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Cost recovery of isolated microgrids in sub-Saharan Africa: causalities and prerequisites

Master's Thesis within the *Sustainable Energy Systems* programme

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Division of Environmental System Analysis
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Cover:
Picture of a typical house in Inhambane province in Mozambique and a distribution pole, merged to one photo (own pictures)

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ABSTRACT

The study examines cost recovery problems in off-grid electrification projects in sub-Saharan Africa. The long term success of isolated microgrid projects is analysed with a System Dynamics approach to consider socio-technical and economic factors. A supply and demand perspective of a microgrid-village system is used to describe feedback mechanisms and map them in a Causal Loop Diagram. Furthermore, a study visit in Mozambique was conducted to interview actors and visit microgrid projects. The data obtained from the study visit is used to strengthen assumptions on causalities in the model. In the analysis, the qualitative model is used to describe that loads from commercial activity can have positive effects on typical evening peaks. They can lead to higher capacity utilization and higher chances for cost recovery. Commercial activity from agriculture is seen as a promising sector to strengthen customer's solvency, if adequate finance to local entrepreneurs is provided. Considerable from a microgrid perspective is that local operators need the capabilities to operate loads in microgrids. Moreover, the definition of prerequisites for a successful implementation of a microgrid project sums up project experiences drawn from the literature and study visit.

Key words: Rural electrification, sub-Saharan Africa, microgrid, system dynamics, causal loop diagram

Preface

The research was conducted at Chalmers University of Technology in the Department of Energy and Environment at the division of Environmental System Analysis from January to May 2014. I am thankful that my 18 days field study in Maputo, Mozambique was financed with a grant from the German foundation: Thomas Gessman-Stiftung.

I'm grateful for the help of my study colleague Jonathan Rothstein, who supported and accompanied me during my time in Maputo. My study visit was a very insightful experience, due to his help. In this regard, I want to thank Mr. Benhe for letting us share an off-grid weekend in his home village. All the best for his cookie business and PV- water pumping projects. Moreover, I would like to express my gratitude to the other interview partners for sharing their experiences. For a nice welcome in Mozambique I thank Dr. Cuamba and his team at the Eduardo Mondlane University in Maputo.

During the whole learning and writing process on the subject I was lucky to have guidance from my supervisor Elias Hartvigsson. Also, I thank Sverker Molander for his support that enabled this study.

I would like to dedicate a final gratitude to my family and friends. Their help and company made the completion of my degree possible and an enjoyable time.

Göteborg June 2014

Michel Sinn

Notations

CD	Codevelopment
CLD	Causal Loop Diagram
DSM	Demand Site Management
ICT	Information and Communication Technology
kW	kilo Watt
kWh	kilo Watt hour
kWpeak	Nameplate power of a photovoltaic solar system
LP	Local population
MC	Microgrid Cooperation
NGO	Non-governmental organisations
PV	Photovoltaic
USD	United States Dollar
SD	System Dynamics
SSA	Sub-Saharan Africa
RES	Renewable Energy Sources

Contents

1 Introduction

1.1 Benefits of rural electrification

An indicator of the energy poverty status in a country is the population without access to electricity. In sub-Saharan Africa (SSA) an estimated number of 585 million lives without electricity and that number is expected to rise, if current trends continue (IEA, 2013). The challenge to supply people living in energy poverty with a sustainable energy system is internationally recognized. It is a main task of the United Nations and World Bank's "Sustainable Energy for all" partnership and access to electricity is declared a major objective as a prerequisite to reach the millennium development goals (UN, 2012). In SSA more than 85 % of the rural population lives without electricity access (Pellegrini and Tasciotti, 2013, p. 161). Often a grid extension to reach small populations in rural area is not the most economical option. Mostly villages are scattered over a wide territory and of little economic interest. Hence, a grid extension for those regions is not foreseeable in the medium-term future. Options in electrification for regions too far from being connected to the national grid are local microgrids or individual generation (Deichmann *et al.*, 2011, p. 226). A microgrid consists of an electricity generation unit and a local distribution network. Microgrids can operate with or without connection to the national grid. An electrification project without national grid connection is denoted as isolated or off-grid.

More than 10 % of the World Bank total assistance to electrification is for off-grid projects and the amount is expected to rise in coming years (ESMAP, 2007, p. xxvi). Benefits from a supply with electrical energy are plentiful. Especially the first kWh delivered per day has the strongest influence on the human development index (HDI) (Chaurey and Kandpal, 2010, p. 2267). Electricity benefits on an increased amount of light hours per day serving in education, health, work and security. Furthermore, electrical light enhances social life quality, as people are able to gather by night in community places. The situation seems even more severe, if one imagines giving birth at night without sufficient light. Beyond lighting services a supply with electricity can serve many needs. For example, electricity can make cooling available to preserve vaccines or food. Moreover, people in an electrified household are able to access information from television, radio or information and communication technology (ICT)(Kirubi *et al.*, 2009, pp. 5ff). Notable in this regard is, that the fertility rate empirically goes down with higher education and access to electricity (Vavrus and Larsen, 2003, pp. 959, 970). Those social benefits from electricity access are contributing strongly to a HDI rise.

Form an economical point of view, chances for local markets are increasing when a region gets electrified (Kirubi *et al.*, 2009, pp. 5ff). It is a prerequisite for economic development supplying power or improving productivity in production processes, agriculture, banking and ICT. In fact, electricity creates new opportunities to undertake commercial activity, since many production processes are only possible with electrical energy or others are gaining significantly in terms of increased productivity and better quality (Karekezi and Majoro, 2002). Additionally, benefits in social and economic dimension are linked, since positive influences on schooling, life expectancy and lower fertility enhance growth as well (Barro, 1996, p. 2).

In order to improve chances for a sustainable microgrid operation various factors besides the electrical system has to be considered. These factors are summed up with the expression codevelopment, when a microgrid system is implemented to a rural society. Ideally codevelopment considers various dimensions for economic growth in a region, this includes cultural, socio-technical, organisational and financial factors. (Gullberg, 2003, p. 20) In the following study a system dynamic (SD) approach is used to understand success factors between codevelopment and off-grid electrification projects that facilitate the transition from a non-electric energy system to an electrified energy system.

1.2 Background on rural electrification systems

Obstacles for a successful implementation of a microgrid system in rural SSA are determined by the low population density and poverty. In SSA nearly 70 % of the population lives with an income of less than 2 USD a day, according to a World Bank figure from 2012 (World Bank, 2014). Thus poverty and a small customer base are main reasons, that electrification projects in rural areas are mostly not commercially viable and unattractive for the private sector. Instead, financial means has to be provided from governmental funds or donors to install and maintain electrification projects. But problems in microgrid management and consumer behaviour can cause failures and threatens the functioning of a system. The most decisive failure is the lack of financing means in microgrid operation. Another challenge in electrification is to implement a technology transfer that enables local inhabitants to maintain and operate an electrical system. These problems in electrification projects are seen world-wide (Bullis, 2013, p. 16)(Chaurey and Kandpal, 2010). In SSA, examples from Nigeria, Botswana, Senegal, Zambia, Kenya and Tanzania show many cases of weak performances in rural electrification (Bhattacharyya, 2012, p. 289).

With a SD model it is possible to quantitatively or qualitatively build a connected structure of variables. Within SD two approaches of presenting causalities were considered. A Causal loop diagram (CLD) is useful to represent feedback structures in a system. It shows a map of links between variables with arrows from cause to effect. A CLD is helpful to communicate a causal structure represented in feedback loops. Another option to describe a system is a stock and flow map, which emphasizes the physical structure of a system. Stocks are quantities of an inventory, like material, money or information, which are changed by flows. (Sterman, 2000, p. 102)

In the electrification context SD has previously been used to analyse structures and problems. Katherine Steel did qualitative and quantitative research on system dynamics in the rural electrification field, mainly in Kenya. She studied consumer choices between on-grid power and individual off-grid generation, when national grid supply is unstable or expensive. An expansion of large scale off-grid generation capacity is forecasted, which competes against on-grid generation. (Steel, 2007) (Steel, 2008) Another model focuses on the dynamics, when a microgrid is installed in a rural region. Notably, the work of Vikalp Pal Sabhlok and Kyoung Suk Cho presents CLD on remote microgrid projects. Vikalp Pal Sabholk points out that electricity demand is crucial for a successful microgrid project. He states, that a growing demand could lead to a system complexity too high to handle or a diminishing demand can lead to cost recovery problems (Sabhlok, 2013). This point of view, especially the causalities between electricity demand and supply with regard to cost recovery are further considered in this study. Finally, Cho uses a CLD to analyse photovoltaic (PV) in rural electrification in China. The low income of rural population is pointed out as the major barrier and subsidiaries are needed in rural economies to excel growth (Cho, 2011).

1.3 Research Goal

1.3.1 Problem definition

It is seen as important for rural development to introduce electricity and promote factors for economic growth, to have a *"proactive private sector development component to build demand for electricity services"* (ARE, 2011, p. 8). But current literature does only partly support the assumption, that electrification drives income generating activities in a region (Cook, 2012)(Ahlborg and Hammar, 2014). A solvent consumer base is necessary to reach a successful and sustainable operation of a microgrid. But productivity and employment in electrified rural SSA areas are not raising enough to enhance economic output. Considering that fact, the question is how the electrification process can be supported in order to improve the balance of a microgrid operation to run without subsidy or donor money in the long term. Regarding the poor economic conditions in rural SSA context a balance of incomes and operation cost in a microgrid project is already a success (Cook, 2012, pp. 32f).

This study should help to understand challenges of cost recovery in rural microgrids. A demand and supply view on a microgrid-village system aims to show causalities and leverage points to increase chances for cost recovery. Solvent electricity consumers, paying a cost reflecting electricity tariff, are important for a successful microgrid implementation in the long run. Regarding these conditions the problem is formulated as:

Why are many rural microgrid projects in SSA not achieving cost recovery?

Above this question formulation lays the wish, that it should be possible to drive competitive production processes from renewable energy sources (RES) in rural SSA. This is needed in order to achieve a sustainable solution for rural development with little impact to the environment.

1.3.2 Scope

The first intention of this study is to give a qualitative map of the cost recovery problem in microgrid systems. Experiences of country specific projects are mapped in general terms that might be applicable for the wider SSA region. Thus, the detail level of used variables in the CLD is low and focuses on an aggregation that can be valid for many off-grid projects. Moreover, it is difficult to reasonably express the qualitative nature of the economic, social and regulatory dimensions in a rural SSA context. That means a quantitative analysis has to make too many assumptions, which impedes a reasonable analysis. Thus, a qualitative SD modelling approach with a

CLD is chosen, to communicate the feedback structure that impedes cost recovery. (Pruyt, 2013, pp. 48f)

It is further assumed, that the considered microgrid projects are financed without commercial interest. Possible funds for such projects could be governmental or from an NGO. A successful rural microgrid project in terms of covered operational cost will qualify the project to be prone for further, external develop funding to enlarge the system (Kirubi et al., 2009, p. 1219). In order to reach that, the model shows feedback loops to analyse, how cost recovery can be achieved in an isolated microgrid system from an engineering perspective. That perspective shows what factors within the technical part of the system can increase chances for cost recovery in off-grid projects. In closer focus is how the electricity supply and demand evolves, when a microgrid is newly introduced in rural SSA. Furthermore, the dynamics between microgrid systems and its surrounding environment are analysed. Therefore, codevelopment factors are tried to map sufficiently in the model. A main challenge viewed in the model is the facilitation of economic growth in electrified, rural areas. Nevertheless, the scope of this work is to analyse variables and causalities that can be leverage for cost recovery from a technical and operational point of view.

Considered time horizon

The time scale in which this feedback loops are considered to have effect is over more than a decade. Since lifetime of some microgrid system components is over a decade and the resilience of the system is taken to the test, when reparation and replacement costs arise.

Limitations

Electricity demands from population growth are not considered in the study. The local economy mechanisms are subject to attract an influx of people first. The size of public sector institutions is connected to the size of the population. In this regard, electricity demand from the public sector, like school, hospitals or administration is assumed to be constant in the first decade of an electrification process. The constant demand from those institutions can be excluded from the model, because the model aims to show changing feedbacks in the electricity demand.

2 Method

The model construction in this study was an iterative process using information gathered from literature and an 18 days study visit in Mozambique. The steps and methodology to structure the data obtained is described in the following.

2.1 Structuring data

The scope of the model is wide and should consider a socio-technical and economical dimension. To distinguish between variables in the microgrid cost recovery CLD three categories are chosen. Each variable is assigned to a category to show responsibilities, perspectives and leverage on variables within the microgrid-village system. Three categories are represented in the model:

- Microgrid Cooperation (MC), including management and electricity supply system, that provides certain quality of electricity supply (technical dimension and management)
- The local population (LP) as electricity consumers with certain need in energy, education and financing services (social dimension)
- Codevelopment (CD), issues not directly related to electrification that need distinct actions from a governmental institution or NGO (economical dimension)

The main focus is on issues that influence long-term success within the responsibility of a microgrid cooperation. To collect relevant data a qualitative research containing a literature review and semi-structured interviews was undertaken. Current literature covering topics from a technical or economical point of view are reviewed. The literature often contains case studies of exemplary projects that also provide social factors for the analysis.

2.2 Study visit and interviews

The research was complemented by a study visit in Maputo, Mozambique to learn about the current situation in South Mozambique. During the study visit interviews with actors involved in rural electrification processes in Mozambique were conducted. Actors involved in one of the categories MC, LP and CD, where interviewed about their perspectives. Thus, a point of view from a governmental institution (FUNAE), foreign aid organisations and local, national actors could be obtained. Moreover, study visits to a small scale, isolated PV-battery microgrids and a rural off-grid enterprise were done for observation. Semi - structured interviews were either conducted in Portuguese or English, for Portuguese interviews a translator was available. A part of the questions asked were based on causal assumptions drawn from literature to strengthen or neglect them in the model. It is notable that the interview results represent national problems that might be less important in other SSA regions. Another point to consider is that actor's perspectives are influenced by function, for example from FUNAE as governmental employer. Likewise, a rural actor is not asked on issues covering microgrid projects.

2.3 Modelling process

The modelling process followed the structure given in Sterman (2000, p. 87). After the problem definition, given in section 1.3.1, the next step in CLD conception is to define model boundaries and identify most important variables. To define variables different expressions identified in the literature were aggregated to one variable. This step helps to show feedback structures in a system without confusing details to allow a reasonable analysis. That also required to omit variables, which have minor impact on the microgrid cost recovery problem (Sterman, 2000, p. 90). In order to reasonably omit variables in the CLD it was necessary to define a set of prerequisites that has to be fulfilled, as seen in subsection 5.1.

After the boundary selection causal links documented from electrification projects are derived from the literature and depicted in a causal structure. Important variables were used to map a conceptual CLD of mechanisms and feedbacks consisting of exogenous or endogenous variables[1]. That iterative process involved discussions with an advisor to refine the model several times. The causalities identified and mapped in the CLD were discussed during interviews on the study visit. Moreover, observations and information gathered on the study visit completed the assumptions made in the final CLD. Finally, the identified CLD is analysed in order to give insights on the research question to show the feedback structure for cost recovery of rural microgrids.

[1] Exogenous variables are important to the model, but they are not changed by the system dynamics in the model over time. So exogenous variables only feed into the system. Differently to endogenous variables, those are changing within the feedback mechanisms in the CLD.

3 Literature review

The literature review focused on important success factors for rural electrification projects. First, section 3.1 discusses issues regarding the technical side of a microgrid system and thematically connects the electricity demand form the local population with it. The section 3.2 mainly focuses on non-technical issues in codevelopment and microgrid organisation, with respect to the local population.

3.1 Economic feasibility of rural microgrids

3.1.1 Financing of microgrid projects

A certain amount of capital is needed to start a transition from a non-electric energy system to an energy system influenced by electricity. Most important is the capital stock to finance the generation and distributions system. But costs of investments on electrification projects in rural SSA have to be spread on a small consumer base in low populated areas. This results in high cost per consumer electrified in economically viable business case for a microgrid project (Pellegrini and Tasciotti, 2013, p. 162). Considering this the transition process is not taking place, without governmental or non-governmental development aid. Purely economic interests in this regions is usually not existent (Bhattacharyya, 2012). Historically, there was always aid needed to undertake electrification processes in rural regions for example in Europe, USA or China (Zerriffi, 2011). But approaches differ widely among countries. In general two options exist: investment subsidy and operation subsidy (Cho, 2011, pp. 24f). One policy implications from Kenya is, that one-off investment subsidy to support communities and private investors has positive effects (Kirubi *et al.*, 2009, p. 1219). In that sense it is documented that positive effects on the number of new electric connections made are related to the existence of a rural electrification agency, a fund and/or a policy to coordinate the access of funding (Eberhard *et al.*, 2008, p. 37). Often rural electrification is tackled, when the country experience high economic growth rates (Pellegrini and Tasciotti, 2013). Still, SSA countries are not as strong in governmental funding, which justifies aid from foreign partners.

3.1.2 Electricity tariff

The technical design of a microgrid system impacts the project's cash flow. Factors like generation technology, storage capacity, distribution grid and controllability are defining upfront costs. Moreover, system design significantly influences operation costs in a microgrid. In a purely economic evaluation total costs should be reflected in the electricity tariff charged by the microgrid cooperation. But since rural microgrids are in a difficult economic environment, electrification projects often fail in terms of a balanced cost recovery in the long term (Bhattacharyya, 2012, pp. 69ff). Nevertheless, in order to be able to cover the system's running and replacement cost a suitable setting of tariffs and subsidies must be designed. A tariff that is able to cover the cost is referred to as break-even tariff (ARE, 2011, p. 7). For low income customers subsidies are considered an appropriate measurement to enable electricity access for basic needs (Pérez-Arriaga, 2013, pp. 435,438).

A break-even tariff is the most important factor for a long-term successful economical and technical microgrid operation (Pérez-Arriaga, 2013, pp. 438f). But some SSA countries have an electricity price set by governmental order, like in Malawi or Mozambique (AICD, 2008). That makes it impossible to charge a break-even tariff in microgrid projects (World Bank, 2011, p. 25). Hence, projects under such constraint pricing will be depended on operational subsidy and once subsidies are reduced the projects have difficulties to run properly (Barnes and Foley, 2004, pp. 4f). Thus, regulatory constraints on electricity pricing are unsustainable for any electrification project in the long run, especially when it is impossible to charge a break-even tariff that reflects running costs (Tenenbaum *et al.*, 2014, p. 240).

3.1.3 Payment method

The electricity payment method can be a system with a fixed tariff or a consumption based system. A consumption based system has to allow meter readings or usage of pre-paid meters. Moreover, meters with network connection can use phone networks to sell certain amounts of kWh to consumers. Still, to introduce a consumption-based tariff system more electrical equipment and organization in metering and billing is necessary, which results in higher cost. But a consumption based tariff system has higher acceptance from costumers. Examples show that people are even willing to pay more, for a consumption based tariff, because fixed billing creates conflict potential (Ilskog *et al.*, 2005, p. 1302). The pre-paid payments system was very successful in the diffusion of cell-phones in Africa, because they address directly the needs of people with low and irregular income. In that sense, a pre-paid market model could also be of advantage for microgrid projects (Welsch *et al.*, 2013, p. 17). Notable from a demand side prospective is that a consumption based tariff is more favourable as well, because it encourages users to lower electricity consumption (Ilskog *et al.*, 2005, p. 1304).

3.1.4 Electricity cost of different generation technologies

Currently, isolated microgrids are often powered by a diesel generator (genset) or a hydropower station. In general to consider, when choosing a generation technology, are higher upfront costs of a RES technology against a diesel genset, characteristically marked with higher operation costs. That favours diesel generation in economic considerations with high discount rates aiming for short payback periods (Banerjee, 2006). Hence, diesel is often used to electrify an off-grid area, due to low upfront costs (Gullberg, 2003). But electricity generation from diesel is expensive, polluting and difficult to maintain in the long run. This means, that microgrid cooperation earnings can be small, due to high operation costs of diesel generation. That leads to underfinancing and a maintenance only by crisis, which causes a low quality service in the end (Kirubi *et al.*, 2009, p. 1218) Therefore, a dissatisfaction with diesel electricity generation in rural microgrids is reported (Ahlborg and Hammar, 2014, p. 122). Such negative characteristics of diesel generation increase chances for a generation from RES in rural electrification projects.

In Figure 3-1 an economic comparison of diesel versus PV is shown for Africa. The figure is generated using a spatial electricity cost model. For the SSA region, it is visible that a PV-battery system is often a more economical choice, especially when transportation costs, lifetime and maintenance is considered. The colour change at country boarder is visible and emphasis, that country specific fuel subsidies and taxation play a crucial role in the economic comparison between diesel versus PV (Szabó *et al.*, 2011).

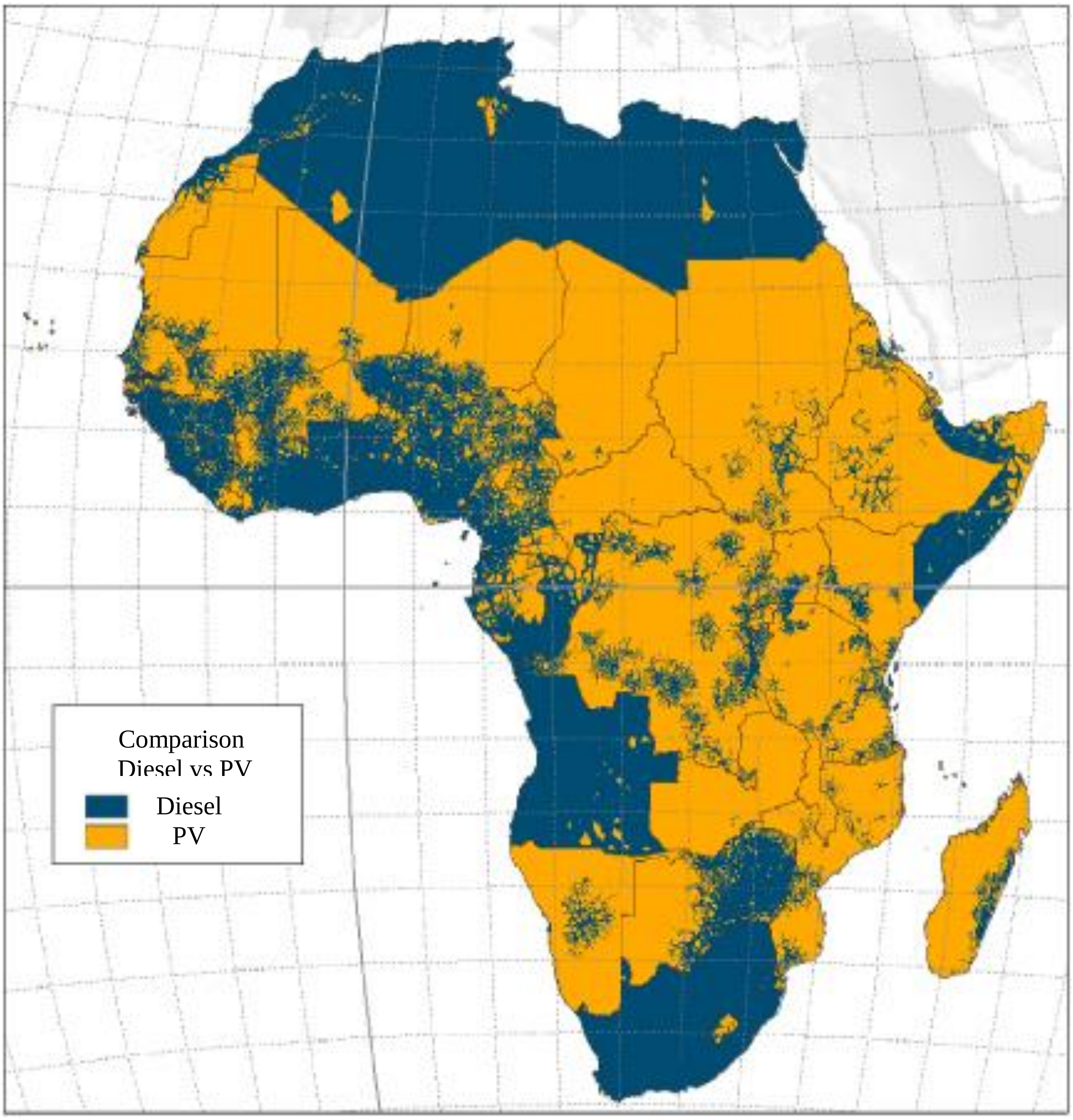

Figure 3-1: Economic comparison of diesel versus PV in off-grid electrification, blue favors diesel and orange favors PV (Szabó et al., 2011, p. 4)

A World Bank study gives estimates about costs of electricity generation in off-grid projects. For a generation of less than 5 kW several RES technologies are more economical than non-RES technology, namely identified were wind, mini-hydro and biomass-gasifier. In isolated networks with loads between 5 kW to 500 kW a biomass, geothermal, wind or hydro generation is seen as the most economical choice. (ESMAP, 2007, pp. xxix–xxx). Nevertheless, the World Bank cost estimations are insufficient to derive an electricity prices for certain project sites. But some tendencies can be found. Microhydro is very likely the most viable option, if hydrological resources are available, due to the relative low electricity generation cost (ARE, 2011, p. 5)(NBCBN, 2005). Moreover, electricity prices from a generation with RES are competitive in rural areas against diesel generation, if RES are abundant and the distance to the national grid is too far (Mahmoud and Ibrik, 2006). An expansion of a generation from RES is even more attractive regarding rising costs of fossil fuels and difficulties to deliver them into rural areas. That leads to an reduced cost of electricity with a high usage of RES in hybrid generation with wind, PV and diesel (Chaurey and Kandpal, 2010, p. 2272). Another study emphases village size and supposes that PV is viable for small scale villages, which exceed a certain population density (Thiam, 2010, p. 1622).

Generally, most small scale electrification projects, apart from sites with good hydro, biomass or wind resources, will use PV, diesel or a PV-diesel hybrid system, as a combination of PV and diesel.

3.1.5 Cost of distribution grid

The used voltage in a distribution grid can be AC, DC or a coupling of both. The decision of voltage levels depends on the technologies and loads in the system (ARE, 2011, p. 57). A major advantage of an AC voltage distribution system is that it allows using regular, available AC electrical devices. Still, it is worth mentioning that a DC distribution is an interesting option for residential PV-Battery microgrids (Welsch *et al.*, 2013, p. 341; Justo *et al.*, 2013). Considering the costs only a negligible difference between an AC or DC distribution is documented (ARE, 2011, p. 56).

Another aspect is the wiring system. Mainly there is a choice between a single phase and a three phase configuration. A single phase configuration has lower initial costs, due to simpler requirements in design and installation (Pellegrini and Tasciotti, 2013, p. 10). Nevertheless, a three phase configuration has lower power losses in the wire, which makes it cost competitive over the project lifetime in hybrid systems with a certain share of costly fossil fuel consumption (Alzola *et al.*, 2008, p. 57). But experiences in Costa Rica, the Philippines and Bangladesh, show that single-phase distribution systems are satisfying against three-phase distribution systems, in particular for networks with low loads (Barnes and Foley, 2004, p. 6).

Many different systems are already in operation and has been analysed. Major findings are that a microgrid simulation model would help to design a system with increased stability and the development of standards for microgrids is necessary (Lidula and Rajapakse, 2011). If a sophisticated microgrid system can be used in a reasonable way in a rural SSA context depends on the control and implementing strategy. Control and operation requirements are raising with the number of different generation technologies in one grid. Such an electrical system is critical to operate in a rural application, due to the need of skilled labour.

In some bigger scale microgrids a hybrid solution between several generation technologies is likely to develop. In that case a coupled AC/DC distribution is likely to emerge, see Figure 3-2.

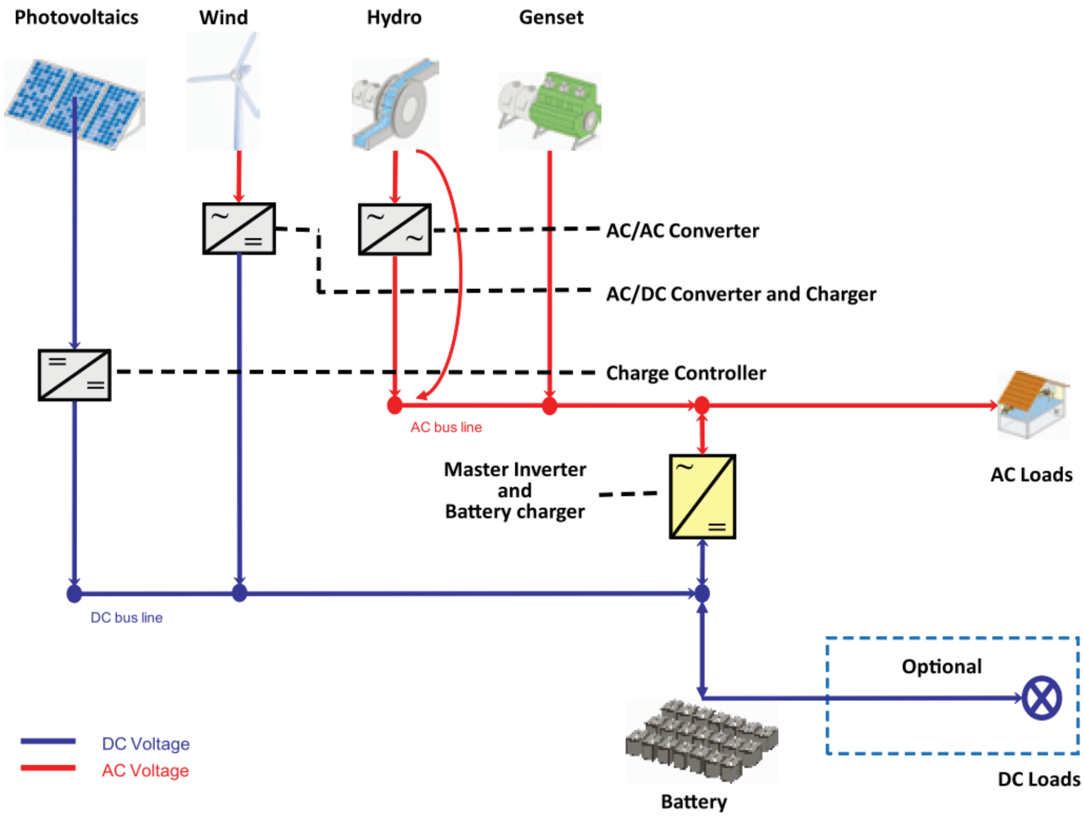

Figure 3-2: Coupled AC/DC distribution grid (ARE, 2011, p. 57)

3.1.6 Electricity demand in SSA

When the share of industrial or commercial electricity use in a village is low, rural electricity demand profiles are defined by household consumers. A typical electrical load profile of a rural SSA microgrid has an evening peak demand. This is due to an increased usage of electricity for light and leisure activities, like music or television, when the sun sets. (Alzola *et al.*, 2008, p. 55)(Kirubi *et al.*, 2009, p. 1214) Moreover, energy usage in cooking and space heating is not likely to change in SSA, where a persistent use of biomass or fossil fuels is seen even after electrification. The main reasons for this are cultural preferences and the fact that alternative energy sources are cheaper. (Howells *et al.*, 2005, pp. 1835, 1845)

Worthy to mention is that after a transition process to an electrified village the demand for electricity will rise. This is shown in an empirical study for Tanzania for the period of 1971 – 2006 concluding that economic growth leads to an growth in electrical consumption (Odhiambo, 2009).

The requirements of a reliable electricity supply rises with the level of sophistication in production processes and expectations on the electricity supply from consumers. The load factor in a microgrid is an indicator to determine requirements of control to ensure reliability. The load factor is given for a certain time period as ratio of average load to maximum possible load in the considered time. For a microgrid operator, high load factors are favourable. A consumer with a high load factor has moderate changes in his electricity demand pattern. Therefore, he imposes fewer control requirements to the grid. In this regard, a low load factor increases cost pressure in any microgrid system, due to high required peak power from the generation side. For example, in a hydro microgrid the highest load defines theoretical turbine size needed. But turbine size is constrained by the available water flow, which can lead to an underpowered system. Moreover, to meet a low load factor in a diesel microgrid a relatively high power diesel engine has to be installed. That engine is in return operated with a low capacity rate, resulting in inefficiencies causing high operation and maintenance costs. Thus, cost pressure or unsuitable system design can lead to unfitting installed capacities that constrains power availability in the microgrid (Gullberg, 2003, pp. 9ff). In that sense, it is advantageous in an off-grid electrification project to avoid relatively high peaks on the demand side to reach a high microgrid capacity utilisation.

3.1.7 Operation of demand and supply

Options exist to control loads and generation in order to make a most efficient use of the installed equipment. From a microgrid cooperation perspective an appropriate demand site management (DSM) can be used to increase system utilisation. The basic idea is to classify loads according to controllability. Those deferrable loads can be used to lower the load factor in the grid (Zamora and Srivastava, 2010). In this regard, knowledge about time critical load demands enables to determine how much generation capacity has to be ensured at a certain time. Accordingly, the size of capacity in generation and storage can be designed in order to reach a cost effective configuration (Hatziargyriou *et al.*, 2007, pp. 83f)(Thiam, 2010, p. 1620).

The intermittent generation of RES requires also measurements in microgrid operation from the supply perspective. In hybrid systems controllable generation from diesel or biomass can be used to ensure back up capacity. But without electricity storage, engines require high power gradients and fast start-up times. More common in rural applications is to incorporate a battery system to buffer sudden changes in generation from RES. The capacity factor expresses the real, produced power of the installed nameplate capacity in a certain time period. Thus, the capacity factor is dependent on the availability of resources and the downtime during maintenance. The capacity factor is an indicator of the system utilisation with regard to the real, covered demand in a microgrid. The World Bank uses capacity factors for wind and solar of 0.2, for hydro up to 100 kW around 0.3 and for controllable biomass or diesel generation 0.8 (ESMAP, 2007). Electrical storage capacity can influence the capacity factor of installed generators in the grid, to reach high demand coverage. The expression demand coverage is further used to describe the amount of time in which the microgrid operation has a balanced electricity supply and demand.

An exemplary profile of demand and supply in a diesel-PV microgrid is shown in Figure 3-3. The negative power of the battery line indicates discharging, when the diesel genset is turned off and the PV supply is insufficient. In night time the diesel genset is operated at higher power than the demand, which shows battery charging. That leads to a higher utilisation and fewer on-off switches of the diesel genset (van Sark, 2012). In such microgrid systems high demand coverage can be reached.

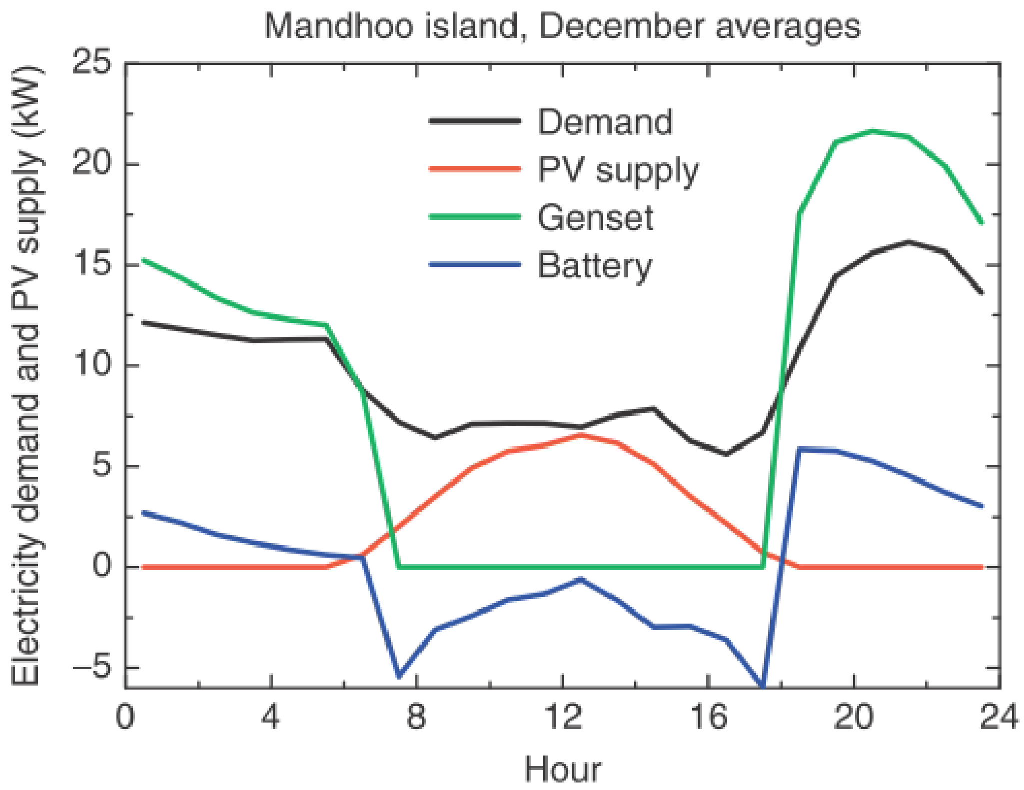

Figure 3-3: Example daily profile of a diesel-PV microgrid with battery storage (van Sark, 2012, p. 689)

In summary, the cost and utilisation of the installed microgrid system can be influenced by DSM and initial system design. But to meet electricity needs in a microgrid with DSM and storage it is necessary to have control equipment and a suitable control strategy. Control system complexity depends on the variety of different loads and amount of different generation technologies in a grid. The daily operation of such a complex system in a rural SSA context is challenging, since skilled operators or expensive control systems are needed. But there is a change to reach high system utilisation on a daily basis, with a working short term management in DSM. In the long run, microgrid capabilities either in generation, storage or DSM have to increase to satisfy consumers, if daily electricity demand will rise after electrification. Taking that point into account the initial installation design should also allow system extension. (ARE, 2011, p. 35)(van Sark, 2012, p. 690)

3.1.8 Maintenance and installation quality

In early renewable energy donor programs before 1990 only 10 % of the total project's capital was spent on promotion of technical and managerial skills in the recipient's region. As a result, projects missed maintenance and experienced inadequate operation. That created dissatisfaction with energy services among aid recipients, in particular in PV installations (Foley, 1995, pp. 54, 63). Another example is documented for a Philippine governmental programme for biogas-powered water pumping in the 1980s. In that programme cost pressure led to the circumvention of technical standards and guidelines in installation. The outcome was that after a few years only 1 % of all the projects in programme were used (Martinot *et al.*, 2002, pp. 313f).

Those experiences highlight that maintenance and a certain quality standard of microgrid systems is required to guarantee reliability of electrical energy supply. Every microgrid system component, like generator, storage or distribution system has different aspects to consider and a varying need of technical intervention. Especially in rural areas a certain quality standard on installations is crucial since supply of spare parts is costly and slow (Quoilin and Orosz, 2013, pp. 202f). In addition to that, these technical systems are usually installed in areas, where skilled technical assistance is scarce. Hence, training of regional labour during the project's implementation of is seen as important, due to a lack of experience and a missing maintenance culture (ARE, 2011, p. 5). Furthermore, trained operation and maintenance in microgrids ensures durability, even after warranties from installation company are over (Bullis, 2013).

3.2 Rural development in the sub-Saharan region

The following section sums up important codevelopment issues when introducing an isolated microgrid system in a rural SSA economy. The successful implementation of such microgrids is highly depended on a balanced usage of aid money, governmental funds and private investments between the technical system and codevelopment. The institutional framework of a country can be a barrier or a driver to forester growth in a certain area. But institutional organisation is generally weak in SSA, notably in rural, low populated areas (Pellegrini and Tasciotti, 2013, p. 12).

3.2.1 Economic output in SSA

SSA off-grid areas are characterized with a very low population density and low income level. Income generating activities are driven by the market attractiveness of the region. In general the following services are seen as most important for an economic development (Gullberg, 2003):

- small scale industrial activities (workshops, agricultural processing, including grain milling)
- cooking
- domestic water (pumping, treating, heating)
- information and communication technology
- lighting
- preservation of agricultural crops
- irrigation

Several of the mentioned services above can benefit from electricity, for example sectors like agriculture, craft, food processing and tourism are promising. This includes enterprises of every size in the informal or formal sector. An exemplary benefit from access to electricity is an increased productivity and cost reductions for carpenters and tailors (Mwakapugi et al., 2010). But there are many reasons documented which impede economic potential in an electrified rural region (Bigsten, 2006, pp. 244–250)(Khan, 1997, pp. 6–14). Thus, empirical evidence shows, that there is not necessarily an income gain from electrification, it is very case specific (Deichmann *et al.*, 2011, p. 216). Overall, market attractiveness is too low, constrained by a small, low income consumer base, which blocks private investments in stores or services on a rural level.

In rural areas economic output is strongly linked to agricultural activity. The agricultural sector includes products from farming, livestock or fishing. Even non-agricultural activity often serves indirectly the agricultural sector. Still, in rural SSA roughly 70 % of the income is generated from agriculture (Haggblade *et al.*, 1989, p. 1178). Moreover, there is a growth linkage between each dollar of additional value added in agriculture, which leads to around $ 0.5 in nonfarm economy income[2] (Haggblade *et al.*, 2009). Therefore, codevelopment of the rural agricultural sector with an electrification project seems to be a promising approach to generate income. In this regard, the agricultural sector is expected to have a great job creation potential in SSA (Mwakapugi *et al.*, 2010, pp. 17ff). But this means that a production of cash crops is crucial. Interestingly, it is found that a switch from subsistence farming to cash crop production is linked to industrial consumption of manufactured goods, such as textiles, processed food, building material or means of transport (Janvry *et al.*, 1991, p. 1416). That implies that a gradual switch from subsistence farming to income generating cash crop farming is dependent on the availability of affordable consumer goods in a region. That is a barrier in SSA, because many local village size economies are still based on goods trading, which is very unattractive for vendors. In that sense electricity offers opportunities, because it is often experienced that after electrification the market activity of grocery stores is increased (Karekezi and Majoro, 2002)(Bhattacharyya, 2012, p. 136). That feedback mechanism for economic growth is strengthened by the link between non-farm and farming activity, which is expected to grow due to a higher availability of manufactured goods in groceries (Haggblade *et al.*, 2009). In particular these linkages are important to consider, for the promotion of productive use in rural microgrids.

Still, among rural inhabitants subsistence agriculture is most common and agricultural productivity is very low and does not even show trends of improvement. In the nineties there was even a decline in agricultural productivity (Khan, 1997, p. 6). Traditional farming patterns are not changed and subsistence farming is not able to provide significant income. Thus, the transformation of farming activities from subsistence farming to cash crop plantation imposes various challenges. For example land ownership is a constraining issue in rural SSA as well, especially in agriculture. But those problems are beyond the scope of the microgrid problem discussed in this context. A comprehensive study on agriculture in SSA is given by Khan, 1997.

[2] Nonfarm economy includes trading, agroprocessing, manufacturing, commercial and service activities Haggblade *et al.* (2009)

3.2.2 Infrastructure

Infrastructure is a major factor for rural development and market attractiveness in general (Canning and Pedroni, 1999, p. 4). A primal condition is the availability of some transport connections with road, rail or ship. Another indispensable prerequisite is a reliable supply of water, keeping in mind that only a rural population of 53 % has access to an improved water source in SSA according to a World Bank figure form 2012 (World Bank, 2014). Further a connection to an information and communication network is related to infrastructure as well. All of those infrastructural factors are a prerequisite for growth, besides modern energy services influenced with electricity. In terms of market attractiveness, measures for infrastructural quality can be days in customs, days without telephone connection and days without electricity (Bigsten, 2006, pp. 244–250). When infrastructural requirements are fulfilled to an acceptable level a market can develop. Thus, a provision of complimentary infrastructure is advisable for codevelopment in an electrification project (Kirubi *et al.*, 2009, p. 1218).

3.2.3 Investments in local entrepreneurs

A local entrepreneur is essential for a meaningful emergence of productive use in microgrids. Local business ventures, which are willing to undertake economic activities with newly gained possibilities from electrification need finance. But accessibility to formal credit from the banking sector is mainly not existent in rural areas. Especially among small enterprises the rejection rate for credits, when they make the effort to apply for a loan, is above 90 %, as surveys from SSA countries show (Bigsten, 2006, p. 246). Financial institutions are not focusing on rural areas, because risks involved in financing rural enterprises are perceived as too high. Potential investors don’t target rural areas mainly due to an abundance of alternatives to invest with much lower risk, like the booming telecommunication sector, mining or tourism. Therefore, governmental funds and subsidies are available for local entrepreneurs (Cho, 2011, pp. 72, 79). Still, a barrier to access money is the legal status of a company. To receive money from a governmental fund the enterprise has to have a formal status. But enterprises with a legal statue have to pay taxes which makes being formal costly (Bigsten, 2006, p. 261). Therefore, the involvement of foreign aid organisations to deliver grants to local entrepreneurs can play a major role to circumvent governmental bureaucracy. But access to financial capital is not easy. Without basic education in ICT usage or business planning people have little chance to develop entrepreneurial skills or gather information about possibilities in production or funding outside of village boarders. In that sense, local entrepreneurs requires special training and support in business planning and production techniques during electrification projects (NBCBN, 2005). Moreover, a change in agricultural activity requires entrepreneurial skills in organization, communication and a willingness to take risks (Petrin and Gannon, 1997).

A promising way of foreign aid is private to private micro financing, which can directly impact local business activities (Hartley, 2010). Other innovative micro credit programmes are established from the Grameen Bank in Bangladesh. They provide credit with a promotion of saving habits and better production practices (Khan, 1997, p. 18).

3.2.4 Addressing the local population

The pace of rural development depends on local circumstances. To choose the location for an electrification project a set of pre-qualification criteria is needed to identify which rural area and socio-economical facility to electrify first (Kirubi *et al.*, 2009, p. 1220). This increases the chances to reach cost recovery in an electrification project, especially if potential local electricity demands are understood beforehand. Still, when a region for an electrification project is identified, the transition process to an energy system influence with electricity means a sensible change in local community lifestyles. This process has better chance for success, if local communities are involved into the project form the beginning. In that sense questionnaires about prospected demands are a success factor for a satisfactory electricity supply (Quoilin and Orosz, 2013, pp. 200f). Information about technical capabilities of the system and electricity use develops trust and awareness for the new system (Domınguez, Juan Leandro del Viejo, 2011, pp. 58–95).

In the following, some examples point out to emphases the importance of a community involvement for electrification projects. In Nepal there are positive effects on electricity theft and timeliness of bill payment reported in community-owned projects (Tenenbaum *et al.*, 2014, p. 290). Moreover, a case in Kenya shows that a community involvement in microgrid projects as a common property resource is a driver for success (Kirubi *et al.*, 2009, p. 1211). Another case in Vanuatu shows a sustainable microgrid operation with a community must-own concept (Mohns and Stein, 2008).

4 Processing literature and interview data

Table 1 sums up all conducted interviews during the study visit. Most of the interviews could be recorded for further analysis. The defined categories MC, CD and LP are used to indicate, which background and perspectives the actor had during the interview.

Table 1: Interviewed actors with a rough definition of their function and perspective (MC = microgrid cooperation, CD = Codevelopment, LP = Local population)

Actor	Function	Interviewee's perspective
Consultant-A	Project realisation	MC, CD
Consultant-B	Project financing	CD
Consultant-C	Project financing	CD
Consultant-FUNAE	Project realisation	MC, LP
FUNAE	Project realisation	MC, CD, LP
Entrepreneur	Private rural actor	LP
University	Advisory	CD, LP

Moreover, two small scale, isolated PV-battery microgrids were visited and questions could be answered by local operators. Additionally, a local, rural entrepreneur was accompanied to his small manioc biscuit enterprise. He is also involved in the implementation of five PV groundwater pumping stations, where he tries to copy a successful PV groundwater pumping project from his home village in other villages.

4.1 Interview summary on causalities

The literature study defined a preliminary set of links and feedback mechanisms considered to be of interest in electrification projects. They were summed up in a preliminary CLD. Based on that CLD semi-structured interviews were conducted in order to strengthen the assumptions used in the model. The interview recordings and notes were processed afterwards. In Table 2 statements on causalities activated by certain variables are structured. It shows comments organised according to the actor's perspective as categorized in Table 1 to indicate different point of views on topics.

Table 2: Interviewed actors opinions on crucial issues according to their perspective

Variable (literature section)	**Codevelopment perspective**	**Microgrid cooperation perspective**	**Local population (consumer) perspective**
Pre-assessment of the region (3.2.1; 3.2.2; 3.2.4)	- Definition of performance indicators, for impact assessment from electrification: usually positive - Baseline study - Rural development value chains[3]	- Social demographic study - Cost-benefit analysis	- Most important for local people is a water supply
Satisfaction with electricity supply (3.1.3; 3.2.4)		- Constrained by unreliable power supply - Prepaid: positive experience	- Thinking that electricity from governmental projects should be free - People like prepaid - People are able to pay for a reliable supply - Payment behaviour can be low
Chances for cost recovery (3.1.1; 3.1.2; 3.1.4)	- Constrained by rural customers solvency (electrification project have a social motivation)	- Constrained electricity pricing by governmental order and high upfront cost, which means no chance to charge a cost reflecting tariff - Share of commercial customers important for cost recovery (grid extension is also done under those considerations)	

[3] The definition by the international labor organization (ILO) of a value chain, Herr and Muzira (2009, p. 3): "describes the full range of activities that are required to bring a product or service from conception, through the intermediary phases of production [...],delivery to final consumers, and final disposal after use."

Variable (literature section)	**Codevelopment perspective**	**Microgrid cooperation perspective**	**Local population (consumer) perspective**
Rural market attractiveness (3.2.1; 3.2.2)	- Missing infrastructure - Constrained by good trading economy		- Diesel is expensive in individual generation - Electricity would increase village economy (cooling in grocery stores) - Most potential seen in agriculture (irrigation, food preservation and processing)
Commercial electricity demand (3.1.6; 3.1.7; 3.2.3)	- Constrained by financing - Cooling demand has potential (positive experience from grocery stores) - PV - water pumping has potential and positive experiences - Little cooperation in electrification projects and codevelopment funding - Good experience with funding for diesel driven multifunctional platform	- Load from mills unsuitable for small scale microgrids, power requirements too high - PV seen as difficult for productive use	- No education (business planning, productive use) - No information about funding possibilities and productive use - Solar home systems are a business opportunity in rural areas, but education constraints
Household electricity demand (3.1.6)	- First goal of electrification project is to provide lighting	- Rising demand over time	- Mainly light, music, television, phone charging and cooling mentioned

Variable (literature section)	**Codevelopment perspective**	**Microgrid cooperation perspective**	**Local population (consumer) perspective**
Microgrid improvements (3.1.7; 3.1.8)	- No enlargement projects of existing projects so far - Unsatisfying local operator training from installation company	- Reparation costs are high (inverter and battery problems) - Diesel microgrid not operational, because there is no money for diesel - Supply is controlled via on off Switch to guarantee charged batteries in night hours - Forbidden high power loads (heating, cooling) in PV microgrids	- Limited satisfaction from electrification projects, due to unreliable power supply

4.2 Identified variables

The variables found in the literature study and during the study visit are evaluated on the suitability to describe the cost recovery problem in rural SSA microgrids with a CLD. Table 3 shows variables used in the CLD. Besides, alternative expressions describing the same or a factor strongly related to the variable are given. The variables are assigned to the categories MC, CD and LP, to indicate who the most leverage on the variable. The last column sums up, how many of the seven interviewed actors mentioned the variable. The notations in interviews strengthen significance of the variables in the Mozambican context. The exogenous variables mentioned are found to be most influencing, exogenous factors in the feedback loops for a successful microgrid operation.

Table 3: Variables used in the CLD for cost recovery problem, maximal number of interview references: 7 (MC = microgrid cooperation, CD = Codevelopment, LP = Local population)

Exogenous variable	**Alternative or including expressions**	**Category**	**Inter-view Ref.**
Complementary infrastructure	Water, phone network, streets, harbour, ITC	CD	5
Access to financial capital	Soft finance, direct cash, grants, funds, group finance, microfinance	CD	6
Knowledge in business planning	Business planning, existence of consultant service	LP	5

Exogenous variable	Alternative or including expressions	Category	Inter-view Ref.
Knowledge in productive use	E.g. irrigation techniques, food processing	LP	4
Community involvement	Local microgrid cooperation	LP	4
Knowledge in microgrid operation	Ability to operate independently, technical training	MC	4
Initial installation design	Cost pressure, share of renewables, capacity factor, control system	MC	1
Endogenous variable	**Alternative or including expressions**	**Category**	**Inter-view Ref.**
Attractiveness of rural market	Export possibilities, internal consumption, population density, trade economy	CD	4
Load factor		LP	0
Evening peak demand		LP	1
Income generating activities (service and agriculture)	Private sector investments: Agricultural activity, groceries, cooling, craftsmanship, ICT-services	LP	5
Average income	Money and food supply, poverty, consumer solvency	LP	4
Household electricity demand	Light, cooling, phone charging all leisure activity related to electricity, like TV, music	LP	2
Commercial electricity demand	Motion energy, cooling, light	LP	3
Payment behaviour	Comparison of urban and rural electricity price, "difficulty of separating between given money or loans", willingness to pay bills	LP	2
Satisfaction with electricity supply	Trust in the reliability, customer complaints	LP	2
Chances for cost recovery	Economical balance of microgrid cooperation, chance to charge a break-even tariff, possibility to raise electricity tariff	MC	3

Endogenous variable	Alternative or including expressions	Category	Inter-view Ref.
Demand coverage	Hours without electricity, load restrictions	MC	2
Microgrid improvements	Investments, DSM, maintenance, fuel, new generation capacity, additional storage capacity, grid extension	MC	4

5 Cost recovery in rural microgrid systems

5.1 Prerequisites for microgrid cost recovery CLD

Once a microgrid is established in a local community it is important that certain economic growth mechanisms can be activated. The data processing from the literature review and interviews showed that certain prerequisites should be fulfilled in order to have a microgrid village system, where cost recovery is possible. Thus the microgrid cost recovery CLD is based on fulfilment of the following assumptions:

- **Consumption based electricity tariff system**

Billing the consumers according to their consumption has positive effects on electricity usage. Recommendable is a prepaid system due to consumer’s preference, strengthening satisfaction with the electricity supply, further in section 3.1.3.

- **Household cooking and heating loads is not done with electricity**

As seen in section 3.1.6, the model takes not into account an emergence of electricity loads for heating. Observed energy demand patterns for cooking or water heating in SSA will not cause an increase in electricity demand. This limitation should be reconsidered for microgrids in Asia, where cooking with electrical rice cookers is practise.

- **Regional economic prospects indicate potential**

In other words, local agricultural habits are promising, for example people already involved in livestock farming, fishing or cultivating crop / vegetable with cash crop potential, which can activate economic output shown in section 3.2.1.

- **Infrastructural conditions**

As stated in section 3.2.2, infrastructural condition should provide at least a reachable source of water, coverage of phone network and a road connection to the designated village.

- **Investments in local enterprises are facilitated**

In order to enable local entrepreneurs to buy equipment for economic activity dedicated funds or credit schemes are assumed to be available, see section 3.2.3.

- **Local community involvement**

Locals are involved in the planning process and partly own the microgrid project. As described in section 3.2.4 addressing local needs with payment and ownership models is crucial and affecting payment behaviour. Partly community owned approaches are promising, because local people have an interest in cost recovery, positively influencing behaviour to pay electricity bills.

5.2 Microgrid cost recovery CLD

The complete microgrid cost recovery CLD is seen in Figure 5-1.

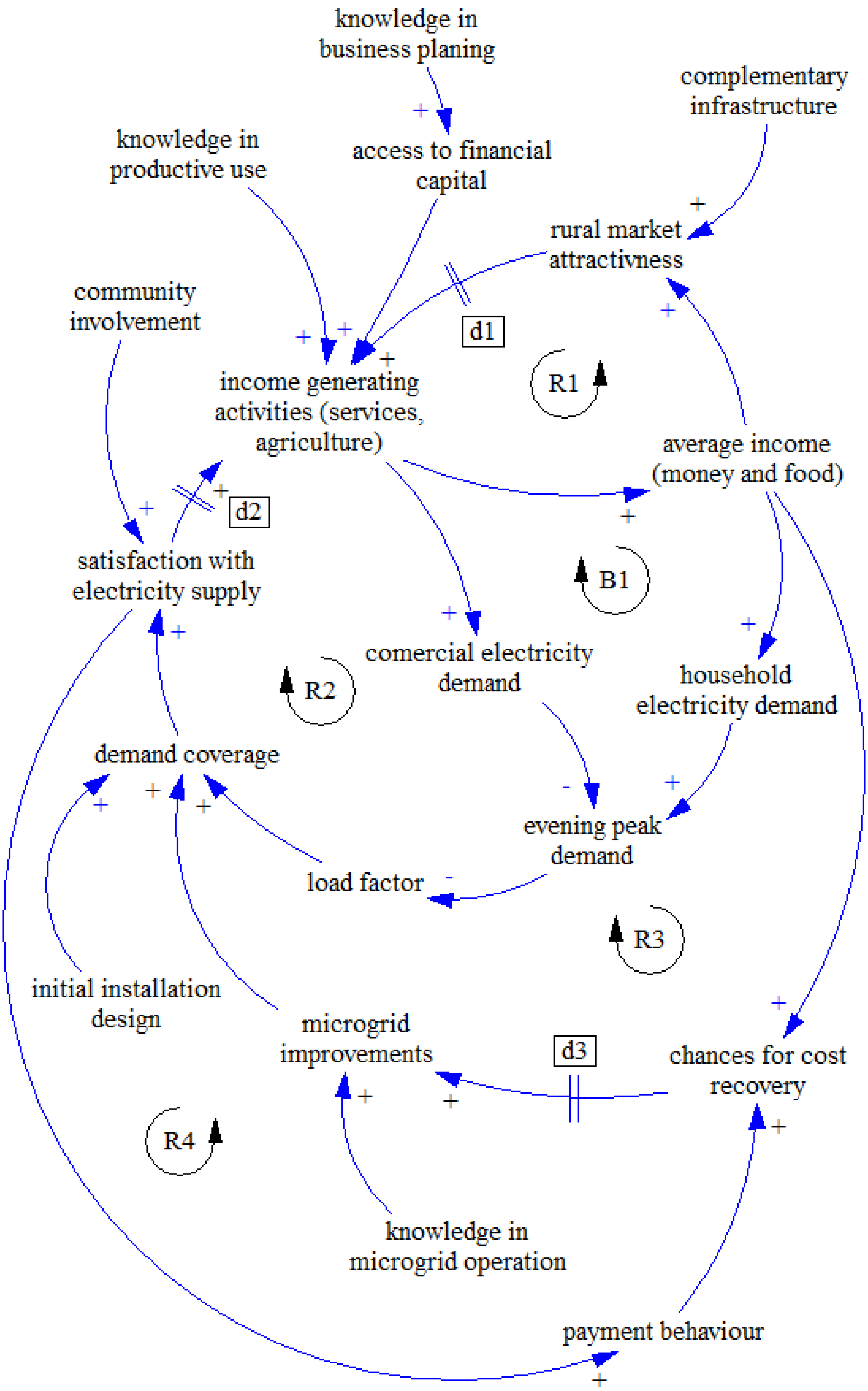

Figure 5-1: Causal loop diagram for microgrid cost recovery

For the conception of the microgrid cost recovery CLD much attention was spend to describe causal links between consumer base and microgrid cooperation. The CDL shows a structure of electricity supply and demand in a microgrid-village system. The identified feedback loops are marked with B1 and R1-4; constraining delays are indicated with d1-3 in the CDL. A detailed description of symbols and terminology used in the CLD can be found in appendix A.

Causal links

A causal link is used in the feedback loops B1, R2 and R3 between satisfaction with the electricity supply and income generating activities. The satisfaction is related to hours of successful delivered electricity. The delay mark d2 indicates that consumers need to develop trust in the electricity supply before integrating electrical devices in any existent or planned income generating activities. That link is further referred to as **trust link**. It is partly based on finding in section 3.2.4. The quality of service provided from the microgrid cooperation is important to strengthen the trust link.

From the income point of view, a link between income generating activity and average income is used in loop B1, R1 and R3, that is further called **income link**. The importance of the income link was mentioned by all interviewed actors. A positive example was made from a project implementer during an interview. After installation of an isolated hydro-microgrid he experienced that the local grocery store owner could manage to finance a refrigerator without any external funding. Since then revenues from the grocery store went up, because it was possible to sell chilled drinks. This shows how income generating activities can affect also electricity demand, if electrical devices are used to increase economic output of the village as shown in subsection 3.2.1.

A third link found in loop R3 and R4 describing the connections of chances for cost recovery over microgrid improvements to demand coverage. That link is denoted as **microgrid management link**. The d3 delay mark indicates organisational and operational problems that may be a barrier for microgrid projects, which should be at least partly managed by locals. Therefore, the exogenous variable for knowledge in microgrid operation denotes the importance of training justified in subsection 3.1.7 and 3.1.8.

Finally, there is a rather technical **demand and supply causality** leading to consumer’s satisfaction. First, the link in loop B1 and R2 expresses the effect of an evening peak on the load factor. A high load factor will decrease difficulties to cover the electricity demand in the grid. Secondly, the electricity supply side in loop B1, R2, R3 and R4 describes the connection between demand coverage and satisfaction with electricity supply. Consumer’s satisfaction is a direct result from quality and reliability of demand coverage in the local village. The possibility to cover electricity demand is determined by the initial design of the installation in generation technology, controllability and distribution gird, as shown in section 3.1.

Feedback loops

The household demand loop, B1: Consumers start using electricity, the first energy services from electricity will be light, phone charging, music and television. Since light will be the most important and affordable for all consumers it will result in an evening peak. Further, a peak load introduced from households can cause low demand coverage and dissatisfaction among consumers over the supply and demand causality. Hence, a high share of household consumers in the microgrid has a balancing effect on income generating activity. A microgrid case study in Nepal shows a lack of productive use from electricity caused a low load factor around 20 % (Fulford *et al.*, 2000). In comparison, another case study in Kenya estimated the microgrid load factor to 43 %, which was reached due to a high share commercial customers (Kirubi *et al.*, 2009, p. 1213)

Rural economy loop, R1: The attractiveness of rural market drives income generating activities. That will lead to an increase in average income resulting in an uptake in electrical consumption from households and commercial use. In Solarin (2011) different empirical studies are summed up on the relation between electricity consumption and economic growth in consideration of capital formation. It shows that electricity consumption is positively associated with the real gross domestic product, which indicates potential economic growth from electricity usage. In this regard, the loop represents growth mechanisms that might develop with electrification. Overall, promising prospects for income generating activities exist. In particular a growing agricultural output can be achieved with the availability of electricity. Promising sectors and economic output is discussed in subsection 3.2.1. The delay mark d1 indicates that development processes can be subject to very slow progress.

Commercial demand loop, R2: Many income generating activities are dependent on electricity. When external finance is provided, loads from commercial activity might get introduced to the system. This increase in electrical demand growth from commercial activity is mainly taking place at daytime, therefore influencing positively the load factor. In this regard an interviewed NGO consultant points out that they train people in order to act as a consultant for local entrepreneurs. They can offer business planning as a service to local entrepreneurs to access governmental funds for productive means. Such services help to set up new business ventures in newly electrified rural areas.

Solvent consumer loop, R3: The income level of the consumers determines the ability to pay electricity bills. Hence, revenues of microgrids depend on consumer solvency. A certain knowledge level is required within microgrid operation to ensure that revenues will be spent on operation and maintenance to guarantee a satisfying service with the installed system.

Payment behaviour loop, R4: This loop is of interest for the problem description because it depicts the behaviour to pay from rural consumers. That is especially important in the rural SSA context, because bill enforcement is difficult due to low income levels. There is practically often no possibility to enforce people to pay their bills. In the long run that can lead to the assumption, it is not necessary to pay electricity bills. Then a negative lemming effect in the village community on payment behaviour diminishes chances for cost recovery. Therefore, community involvement within the electrification process plays a role for a satisfaction with the electricity supplier, as seen in subsection 3.2.4.

6 The system perspective on rural microgrids

The microgrid cost recovery CLD is used in the following to show reinforcing and balancing factors in rural microgrid village systems. The microgrid cost recovery CLD consist of one balancing and four reinforcing feedback loops. The balancing household demand loop constrains uptake of all reinforcing loops in the model. To analyse feedback structures in the system three phases of development in microgrid project are chosen. That project phases express time steps in the model from newly installed to maturity in the considered time scope of over a decade of years. Causal strength shifts during project phases with time, when the electrical demand changes due to commercial activity.

First phase (overcome d2 and d3 and develop trust):

According to the model, causalities in the household demand loop are important in the first phase of an electrification process. After installation of a microgrid project non-commercial loads are likely to dominate the demand structure. Household electricity demand balances the system due to an unfavourable evening peak demand. That leads to a costly, low load factor, when a promotion for productive use of electricity is lacking. This is a crucial point is the beginning of a project, because then a low load factor, unexperienced operators, high attention from new electricity consumers and possible deficits in the initial installation design endanger consumer's satisfaction with the electricity supply.

At this point the microgrid management link plays a significant role to satisfy its customers. Community involvement and initial installation design can be leverage in the payment behaviour loop to increase customer satisfaction and strengthen the trust link. But even if the financial balance is in favour of cost recovery, positive feedback from the payment behaviour can be delayed. The d3 delay indicates these constraints in microgrid management. They can result, for instance from inefficient payment handling or bookkeeping from unexperienced local operators. Still, microgrid improvements should ensure most important services, for example an organisation of loads in DSM or maintenance of the microgrid. That will lead to higher demand coverage and gains in satisfaction. Then local entrepreneurs can develop trust in the electricity supply, which will foster investment in electrical devices for income generating activity. In order to overcome d2 in the trust link it is within microgrid management responsibility to ensure supply and consumer's satisfaction in the first phase. Thus, in the first years of a microgrid project the microgrid management link (in R3, R4) has strong influence on the system. That link especially, can impact the balancing level of the goal-seeking behaviour in the household demand loop.

Second phase (overcome d1 and commercial activity emerges):

When microgrid operation in the first phase takes effect, the reinforcing rural economy and commercial demand loop will be dominating the system's outcome. In this regard, the importance of income generating activates for the whole microgrid-village system is emphasized. It is visible in the CLD that four out of five feedback loops depend on income generating activities. They spur an increase in commercial electricity demand and in average income. That has two implications on the system, in particular in the second phase of the project:

Rural economy loop (R1): In order to achieve an emergence of income generating activity the rural economy loop needs to be activated. Nevertheless, electricity can only be a supplement for income generating activities to develop. Complementary infrastructure can raise attractiveness of rural markets within the responsibility of codevelopment measurements. But difficulties in rural SSA market delay the rural economy loop to spur activity. To overcome d1 economic activity in a region needs to be facilitated. Examples for measures to overcome d1 are the provision of an internet connection or a service company that organises transportation of produced agricultural goods. Moreover, for rural enterprises providing tools and financial capital is essential for economic development. Therefore, the indication of exogenous variables in knowledge and financial access are shown, to address the entrepreneurial problems in financing. A slow uptake can also start with self-financed services in rural villages, like a barber shop, phone charging or the use of chillers for food storage or cold drinks sales. That activates the income link.

Commercial demand loop (R2): With an uptake in income generation powered with electricity some controllable and relatively big electrical loads from commercial activity can emerge. Loads can be, for example, from water pumping or food processing machines. Hence, commercial loads can be used positively in DSM on the load factor. These influences in the supply and demand link can lead to a more even demand profile and an overall higher kWh per day consumption. Such a higher consumption leads to better utilization of the microgrid facilities. More successfully provided kWh per day results in more satisfied consumers activating the trust link again.

<u>Third phase (maintain and improve the system: long term success):</u>

At this point it is notable that a well implemented rural market economy development might be impeded by an insufficiently managed electricity supply from the microgrid cooperation. Then a situation like in the Tanzanian national grid supply might emerge, were companies state the electricity supply as the major constraint in businesses (World Bank, 2006, p. 4). Likewise, another situation might be considerable, were the actual supply from the microgrid is given, but no commercial activity will occur, due to a lack of finance for local enterprises or other exogenous factors from the codevelopment side.

In the long run, when demand rises, a barrier can be the microgrid management link to fulfil high demand coverage. Inadequate microgrid operation affects appreciation of the microgrid electricity service from local people. Especially, enterprises depending on electricity are reacting sensible to low demand coverage, where household demand might stay stable. Thus, the load factor influenced by the ratio between household and commercial consumers seems to be crucial for a satisfying electricity supply. When some economic development is taking place and commercial activity is emerging electrical demand in commercial and household appliances will increase. Thus, richer household will spend more on electrical devices activating balancing effects on the demand link. Nevertheless, market attractiveness will rise from a higher average income, since poverty of rural areas impedes foreign investments. Moreover, from a higher average income microgrid consumers are improving their solvency. This leads to higher revenues and increasing chances for cost recovery, when electricity bills are paid.

Improvements in the microgrid and control strategies for new productive loads are important to prevent the commercial demand loop from turning into the negative direction. Dissatisfaction with the electricity supply among enterprises can cause a falling share of commercial loads in the grid. In return that leads again to a low load factor and higher stresses on electrical system components. Then cost recovery problems threaten the success of a microgrid project. Because an inflow of money is missing and the average income level of village inhabitants stagnates. That threat in customer solvency leads to underfinancing, causing microgrid deterioration and failure in the longer run as seen in many electrification projects.

Finally, when a system is getting mature and a certain share of commercial load is sustainably supplied with electricity, prospects are promising for cost recovery in the microgrid cooperation. Then, for further development, external financing of major microgrid investments on extension or replacements can be considered. At this point, the population might grow due to a more attractive regional market and employment opportunities. In such a case the model should be reconsidered to take a growing public customer base into account.

7 Conclusions

The study presents a causal feedback structure for cost recovery in a rural microgrid. Some factors that increase chances for cost recovery are pointed out. It is described that, currently the electricity demand in an isolated microgrid is mostly characterized by an unfavourable evening peak introduced from households. But an appropriate microgrid system design should allow loads from commercial activity in the grid. Therefore, it is recommendable for an off-grid electricity provider to foresee some potential electrical loads from agricultural, grocery stores, food processing/preservation and crafts.

In the first decade of a microgrid project the system's long term resilience is dependent on the emergence of commercial loads. But upfront cost pressure in microgrid projects can result in an unfavourable system design for economic development from electrification. Therefore, a high utilisation of available microgrid capacity is essential. In that sense, income generating activities can have two favourable impacts. At first, they raise average income and consumer's solvency. Secondly, they can be used positively to increase the load factor in the gird. Emphasised is the possibility of DSM with productive loads, which can have positive effects on the demand profile and system utilization. Thus, without DSM of productive loads in the microgrid a high stress on the system is imposed and system utilization stays low.

Especially in the first years after microgrid implementation, the microgrid operation management is seen as important to develop consumer's trust in a newly introduced electricity supply. Hereby, satisfaction with the electrical supply is seen as crucial for an incorporation of electricity in a commercial activity. Still, an increasing income generating activity is also depending on access to knowledge and finance for local entrepreneurs. Moreover, customer's payment behaviour should be considered, which depends on involvement and ownership of the local community in a microgrid-village system.

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Appendix

A. Explanation of Causal Loop Diagrams

Two different types of links can be found in a CLD. There are links with a positive or a negative causal influence. Positive means that if the influencing variable increases or decreases the connected variable changes in the same direction. A positive link is marked with a “+“ in a CLD. Contrary a negative link descripts a reverse relationship; if the influencing variable increases the other variable decreases or vice versa. This causal influence is marked with a “–“ in a CLD (Pruyt, 2013, p. 37).

Causal links between variables form feedback loops in the system. A reinforcing or positive feedback loop is characterised with a self-enhancing behaviour. An initial increase or decrease of a variable X in a reinforcing feedback loop spurs causalities that feedback to a higher or lower value of the variable X. This leads to an exponentially rise or fall over time. A negative or balancing feedback loop has a goal-seeking behaviour. It stays with an oscillatory behaviour around a certain level. To determine the type of a feedback loop the number of links marked with a “–“ are counted. If the number of negative links is zero or even, than it is a reinforcing feedback loop. If the number is odd, than it is a balancing feedback loop.

Feedback loops in a system hardly ever exist in solitary, they are connected and have a relative strength among each other (Pruyt, 2013, p. 37). Problematic in the rural development is that some economic feedback mechanisms have a delay over years, before effects are taking place. These delays are important to consider in the relative strength of connected feedback loops. Delays are marked with crossing parallel lines on the connection arrows in the CLD.