mini-grids in rural areas could therefore aid in the correct sizing of national grids and reduce failure due to poor sizing as well as improve their efficiency.

Paper I, II, IV and V used various implementations of system dynamics, and involved some level of qualitative modelling. A benefit of qualitative models is that they describe system structures and are thus more general than qualitative models. The large size of national electric power systems and operators can be a barrier in terms of analysis. Since mini-grids act and operate to a large scale independent, they share a number of characteristics with large scale electric power systems. Thus, findings regarding systems structure could be similar and some findings could potentially be relevant in other contexts. Even if Paper I and IV used data from cases to formulate the simulations models and thus their behaviour, the system structure they describe is more general. Similar behaviour to the results found in Paper I was found on national level in Kenya (Steel, 2008), and in Paper IV was found on national level in Tanzania (Jordan, 2013).

Question 4: *What interventions could improve the viability of mini-grids?*

As is shown in Paper I, II, IV and V, and as discussed regarding research question 1, there are distinct endogenous system structures that impacts the viability of mini-grids. Even though the papers appended in this thesis have tackled specific problems, it was shown in Paper II that rural electrification is messy and wicked, as such there are multiple possible problem formulations. The fact that issues of mini-grid viability can be described by a closed causal feedback structure within the mini-grid system has implications on the formulation of interventions.

When it comes to intervention types identified in the literature, they are often target specific and assume a linear cause-effect relationship. This includes some types of subsidies programs that have a very narrow focus. Such as targeted subsidies for reducing connection costs, bulk purchase of electricity by a third party, investment in additional generation capacity. In cases when the perceived problem mainly originates from endogenous structure, a linear cause-effect relationship will likely result in unwanted results with the possibility that the problem becomes worse. Thus, in order to improve the long-term viability of mini-grids, it is important that there are interventions to address the problematic structures, and how these can be avoided or changed. This makes formulating successful interventions complicated since a systems understanding is appropriate to solve the problems. In order to analyse the problems using systems tools, a specific problem statement is required. In order to keep the modelling approach relevant, it is desirable that the problem statement is shared amongst the relevant actors. Constructing shared problem understanding has been dealt with in system dynamics (Mashayekhi & Ghili, 2012; Vennix, 1999). A first step in the formulation of efficient intervention is to make sure that the actors have similar goals. Regardless if a top-down or bottom-up approach is implemented, it is important that the problem formulation process consider the relevant scale, e.g. local-national and the diversity that exist amongst actors at those levels.

Paper I gave an example of possible interventions to improve reliability in a mini-grid. A number of interventions were tested in a modelling environment, and some showed improvement. However, neither of the suggested interventions would have prevented the initial problem of occurring. In order to do that, interventions would have had to be done prior in order to prevent the situation to occur. The purpose of these interventions would have been to prevent the establishment of the viscous (undesired) feedback loops and would have thus require structural changes. In order to change causal structures with the desired outcomes (and preferably without undesired outcomes), systems knowledge is necessary. Furthermore, paper IV showed that it is necessary to take into account the feedback from reliability into capacity expansion strategies.

In order for organisations to be viable, there should be "requisite variety" amongst the various sub-systems. This means that there is sufficient absorption and production of variation between sub-systems. For example; a technician needs to provide an appropriate amount of variety (detail) about the state of the technical system to his or her manager so that they can take appropriate action; and the operator need to provide and receive sufficient

level of detail to and from the community. This suggests that it is important to a certain level of transparency in the operation of mini-grids.

A discussed through this thesis, a mini-grid can be considered as a system. And in order for a system to be viable it needs to be controlled, e.g. reacting to changes with a specific outcome. In order for a regulator (the entity controlling the system) to control a system, it should be a model of that system (Conant & Ross Ashby, 1970), which implies that for a complex system an intervention based on a model approach aimed at achieving a specific outcome, should to take into account the systems complexity. Members and actors of mini-grids are likely the main actors of control, their decisions are the basis for change in specific directions and originates from their own mental models. Thus, it is important that they have adequate knowledge and tools so that their mental models are sufficiently well informed about the system and its complexity. Thus, if viability is a complex problem (as argued by the author), improvement in the viability of mini-grids (and not the various sub-systems) likely arise from the operator, the community, their interactions and understanding of the system.

7.2 - Synopsis

Based on the systems and viability approach implemented throughout this thesis, mini-grids long-term failure is attributed to their lack of viability. The lack of viability is described based on the conceptual understanding of mini-grids as systems and presented in Figure 1. Since each of the sub-systems needs to be viable in order for the mini-grid to be viable, lack of viability of a mini-grid could be explained by lack of viability in either of the sub-systems. Such examples would be independent destruction of either of the sub-systems. However, due to the sub-systems dependency, it is unlikely. Thus, the lack of viability of a mini-grid is more likely due to the "emergent properties" that these sub-systems show, which is dependent on their relationships. Therefore, the main focus of study in terms of viability should be on these relationships and how they impact the outcomes of mini-grids. One such example that was highlighted in this thesis was reliability. Reliability is not merely a technical issue but originates from inappropriate operation and maintenance practices with direct impacts the community and the operator. As such it is influenced by and influence both the operator and community.

Furthermore, as have been shown, the system and environment in which mini-grids exist can be described as complex, messy and wicked. Formulating and agreeing on problems thus becomes difficult. In addition to the three main sub-systems shown in Figure 1, a multitude of boundary selections within the system described in Figure 1, can be done, each which incorporate different actors and functions. It therefore becomes increasingly likely that these boundary selections have different, and possibly conflicting goals. Conflicting goals can reduce a systems viability and can make a system unviable. Thus, it is

important that the various actors share similar goals and work towards common goals and problem formulation.

The complexity adds additional difficulties for mini-grids. Social systems are complex and their behaviour often appear counterintuitive (Forrester, 1971). Their complexity makes it difficult to predict the outcome of decisions. If the outcomes cannot be sufficiently well estimated, controlling a mini-grid becomes an insurmountable task. Control is one of the central processes for a system to adapt to changes and therefore important for viability. In addition, it is possible that the lack of understanding of the complex environment encourage decisions where the outcomes can be predicted with a reasonable certainty. This could encourage a focus towards short-termism, responding to problem when they occur rather than acting pro-active. In addition, it limits the ability to understand and tackle effects that arise due to relationships between factors.

Chapter 8 Main findings and future work

8.1 - Main findings

The aim of this thesis was to investigate "*why do mini-grids fail?*". As have been shown, mini-grids are part of a complex system, making it difficult to attribute viability outcomes to individual factors. The issue of viability has been analysed using a system dynamics approach and with a specific focus on issues relating to electricity reliability. Based on the research, the following main findings have been drawn from the work.

- **Bottom-up approaches are advisable in order to efficiently improve electricity access.** The environment of mini-grids is complex, messy and wicked, this makes identifying problems that actors agree upon difficult. In addition, it makes it difficult to attribute behaviour in mini-grids to specific changes without sufficient knowledge about the relevant system structure. Due to the high socio-technical complexity faced in rural electrification and mini-grids, it is difficult for top-down approaches to tackle this complexity efficiently. Therefore, bottom-up approaches are advisable in order to realize the benefits that electricity access can bring.

- **Supporting mini-grids viability is difficult, necessary and should be done with specific long-term goals of the national electric power system in mind.** Operating and maintaining a technical complicated system such as a mini-grid is difficult and requires substantial resources. However, the ability to engage the local community and handle issues more directly in mini-grids and the lack of reliable supply in national systems suggests that mini-grids are appropriate in order to reach electrification goals with an acceptable reliability. In addition, it is important to consider what mini-grids role will be in the future electric power system. Without long-term plans and goals for how electricity will be supplied, it is possible that a competition will arise between grid extension and mini-grids, which could have negative consequences. Thus, mini-grids has a role in the future electric power systems in developing countries but their diffusion needs to be supported with specific long-term goals in mind.

- **It is important to consider capacity expansion and load modelling in mini-grids endogenously.** Available capacity, was shown to play an important role

for reliability in mini-grids. As reliability influence individual electricity usage and the economic viability of an operator, it is important to consider it as dynamic. With low access to appropriate financial institutions, increasing generation capacity becomes difficult. It is therefore important that the planning of generation capacity in mini-grids consider reliability into account as an endogenous factor.

- **Interview-based methods for estimating electricity usage and power demand can be problematic.** Using interview-based data collection methods for estimating electricity and power demand can be problematic. Specifically, the underestimation of energy and load factor for households using interview-based data can result in underestimation of the economic viability of mini-grids with a large number of households. However, there is also a risk of overestimation, especially in mini-grids with large number of heavy electric loads (e.g. electric machines). More accurate estimations of electricity and power demand could lead to more appropriately designed mini-grids, higher reliability and thus a lower failure rate.

- **Reliability in mini-grids needs to be considered from a systems perspective**. Even though deteriorating reliability is an outcome from the failure or malfunction of technical components, the choice of components, appropriate maintenance and the operational environment are the result of human decisions. As shown in this thesis, it is possible that operators get stuck in viscous feedback loops that lead to a deteriorating reliability and economic performance of the operator. In order to improve reliability, it needs to be considered from a sociotechnical systems perspective and include feedbacks from non-technical factors.

8.2 - Future work

Through the use of system dynamics and load assessments, this research has provided new insights on how the viability of mini-grids and electricity usage can be modelled. Even though the papers have provided specific results, the overall process has also led to additional understanding of the problems in rural electrification and how these can be tackled. As an outcome of this process, a number of additional questions have been raised. A few of these questions and problems are presented below.

Even though systems dynamics provides a relevant perspective on how to link system structure and behaviour, it provides limited insights why the problematic structures appear. Additional research aimed towards identifying the driving forces of these structures could

provide important insights towards improving the viability of mini-grids. Examples of such processes are the impact of social norms on the establishment of managerial and operational practices. During the interviews for Paper I, it was apparent that the operator was aware of the technical issues that were attributed to overloading and use of poor-quality components. But these issues were not sufficiently taken into account during the decision process. Thus, improved understanding of the process that form social norms in mini-grids is important to reduce the occurrence of problematic systems structure.

Quantitative system dynamic models were developed in Paper I and IV, and Paper II and V presented additional feedbacks considering the wider context and are likely relevant for viability. The quantification of these feedbacks would allow for a wider consideration of viability and bring new insights, especially regarding mini-grids viability and local development through the energy-development nexus.

During the case studies, a difference between reliability (measured) and perceived reliability (obtained from interviews) was noted. It is likely that perceived reliability is affected by additional factors such as at what time a power outage or reduced voltage occurs, customer type and what electricity is used for. Investigating the difference between perceived reliability and reliability and which factors additional factors that impacts perceived reliability could therefore provide important insights into the dimensioning and operation of mini-grids.

As shown in Paper III, the generation of load profiles from interview data can be problematic. However, the importance of interview-based load profiles should not be understated. Additional case studies with comparisons are needed to establish the extent of these differences. Researchers have proposed methods for more accurately generated load profiles for smaller systems (Mandelli, Merlo, et al., 2016), but methods for generating load profiles efficiently for large systems is still lacking. Furthermore, additional comparisons with measurements are needed to avoid the use of misguided assumptions regarding electricity usage patterns. The lack of high quality data on electricity usage in rural areas in developing countries presents a major barrier for research and policy development. The establishment of open databases were researchers and practitioners can easily and efficiently share data could improve rural electrification research.

Chapter 9 References

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