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Micro-grids supplied by renewable energy

Improving technical and social feasibility

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Abstract

Universal access to electricity stands high on the global agenda and is regarded as essential for positive development in sectors such as health care, education, poverty reduction, food production and climate change. Decentralized, off-grid electrification is deemed an important complement to centralized grid extension. By utilizing a renewable energy source, solar technology for the generation of electricity, photovoltaics (PV) is being considered as a way forward to minimize the environmental problems related to energy use.

This thesis aims to contribute to improving the technical and social feasibility of PV and PV-diesel hybrid micro-grids for the purpose of providing access to electricity to people in rural areas of countries with low level access to electricity. In line with these general aims, the focus has been to address three questions related to challenges in three phases of rural electrification. The work has a multi-disciplinary approach, addressing mainly technical and social aspects of long-term sustainability of micro-grids, in a local context, and the changes these are intended to generate. One specific micro-grid in Tanzania has been used as a major case study.

The thesis is developed through three papers, all presenting methodologies or aspects for investigation in rural electrification projects and studies in general, and for PV-diesel hybrid micro-grids in particular. Paper I puts forward a methodology to facilitate non-social scientific researchers to take social aspects increasingly into consideration. Paper II is a guideline to support system users to increasingly apply an evaluation based system operation. Paper III specifically highlights the importance to consider blackouts when investigating how an existing off-grid PV-diesel hybrid system shall be utilized when a national grid becomes available.

List of Papers

This thesis is based on the following papers, which are referred to in the text by their Roman numerals.

Paper I — Bastholm, C., Henning, A. (2014) The use of three perspectives to make energy implementation studies more culturally informed. *Energy, Sustainability and Society, 4:3*

Paper II — Bastholm, C. (2015) A user guide to simple monitoring and sustainable operation of PV-diesel hybrid systems – Handbook aimed for systems users and operators. *Report IEA-PVPS T9-16: 2015*

Paper III — Bastholm, C., Fiedler, F. (2018) Techno-economic study of the impact of blackouts on the viability of connecting an off-grid PV-diesel hybrid system in Tanzania to the national power grid. *Energy Conversion and Management, 171: 647-658*

List of Papers not included in the thesis

Nielsen, C., Fiedler, F. (2012) Evaluation of a Micro PV-Diesel Hybrid System in Tanzania. *6th European Conference on PV-Hybrids and Mini-Grids, Chambery 2012*

Fiedler, F., Nielsen, C. (2012) Design study of a PV-diesel hybrid system for a micro-grid in Tanzania. *6th European Conference on PV-Hybrids and Mini-Grids, Chambery 2012*

Bastholm, C. (2013) Using locally available components and local knowledge to build sustainable stand-alone power systems. *3rd Symposium Small PV-Applications, Ulm 2013*

Henning, A., Bastholm, C. (2013) A 'Three-Step-Approach' to Energy Implementation–Examples from a PV hybrid grid in Tanzania. *Micro perspectives for decentralized energy supply, Berlin 2013*

Tjäder, J., Ackeby, S., Bastholm, C. (2016) The role and interaction of micro grids and centralized grids in developing modern power systems. *India Smart Grid Week, New Delhi 2016*

Ackeby, S., Tjäder, J., Bastholm, C. (2017) The role and interaction of micro grids and centralized grids in developing modern power systems. *Cigré 8th Southern Africa Regional Conference. Electricity Supply to Africa and Developing Economies: Challenges and Opportunities. Cape Town 2017*

Note: Bastholm was previously known as Nielsen.

Notes on author's contributions

Paper I — The basic elements of the Three-perspectives-approach, which is described in the paper, were originally suggested by Annette Henning as a way for Caroline Bastholm to carry out fieldwork and analyze data. Since then, it has been continuously developed through field tests by Caroline Bastholm and repeated discussions. The paper was co-written by Annette Henning and Caroline Bastholm.

Paper II — Caroline Bastholm has authored the majority of the guideline and conducted the main literature review. She has also conducted the majority of the field work, collected the data and been active in the data analysis. Corinna Fritz has had an active role in analyzing data, reviewing literature and in the early drafting of the guideline. Frank Fiedler originally suggested the development of an easy-to-use monitoring and evaluation guideline. He has been active in the set-up of data collection and has supported the work throughout the process.

Paper III — Caroline Bastholm has formulated the research question and methodology, conducted the majority of the simulations, and authored the majority of the paper all with support from Frank Fiedler. Ewa Wäckelgård and Xingxing Zhang have given valuable suggestions on the style and structure of the paper.

Abbreviations

COE	Cost of energy
IEA	International Energy Agency
IEC	International Electrotechnical Commission
NPC	Net Present Cost
PV	Photovoltaic
PVPS	Photovoltaic Power Systems Programme
SDG	Sustainable Development Goals
SIDA	Swedish International Development Cooperation Agency
UN	United Nations

Contents

1 Introduction

To “ensure access to affordable, reliable, sustainable and modern energy for all” is one of the 17 Sustainable Development Goals (SDG), shown in Figure 1, adopted by the United Nations (UN) and the world leaders [1]. Included in this SDG 7 is electricity, and access to electricity is regarded as essential for positive development in sectors such as health care, education, poverty reduction, food production and climate change [1-3].

Figure 1: The United Nations Sustainable Development Goals.
Source of graphics: www.un.org/sustainabledevelopment/

Electricity can be provided to areas not yet electrified either by the extension of an existing power grid, or by the construction of a local power system. A local, so called off-grid system, may power an individual household, a company or institution, a village, city or larger area. Utilizing a renewable energy source, solar technology for the generation of electricity is being considered as a way forward to minimize the environmental problems related to energy use caused by emissions. In the last decades, photovoltaics (PV) has gone through significant change and moved from being an expensive niche towards a widely used and economically competitive technology both for on- and off-grid electrification [4].

For off-grid electrification, a possible choice of technology is to combine PV and conventional generators to create a PV-diesel hybrid system. This type of system offers both the low operational costs of a PV system and the low investment cost of a diesel generator, and can thereby become cost efficient compared to a pure PV system or a pure diesel generator system [5]. By having the generator compensating for the intermittent nature of the sun, the system can also provide highly reliable power access.

Many off-grid PV systems and PV hybrid micro-grids have been installed worldwide at, for example, schools, hospitals, organizations, community centers and villages [6] ([7-13] provide examples). Most countries with low levels of electrification have electrification plans in which off-grid systems are promoted in parallel with the centralized extension of national grids [14]. Thanks to the combination of decreasing prices and increasing interest for PV, rapidly expanding economies in countries with low levels of electricity access, global focus on access to electricity, and strategic promotions of renewable energy and off-grid rural electrification, it is rather certain that substantially more off-grid PV and PV hybrid systems will be constructed in the coming years. In addition, as centralized extension of national grids is promoted parallel to decentralized solutions, situations where national grids and off-grid power systems are both present at a certain location are likely to occur at more and more places.

This thesis is based mainly on results from the project ‘Micro-grids supplied by renewable energy - improving technical and social feasibility’, conducted at Dalarna University from 2011 to 2018. The majority of the work was conducted between 2011 and 2014, and was funded by the Swedish International Development Cooperation Agency (SIDA). The ultimate aim of the project has been to support rural development in low income countries. By working to facilitate the use of small scale power systems using renewable energy sources in general, and PV-diesel hybrid micro-grids in particular, the project has aimed to contribute to increased electricity access. The project has applied methods from different scientific disciplines mainly technology studies and social anthropology, and to some extent economics. The work and the results presented in this thesis are strongly based on field work carried out as a part of this project.

1.1 Problem statement

Any electrification project is going through different phases from being an idea until it is eventually operating as part of an established infrastructure and potentially one day taken out of service. In this thesis, focus is set on three challenges related to three different phases of off-grid electrification:

Phase 1. Planning and implementation

Social, cultural, institutional and political aspects of rural electrification receive limited attention in research as well as in energy implementation projects [15-17]. This limits the possibilities to adjust projects to suit local requirements and interests. It is rather unlikely that a significantly increased number of electrification projects can and will prioritize a comprehensive social study prior to implementation. What is also important though are multi- and trans-disciplinary studies. The majority of professionals involved in electrification projects have a background in technology. With limited training, it poses a challenge to approach the large and complex topic of social and cultural aspects associated with technology implementation and to make use of related social scientific studies.

Phase 2. Operation and management

Operating a PV-diesel hybrid system requires a considerable amount of knowledge of PV and power systems in general as well as about the specific implemented system [18]. This is a challenge, especially for organizations with limited experience in power system operation and with limited financial and human resources to acquire and use advanced and expensive equipment and methods [19, 20]. A low cost and easy to use tool which offers guidance to monitoring and evaluation, as well as support on how to take action based on evaluation results, was identified as necessary in the research preceding this thesis. This type of tool is currently not available among existing tools and methods [21-23].

Phase 3. Future grid connection

In many of the electrification plans established in countries with low levels of electrification, details on how decentralized electrification shall be realized and on how decentralized and centralized systems shall interact are insufficient [14]. For off-grid power system owners and users, this results in uncertainty regarding whether and how an off-grid system can be used if the national power grid is extended to the site [24]. Scholarly works which explore the options of retro-fitting existing off-grid systems to become grid connected are rare. In many national grids in countries with low levels of electrification, blackouts are common occurrences [25]. Blackouts are however rarely considered in scientific publications investigating electrification possibilities.

1.2 Scope and thesis outline

This thesis aims to contribute to improving the technical and social feasibility of PV and PV hybrid micro-grids for the purpose of providing access to electricity to people in rural areas of countries with low levels of electricity access. In line with these general aims, the focus has been to address the following research questions:

Question 1. How can social aspects become better integrated into practice in rural electrification projects?

Question 2. How can operation and management of small PV-diesel hybrid systems become improved when financial and personal resources are limited?

Question 3. How can an existing off-grid PV-diesel hybrid system be utilized when the national grid becomes available arrives?

Three papers are presented in Chapter 4. Each one is connected to a particular phase and research question, visualized in Figure 2.

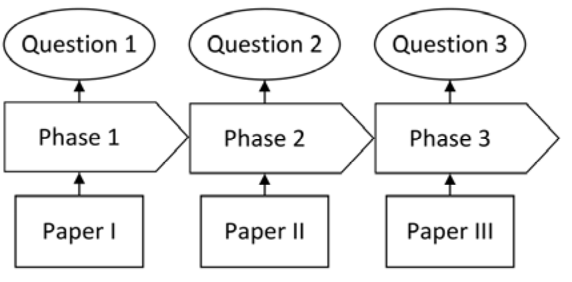

Figure 2: A schematic visualization of how the three papers contribute to address the three research questions regarding the three phases of electrification

Paper I mainly targets the planning and implementation phase with the focus being on facilitating multi-disciplinary investigations in electrification projects. By presenting the approach which has been used in the research preceding this thesis a methodology, which facilitates professionals with limited training in social sciences to take social aspects into consideration in electrification projects, is made available. The methodology is summarized and its application is exemplified in Section 4.1.

After planning, designing and installing a power system, it requires operation and maintenance in order to provide the intended service on a long term basis.

Paper II presents a set of guidelines for systems users and operators to facilitate simple monitoring and sustainable operation of PV-diesel hybrid systems. The guidelines are summarized and further discussed in Section 4.2.

Paper III presents a techno-economic case study of how an off-grid PV-diesel hybrid micro-grid in Tanzania can be utilized if a national grid becomes available. With special focus on the effect of blackouts in the national grid, the viability of different system configurations has been studied. The results of the study are summarized in Section 4.3.

2 Background

2.1 Development, Electricity and Electrification

Around 12 % of the world's population, hence just under one billion people, lack access to electricity [25]. Ten years ago, the number was nearly 20 %. In sub-Saharan Africa, though, population growth has outpaced the electrification rate and more people now live without electricity than twenty years ago [26]. Today, around 60 % of the population in sub-Saharan Africa lacks electricity access [25]. In rural areas, where about 60 % of the population live, the figure is 75 %. Roughly half of the people in the word without access to electricity are hence living in rural sub-Saharan Africa.

Access to energy is directly linked to poverty elimination, economic growth, food production, health, clean water, security, well-being, education, employment and gender equality [1, 2]. The UN states that "energy is central to nearly every major challenge and opportunity the world faces today" [3]; the energy sector accounts for over two thirds of the global greenhouse gas emissions [27]; and, an energy crisis has the potential to generate economic and political instabilities with significant social consequences [2]. As embedded in SDG 7, to "ensure access to affordable, reliable, sustainable and modern energy for all" is hence not only a matter of assuring universal access to energy, but also doing so in a wise way [1].

Electrification of not yet electrified areas of the world receives a lot of attention from global institutions; The UN, The World Bank, Sustainable Energy for All, Power Africa among others all work actively towards sustainable and increased electricity access [2, 14, 28, 29]. Most governments in sub-Saharan Africa have developed national electrification strategies, mostly containing two tracks to be implemented in parallel. [14]. On the centralized track, electrification occurs primarily by extension of the national grid and is undertaken by governmental entities. However, limited economic strength, low energy consumption levels and long distances to and between rural customers pose challenges to this strategy [30]. The decentralized track promotes construction of local off-grid systems, mostly implemented by non-governmental entities [14].

Several rural electrification programs using different technologies, financing methods and customer interaction strategies have been implemented and are ongoing worldwide. Many are successful and show that there is good potential for off-grid rural electrification initiatives and strategies [31]. Important aspects highlighted as necessary components for success include creation of effective institutional structures, political commitment, assurance of cost recovery, clear priorities in terms of geographical areas, involvement of local communities in all stages, commitment among relevant stakeholders, accessibility of necessary products and competences, and suitable customer connection and operational charges [30-36].

2.2 Related literature

Scientific studies of rural electrification and electricity access are relatively common. Comprehensive reviews of works addressing decentralized rural electrification are, for example, provided by Mandelli et al [11] and Chaurey and Kandpal [37]. Case studies of electrification strategies and off-grid system design are numerous ([38-43] provide examples). Investigations into whether to provide electricity to a location by applying centralized or decentralized solutions are also common [38, 44-48]. Operation and control optimization [49-51] and performance analysis of off-grid systems [52] as well as automatic control and energy management of larger off-grid systems [53, 54] are frequently appearing topics of research.

Recurringly, there are reports of off-grid power systems performing unsatisfactory [31]. Unfortunately, studies on energy and development in sub-Saharan Africa show that many rural electrification projects fail to result in the anticipated impact [36]. Unforeseen power cuts may have devastating immediate consequences if it happens in the middle of, for example, a surgery. Frequent cuts can also impair the reputation of a technology by demonstrating it as unreliable. Most failures in off-grid PV systems are related to battery damage [18]. The cause of these seemingly technical problems can most often be associated with a lack of organizational structures for system operation, energy management and maintenance [19, 20, 55]. Related literature is however dominated by technical and economic studies [15, 16]. Nevertheless, a growing body of work on social, cultural, political and institutional aspects of decentralized rural electrification provides important insights into why or why not electrification projects succeed to achieve their goals. Currently, there is a gap in the literature analyzing these aspects from a local perspective [36].

Sometimes, the term 'misused' is used to explain why a system is not functioning as intended. One could however also reverse the reasoning and use the term ‘misdesigned’. Load related uncertainties in the design phase are common and can result in over or undersized systems causing unnecessary costs, lower efficiencies, and unreliable power supply [19]. Sizing, optimization and feasibility studies of PV-diesel hybrid systems are common topics in scientific publications (examples in [12, 56-59]). Further, methodologies and software tools for system design and optimization are frequently discussed [60-68]. Online documents as well as books and compendia providing guidance on how to design and install PV systems and PV hybrid systems exist [5, 9, 69-73]. System sizing and design is however still a challenging task, as the future behavior of people using and operating a yet non-existing system can only be estimated. Similar to the previously mentioned works targeting operational challenges, most studies targeting the design phase are applying a rather technical approach with limited consideration of social aspects. Not only does a system designer need to have good knowledge about each component in the system and their mutual effect on each other, local knowledge and capacities at the site of implementation must also be regarded in all phases, and solutions often need to be tailor-made [12, 74].

To facilitate the consideration of social aspects in project implementation, several international organizations are using project management tools such as the ‘Logical Framework Approach’ (LFA) [75, 76], ‘User-Centered Design’ principles [77], the ‘Technology Assessment’ approach [78, 79] and the ‘Product Service System’ approach [80-82]. Among scientists and other investigators, the approach identifying ‘drivers-and-barriers’ is commonly used in studies of technology implementation [83-87]. This approach has been criticized, however, as it implies that identified barriers must be removed and behaviors must be altered, instead of encouraging a review of the project idea itself [88, 89]. Social scientists have directed criticism towards how technology implementations and transitions are commonly viewed as a one-way process, and that non-technical aspects are regarded as obstacles to technological progress and intended improvements [17, 90]. The predefined potentials for change which energy technologies are commonly assumed to carry with them have also been questioned and discussed [91-93].

Frameworks facilitating the consideration of social aspects in technical and multi-disciplinary research, as well as for transfer of knowledge between different disciplines, have been pointed out as desirable in order to bridge the gap between social and technical challenges [94, 95]. Despite challenges highlighted by scientists from different disciplines, and difficulties encountered in many rural electrification programs and projects, successful examples of rural electrification initiatives in various countries show great potential for challenges to be overcome [31].

2.3 PV hybrid system technology

Electrification can be achieved through extension of national grids, construction of local micro- and mini-grids or through small single-user systems. Using renewable energy sources available at the location, such as the sun, wind, or running water does not only avoid emission of environmentally unfriendly substances, it also prevents dependency on access to fuel [96]. A system relying on an intermittent resource, may, however, require extensive energy storage. In order to achieve high autonomy, the storage also needs to be somewhat oversized compared to the average power generation and load [97]. Combining more than one renewable energy technology implies less dependency on only one intermittent source [96]. Such hybrid systems can therefore achieve better reliability and become more financially viable than single-source systems.

Another option is to use fueled generators in combination with renewable energy [96]. Such systems have good potential to reduce investment costs significantly at the same time as running costs can be kept low. In addition, a high availability of electricity can be achieved [19]. It is common worldwide to supply electricity to remote locations by using autonomous diesel generators [12]. An important application of power system hybridization is thus to complement existing diesel based power systems with renewable energy [96]. This can extend the operation hours and also lower running costs and greenhouse gas emissions [98]. This thesis focuses on PV-diesel hybrid micro-grids.

Both the design and operational phases of PV-diesel hybrid systems are more challenging than those of single source systems [5]. Configured or operated in an inappropriate way, a PV-diesel hybrid system can be rather inefficient and carry unnecessary operation and maintenance costs. Since hybrid systems have at least two power sources, reduced performance of one source can easily be overlooked if the other supplies the load demand [99]. However, this can lead to increased costs and damage to system components.

As solar energy is an intermittent source, and a diesel generator is associated with high operational costs, it is often viable to include batteries in PV-diesel hybrid systems [5]. In this way, the use of power from the PV can be optimized in relation to the total power generation. Any PV or PV hybrid system also requires power management device(s). A charge controller regulates the power coming from the PV as well as the power going to the loads. It keeps the batteries from overcharging or over discharging. In order to supply AC loads, an inverter is needed which converts the DC power from the PV and batteries to AC. In PV-diesel hybrid systems, either a bi-directional inverter or a rectifier is used to convert AC power from the generator to DC for the purpose of charging the batteries. The functionality of hindering power from the generator entering the batteries when these are fully charged is also important. These power management functions (charge controller, inverter and rectifier) can be either different components, or combined in one device, as illustrated in Figure 3.

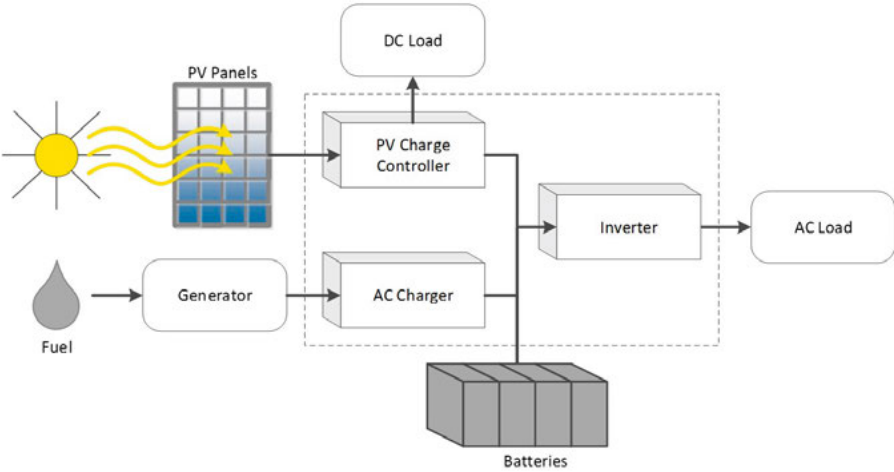

Figure 3: A schematic drawing of components included in a PV-diesel hybrid system

2.4 Micro-grids in a social context

This section will describe the social contexts of the focus areas within this thesis. The descriptions are based on the author's own observations as well as on discussions with other professionals with experience from similar contexts. It is not claimed to describe the social contexts in which all or most micro-grids are used, but rather to show some general aspects associated with the social contexts encountered and studied in this thesis.

Regardless of whether they are located at schools, hospitals or community centers, the small micro-grids encountered during the research preceding this thesis are typically used as support systems for other core businesses. They hence differ, not so much technically but from an organizational and economic point of view, from power systems used for village electrification. They differ by not having any customers paying directly for the electricity, and by not being administrated by a company or organization with the core objective to provide electricity. These power systems often exist because of a lack of reliable power from the national grid, and the locations are often rural. Common for many existing off-grid PV and PV hybrid systems is that the design and installation of the system has involved technical experts from outside. This may be an international donor supplying both experts and equipment, or a company from a nearby city. Frequently, the purchase and installation of the power system is financed by a governmental program, or international or local donors.

Once a power system is installed, the system owner or user is often responsible for its operation, maintenance, component replacements and adjustments. Even though an organization has competent members of staff to fulfil its core businesses, such as teachers, doctors, nurses, and support staff such as administrators, janitors, watchmen, and possibly a technician, it is rather rare that there is any PV system expert among the staff. To recruit an expert to handle the power system can often not be justified. Instead, the responsibility for the power system is appointed to one or a few already present staff members. Another similarity among encountered organizations is limited financial strength. Apart from having a strained financial situation in general, costs associated with the power system are general overhead costs which cannot be charged to anyone. Sometimes, costs appear as a surprise due to limited knowledge about a system's lifetime costs or early component failures resulting from unfavorable operation.

3 Methodology

The work presented in this thesis has a multi-disciplinary approach. It addresses mainly the technical and social aspects of long-term sustainability of micro-grids, as well as the changes these are intended to generate, from a local perspective. The research has focused specifically on one particular micro-grid in Tanzania. Field visits to Tanzania have played a major role in the identification of suitable tasks to be investigated, and also contributed significantly to the results. Field trips were conducted as follows: two weeks in 2011, four months in 2012, three weeks in 2013, and one month in 2015. In addition to the main case study, visits to other micro-grids, literature reviews and discussions with professionals in related areas have contributed to the overview and enabled generalization. The methods listed in Table 1 have been used and combined in the work preceding the respective papers.

Table 1: Methods used in the work preceding the included papers.

	Paper I	Paper II	Paper III
System monitoring and data acquisition and analysis		x	x
System modelling and computational simulations			x
Interviews	x	x	
Participant observation	x	x	

Paper I is a social scientific publication targeting professionals with a background in technology. Primarily the qualitative social scientific research methods interviewing and participant observation have been applied [100, 101]. The use of theories and analytical concepts from social anthropology, sociology, science and technology studies, and the history of technology are further described in Paper I [91, 102-104].

Paper II is a product based on system monitoring, data acquisition and analysis as well as results from applying the approach presented in Paper I. Participant observation and interviews were used with the purpose of gaining understanding in regards to current system operation and management, daily routines, level of knowledge about PV power system technology, experience of technical investigations, etc. [100, 101]. Monitored system data was analyzed to verify the level of useful system information which can be obtained from less frequent and extensive measurements [21].

In Paper III, monitored system data has been used to obtain accurate load profiles and system and component performance parameters for a model of the system in the major case study [21, 105]. The approach presented in Paper I as well as technical investigations on site have been used to identify parameters for further analysis in computational simulations.

3.1 Multi-disciplinary approach

The way technology is used, handled and perceived is influenced by individuals, situations and contexts in which they appear [88, 91-93, 106, 107]. As elaborated in Section 2.2, many problems associated with energy implementation projects are related to social aspects. Social scientists have addressed the importance of taking local context and knowledge of various social actors into consideration in all energy-related studies [108-112]. To increase the focus on social and cultural aspects, not only are an increased number of in-depth social scientific studies needed, multi-disciplinary research is also needed as well as better trans-disciplinary understanding [94, 95].

Researchers with multi-disciplinary profiles can contribute to decrease the gap between different scientific fields, and make energy related projects more culturally informed. This research has been carried out by a PhD student in engineering physics, taking on a multi-disciplinary approach with support from one supervisor in technology and one in social anthropology. The use of both technical and social scientific research methods, applied by the same person, has enabled the possibility to explore the mutual effect of social and technical aspects on each other.

3.2 Case study

Any case study aims to describe something in general terms by looking at something specific [101]. In the main case of the research presented in this thesis, this "specific" comprises energy related issues at one particular place. Using a case study methodology is suitable when the researcher is not only interested in what is happening, but also in why [100, 101]. It enables the researcher to gain insights which would probably have been difficult to gain if using a research strategy including a larger number of places or systems. It also allows the researcher to combine a wide range of qualitative and quantitative methods and thereby to apply a holistic approach.

The main case study used in the research preceding this theis was not selected or identified by the PhD student. It was a part of a collaboration between Dalarna University and the organization, which was already framed when the PhD student entered the project. Originally, the choice of partner was based on an already established contact and a common interest in the research topic.

The micro-grid used as the main case in this study is owned by a community based organization and is used at their community center near Mwanza in Tanzania. There, the organization runs vocational training in sewing, carpentry, masonry and welding; it has a pre-school; it hosts large meetings; it offers computer courses; and it offers typing and printing services. The organization also organizes outreach activities and projects such as women's groups, credit-saving groups, facilitation of collaboration between schools, and peer education programs dedicated to people infected by HIV/AIDS.

The micro-grid was built in 2008 in conjunction with the establishment of a carpentry workshop and the purchase of a generator to power workshop machines. Some already existing PV modules were complemented with additional PV modules, and the generator was used to form a hybrid system. The generator primarily serves the carpentry workshop, and supplies power to the hybrid system via a manual switch. A 12 V DC distribution system supplies lighting, and 230 V AC distribution is used to power the meeting hall and its TV, a small shop, a computer room, offices and classrooms. Figure 4 shows a schematic drawing of the system, including basic component specifications.

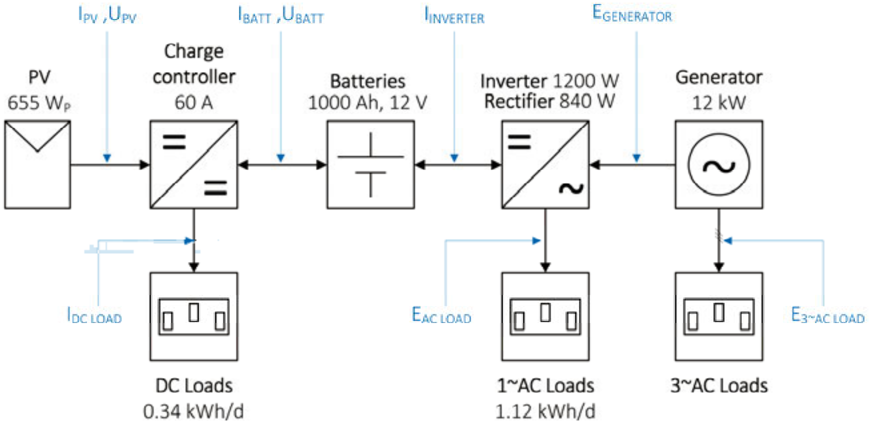

Figure 4: Schematic drawing of the system in the main case study, including basic component specifications and measurement points used for system monitoring.

While the research project was ongoing, the national power grid was extended to the location. The organization's management expressed interest in connecting to the national grid, but also to keep the existing system for reliability purposes. Further, it was considered by the management team as financially feasible to continue using the already existing system instead of purchasing all required electricity from the grid.

3.3 Methods

3.3.1 System monitoring and data acquisition and analysis

For the purpose of studying the technical performance of the power system in the main case study, it has been monitored following the IEC standard 61724 [21, 113]. The monitoring system was installed for research purposes in 2011 by researchers from Dalarna University [113]. Measurements are indicated in Figure 4. The energy measurements (E) were obtained using accumulative energy meters. The measurements of voltage (U) and current (I) were obtained by use of resistors and shunts selected to generate signals within ranges suitable for a Campbell data logger, in which hourly values of all parameters were stored. In addition to these measurements, an Inensus Aeolog monitoring system was used to monitor solar irradiation, wind speed and ambient temperature. Measurement accuracy and storage intervals followed the requirements of the IEC standard 61724. Detailed descriptions of the monitoring systems, installation and accuracy are given in [113].

In addition to the evaluation parameters proposed in the IEC standard 61724 aiming to evaluate system performance over time, detailed analysis of hourly measurements was conducted with the purpose of gaining understanding about daily, weekly and monthly electricity use, battery charge and discharge cycles, power generation, etc. Examples of such analysis can be found in [10].

3.3.2 System modelling and computational simulations

Modelling and simulation has been done in HOMER, Hybrid Optimization Model for Electric Renewables [105]. HOMER is a powerful simulation tool developed especially for techno-economic analysis of micro-grids and hybrid systems. The main intention with HOMER is to optimize on- and off-grid hybrid systems based on economic viability and power availability. Parameters describing the considered system configurations, component specifications, economic parameters, resource availability, energy demand and operational boundary conditions are specified by the user. System operation is simulated by energy balance calculations for each hour of one year. HOMER generates a list of design options with the lowest net present cost (NPC) and cost of energy (COE) for each considered system configuration.

HOMER has some limitations in terms of detailed technical modelling and is, in some respects, rather simplified compared to other simulation tools, such as PVsyst [114] and PolySun [115]. In HOMER, the efficiency of the power converter is, for example, always constant, and losses in PV modules related to operation cannot be modeled in very great detail. The simulations are carried out for one year only, and the results are used to calculate parameters presented as lifetime costs and performances. Despite this, HOMER has over 100,000 users worldwide, and is widely used for scientific studies [116]. As shown in [117], accurate technical modelling of the studied power system is possible when system and component parameters can be derived from measurements.

3.3.3 Interviews

Interviews of a semi-structured nature have been carried out [100, 101]. Open ended questions were posed by the researcher, and the subsequent questions and discussions were influenced by the answers given by the respondents. The interviews often included digressions from the planned questions resulting in new, unexpected information. All interviews were all carried out face to face during fieldwork. Some interviews were scheduled beforehand, and some occurred more spontaneously. Some interviews were conducted with groups of respondents and others with one person at the time. Most interviews were conducted during the second field trip after the researcher had already been present at the site of the main case study for a couple of months and had built a relationship to the respondents. The interviews focused on the use and non-use of existing energy services; potential energy services; changes in work tasks and routines due to the presence of electricity; altering roles, responsibilities and power relations as a result of the introduction of electricity; and perceptions and views on electricity and PV. In the interview situations, the researcher tried to trigger the memory of the respondents by associating energy use to a time axis, to social contexts and networks, to activities, and to different locations.

Respondents were selected in accordance with the method of how to identify relevant social actors described in Paper I. Paper I also describes in greater detail in its results and discussion section how respondents were identified and selected in this particular research project.

Interviews were mainly carried out in Swahili and to a lesser extent in English. The researcher is fluent in English, and speaks and understands 'everyday-

Swahili'. All informants were fluent in Swahili, and their knowledge of English varied between barely any to the ability to maintain a conversation without hinder. No interpreters were used. This choice limited the extent to which subtleties of the language were comprehended, and sometimes the conversations were interrupted by the interviewer asking for explanation for expressions or words. Using Swahili as the language of communication, without involving any interpreter, had the advantage that many of the interviews could occur spontaneously when suitable for the respondent. Further, the advantages of established personal relationships with the respondents were not limited by the presence of a third person.

3.3.4 Participant observation

Participant observation is a social scientific data collection method. It involves the researcher integrating into a culture, to distant oneself from it, to intellectualize what has been observed, to put it in a perspective, and to describe it [100]. In this research, the method has been used in combination with the other mentioned research methods. Behavioral patterns in relation to energy in general and electricity in particular; how people become affected, directly and indirectly, by the presence of the studied power system; and people's interaction with the technical system, were studied. Thanks to recurring visits and at one time lengthier fieldwork (4 months) the researcher could observe and interpret the everyday work routines at the center.

An important component of the participant observation has been the informal and every day conversations which have taken place, where answers to questions that the researcher had could be sought out without putting special focus on electricity and the research as such. These so-called unstructured interviews, in combination with the personal relationships which were built up during the course of the fieldwork, were crucial for the researcher's ability to become acquainted with the respondents' personal experiences related to energy and electricity. In addition, the possibility to observe how, by whom, when, etc different energy related activities occurred, as well as insights into work structures and routines have given valuable information. The language of communication during participant observation has been Swahili and to a minor extent English. These conversations hence carry similar limitations and advantages as the interviews.

4 Results

In this Chapter, the results from the three included papers are summarized and exemplified. Section 4.1 covers Paper I, Section 4.2 covers Paper II, and Section 4.3 covers Paper III.

4.1 Considering social aspects – Planning and Implementation

With the purpose of facilitating for researchers and technology implementers with limited experience in social scientific research to better take social aspects into consideration in electrification projects and studies, a senior researcher in social anthropology and the PhD student developed and proposed a methodology which was used by the PhD student in the research project preceding this thesis. The basic elements of the methodology were suggested by the senior researcher as a way for the PhD student to approach social scientific investigations in the multi-disciplinary research preceding this thesis. The methodology was then tested and adjusted based on the experiences during field studies, and resulted in the Three-perspectives-approach. The Three-perspectives-approach is found in Paper I and summarized in Section 4.1.1. Section 4.1.2 gives some examples of how the methodology has been and can be applied.

4.1.1 The Three-perspectives-approach

The suggested methodology primarily supports the investigation of social aspects in a local context. It facilitates analysis of how the social contexts influence the long-term sustainability of a power system, as well as the social changes that the power system (will) cause. These aspects play important roles in the process of determining if a project has what is needed to become sustainable long-term and fulfill the intended goals, or must be adjusted to better suit the local context. The approach is composed of three perspectives to be considered one by one: identification of social actors, focus on social change, and estimation of long-term sustainability.

The first of the three suggested perspectives is to identify social actors. A social actor can be an individual, organization, company or group of people. All actors affecting or being affected by the power system shall be considered. This may include users, operators, owners, related companies, policy and decision makers, local authorities, non-users in the vicinity of the technical system, and other actors working within the same field and areas. The concept *socio-technical system* and the concepts *energy service* and *energy carrier* are used to facilitate the process [91, 102, 118]. After a broad identification of social actors, patterns among the social actors are investigated: whether certain activities are done by young people, women, the wealthier, employees, etc. This social differentiation supports the assessment of which social actors are relevant to include in the study. To make the selection, the aim, the scope and the practical conditions of the study must be considered. The involvement or exclusion of actors from the investigation should be a conscious choice rather than the result of a poor investigation.

The second perspective is focusing on change which explores the everyday life and perceptions of the relevant social actors. How the power system contributes to changes in the society and in people's lives is investigated, and how important these changes are to people in relation to other things in life. The effects of introducing new services are regarded as well as how the society is affected when already established services are provided via new means. The goal is to understand the inside perspective of change, i.e. the view from inside the society and the relevant social actors. As an outsider, it is easily taken for granted that electrification is always sought after and automatically leads to desired improvements. What is important is that it is not primarily the changes observable from an outside perspective which influence the outcome of an electrification project but the way people subjected to the change perceive the changes.

The third perspective involves an investigation of potentials and risks for the long-term sustainability of an energy project. Based on the outcomes from the previous steps, conformities and possible gaps are sought between social actors who perceive that they benefit from a certain change, and social actors who are in power to have an impact in the particular context. It becomes important to understand what differentiations are expressing differences in power and what are the divisions of responsibilities. Examples of important aspects are whether the technology and the social actors who promote it are considered credible by other social actors, if social actors with long-term commitment are present, and whether there are actors with political and financial strength to accomplish the project. Other practical aspects crucial for long-term sustainability are that enough knowledge and interest among producers, suppliers and end-users are available and that there is a complete chain of coordinated companies and products to operate and maintain the power system.

4.1.2 Application of the Three-perspectives-approach

This section exemplifies how the Three-perspectives-approach has been used in the research preceding this thesis and by engineering students. It also illustrates a situation where application of the approach would be beneficial.

In the process of forming the guidelines presented in Paper II, results from the application of the Three-perspectives-approach have been used. Investigations of different power systems, particularly the main case study, showed that it is not only necessary for a user to have access to measurement data and parameters for evaluation. In addition, guidance on how to act based on the obtained information was found to be necessary in order for any adjustments in system operation to take place. Consequently, guidance to action was included in the proposed guideline. Furthermore, the level of knowledge about power system technology among relevant social actors has shaped the level of information and details in the guideline. The researcher's perception of roles among staff in the main case study as well as at other places visited as a part of the research has resulted in the conclusion that the use of the guideline shall not require any computer, and that the suggested routines shall be presented in such a way that measurements and evaluation can be done by different individuals.

The Three-perspectives-approach is used by master level engineering students as a part of their course work at Dalarna University as well as at the University of Twente in the Netherlands. At Dalarna University, solar engineering students perform an exercise where the methodology is used to analyze the social context of an energy system. The Three-perspectives-approach has also been applied by students carrying out research for their master thesis. For example, it has been used by one student in combination with energy measurements in order to identify the power consumption associated with different activities at a boarding school in Tanzania, and their influence on the learning environment as well as on the used off-grid PV-system [119]. The student could make suggestions that he perceived as positive for the learning environment without violating the long-term functionality of the power system. For example, he concluded that increased use of projectors would have significant positive impact on the students' learning environment, without overloading the power system.

The development of an off-grid power system is often a continuous process dependent on access to funding, different experts' choices and judgments, and altering needs as a result of the continuous development of an organization and its activities. This is the case at several locations visited as part of the research preceding this thesis, for example those described in [10, 119, 120] and the one shown in Figure 5. This can result in power systems which are not optimized from a technical point of view. It would however neither be possible nor financially viable to construct a power system covering all potential needs several years down the road. However, it would make financial sense to reuse already available system components when needs and conditions are altering. Balancing social, technical and economic aspects of electrification is important for any technology implementer, in order to design power systems which are feasible now as well as when conditions are altering in the future. The Three-perspectives-approach can, with advantage, be used to facilitate such investigations.

Figure 5: A picture visualizing the continuous development of the power system at a hospital in Tanzania.

4.2 Facilitating small scale – Operation and Management

In order to facilitate the entire chain of obtaining, understanding and using system information, 'A user guide to simple monitoring and sustainable operation of PV-diesel hybrid systems – Handbook aimed for systems users and operators' has been developed. The guide is found in Paper II, and covers guidance to *monitoring*, *evaluation* and *action* based on obtained parameters. It intends to support the user to make conscious decisions on power system operation. In order to be suitable for the specific context discussed in this thesis, the tool has been made *easy to use* by somebody with no prior experience in power system operation and evaluation, as well as obtainable at *low cost*. Section 4.2.1 contains a summary of the guidelines presented in Paper II, and Section 4.2.2 gives an example of the potential application of the guidelines.

4.2.1 The proposed guidelines

The guide is customized for small hybrid systems based on PV and fueled generators (denoted as PV-diesel hybrid systems, although any liquid fuel generator can be used). To use the guideline in full, generators should be manually operated, and the system should have a series type charge controller. If a shunt type controller is used, the guide can be used if the system has no DC load. The system must have lead acid batteries customized for PV applications, and should be located at low latitude.

The suggestions for *monitoring* contain daily measurements of battery voltage (assumed daily minimum voltage, V_{Batt}), daily generated energy from PV (E_{PV}) and generator(s) (E_{Gen}), and daily energy distributed to AC ($E_{Load\ AC}$) and DC ($E_{Load\ DC}$) loads. Measurements are taken at the same time every day, when the battery voltage as well as the load have their daily minimum levels and there is no generation in the system. This might occur in the early morning hours before the sun rises. The measurement points are shown in Figure 6.

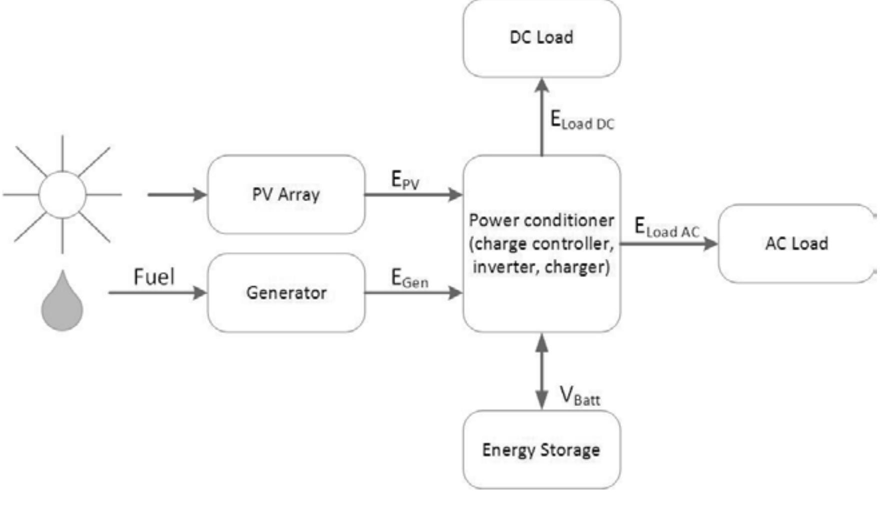

Figure 6: Measurement scheme in the proposed monitoring approach

The weather is noted with fuel logging (Fuel) being optional. For energy measurements, the use of accumulative energy meters is suggested. To measure battery voltage, an ordinary voltage meter or voltage measurement displayed on the charge controller or inverter can be used. It is recommended that the optional fuel measurements are carried out with automatic fuel logging, although manual logging of fuel fills is a possibility. As stated above, measurements are taken at the same time every day: when the battery charge level is at its presumed daily minimum, there is no generation and as little energy consumption as possible. The optional fuel measurement is taken monthly.

Losses in the distribution system are regarded as a part of the load. Losses in the charge controller and in the conversion process between DC and AC are regarded as system losses.

The *evaluation* routines require only pen and paper. They are based on easy calculations and pre-printed templates for tables and graphs. The short-term evaluation is intended to be carried out daily. It uses mainly the assumed daily minimum battery voltage (V_{Batt}), energy consumption (Total Daily E_{Load}) and generation (Total Daily $E_{Generated}$) over the last 24 hours. The table used to log measured and calculated values is shown in **Fel! Hittar inte referenskälla.**. Graphs showing how the major evaluation parameters are to be plotted in templates are found in **Fel! Hittar inte referenskälla.**. Strong focus is set on the internal relation between these three parameters. The PV energy contribution in relation to the total generation (Share of PV) and the weather conditions are used to understand where the generated energy comes from.

Template 1: Table for measured data and calculations for short term evaluation

Day	Time [hh:mm]	V_{Batt} [V]	E_{PV} [kWh]	Daily E_{PV} [kWh/day]	E_{Gen} [kWh]	Daily E_{Gen} [kWh/day]	Total Daily $E_{Generated}$ [kWh/day]	E_{LoadAC} [kWh]	Daily E_{LoadAC} [kWh/day]	E_{LoadDC} [kWh]	Daily E_{LoadDC} [kWh/day]	Total Daily E_{Load} [kWh/day]	Share of PV [%]	Logbook	Sign
1															
2															
3															
4															
5															
6															
7															
8															
9															

Figure 7: The template used to log measured and calculated values

Long-term evaluation is carried out monthly and yearly, and several months and eventually years are compared. It uses monthly averages of the same parameters as the short-term evaluation, as well as normalized PV yield, system losses and fuel consumption. Share of PV can, beyond identifying where the energy comes from, be compared to the system's design value in order to understand if the system is used as intended or not. The normalized PV yield helps to identify possible faults in the PV array. In the system losses, the user can look for variations in losses, enabling understanding of favorable system use. The two parameters System Losses and Share of PV can also be used to compare the evaluated power system with other power systems. Generator Fuel Consumption is used to investigate generator performance, and can be used to compare different generators. System Fuel Consumption is mainly used for comparison of system operation from month to month.

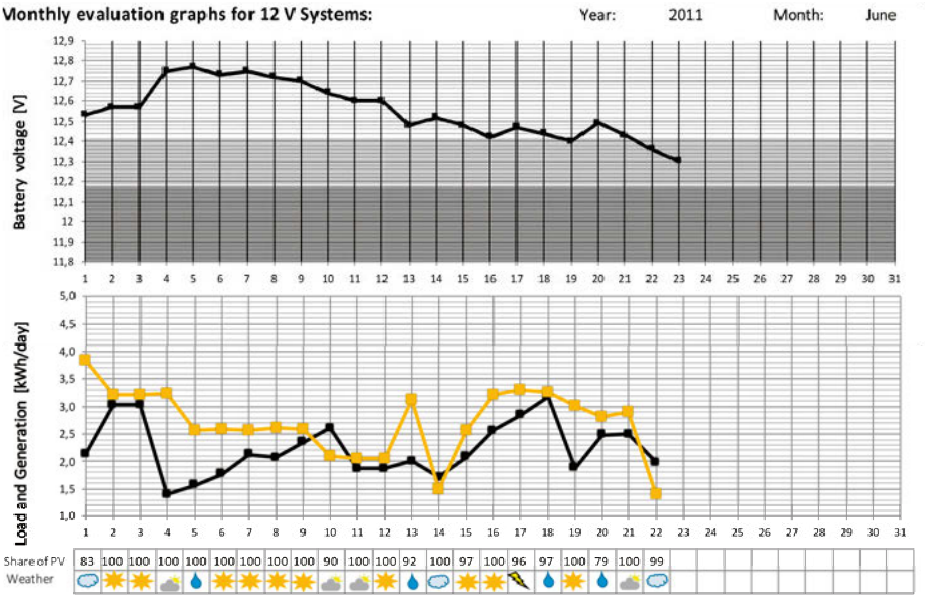

Figure 8: Example of a filled in graph template for short-term evaluation.

After entering the measured and calculated values into the templates and graphs, the guideline proposes further *actions* based on what is seen in the graphs. Among different scenarios, the user would pick the description best fitting to what he or she sees, and find appropriate suggestions for further investigations and/or adjustments in system operation. When carried out daily, the short-term evaluation gives direct feedback on system status and operation to the user. This facilitates early detection of unsustainable operation and faults in the system, and enables immediate action. The long-term evaluation uses a similar structure as the daily, but it aims to discover slow changes in system performance. It clarifies further the different parameters' mutual effect on each other, and allows the user to adjust operation based on factors and changes visible over time.

4.2.2 Potential use of the guideline

In this section, experiences from fieldwork conducted as a part of the research preceding this thesis are used to illustrate how the suggested guidelines can contribute to increased sustainability of PV hybrid systems.

A PV-diesel hybrid system visited as part of the research project was malfunctioning due to battery failure. This is unfortunately not uncommon [18]. The system, located at a hospital, was supplying power to computers in an administration block, among other things. At the time of the visit, the computers were only operational at times with sunshine or generator operation, due to the batteries' very limited energy storage capacity. According to the hospital management, the power system had initially been functioning well. Earlier than expected from normal degradation, the supply of electricity was more and more frequently automatically shut down. The technician had identified the shutdowns to be due to low battery state of charge, and could determine that the batteries had become permanently damaged.

In this case, the proposed guidelines could have helped the technician to identify early on the systematic system overload which is believed to be the cause for the rapid battery degradation. The guidelines would not only have made the technician aware of the unsustainable relation between load and generation, but would also have provided suggestions on how to proceed in order to improve the operation and thereby avoid component failure. After excluding technical malfunction in the system, the technician would have been advised to either adjust the generator operation to meet the power and energy needs, or to investigate the opportunities to adjust the load. The technician could hence, for example, have engaged the management and the administrative staff in a discussion on possibilities to adjust the use of computers (which was a major load on the system) to better conform to the power generation.

4.3 Grid connection of an off-grid system – A future scenario

This section contains the results from an investigation of whether and how the particular PV-diesel hybrid micro-grid which is the main focus of this research can be connected to the national grid in Tanzania. A major objective has been to investigate the effects of blackouts on the costs associated with different system configurations, and to compare these costs to the effect of other factors. The study is summarized in Section 4.3.1 and 4.3.2 and is further elaborated in Paper III.

4.3.1 System modelling and configuration alternatives

The simulation software HOMER has been used to model the PV-diesel hybrid system [105]. System related information and input values have been determined based on measurements and observations during field trips, and selected to represent the particular power system as well as possible [117]. With the intention of finding the best way of utilizing the existing power system in part or fully, the following system configurations have been evaluated:

- to continue to use the off-grid micro-grid
- to convert the off-grid system to an on-grid system with batteries
- to convert the off-grid system to an on-grid system without batteries
- to only use the national grid

In order to study and compare the impact of different parameters, the load, the generator size and the extent to which blackouts occur in the national grid were varied. In addition, a sensitivity analysis of battery price, diesel price, grid tariffs and sales of excess electricity has been done. The cost of energy (COE) was used as the main parameter for the evaluation of financial viability.

4.3.2 Techno-economic analysis

Without blackouts, the simulations show that there is little benefit in maintaining the existing micro-grid despite the fact that the existing power system does not carry any investment costs. The operation and replacement costs associated with the particular PV-diesel hybrid system were shown to exceed the connection and operational fees of using the grid.

When taking blackouts into consideration, using only the national grid is not an option unless interruptions in the power supply can be accepted. Depending primarily on the system load and the extent of blackouts, different system solutions were shown to be the most cost effective. **Fel! Hittar inte referenskälla.** shows which of the evaluated system configurations were found to be the most financially beneficial for different combinations of load levels and hours of blackouts.

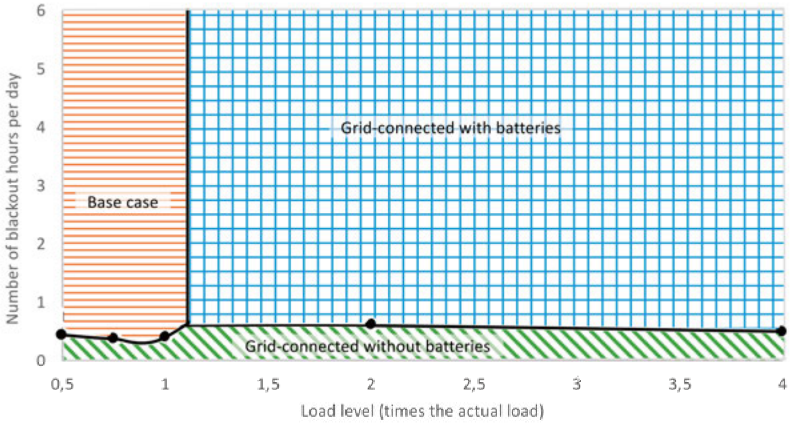

Figure 9: Colored fields indicating the most economically viable system configuration at each simulated combination of load level and number of blackout hours. Base case refers to the existing off-grid system.

If blackouts occurred for less than around 0.5 hours per day, the simulations showed that the most financially beneficial system configuration was to connect the particular PV-diesel hybrid system to the grid without using any batteries. At times of blackouts, the generator would be operated to supply power. In situations with blackouts occurring for more than around 0.5 hours per day and with loads lower than or around the actual load, the most financially beneficial solution was to continue to use the PV hybrid system as an off-grid system. At higher loads and more hours of blackouts, grid connecting the PV-diesel hybrid system with batteries was shown to be the most cost efficient.

The particular power system has a very oversized generator, affecting the system operation costs significantly at times of generator operation. Using a more appropriately sized diesel generator would improve the feasibility of connecting the PV-diesel hybrid system to the grid without using any batteries for an extended number of blackout hours per day. Other factors which were investigated but were shown to affect the total power system economy to a limited extent in relation to load, extent of blackouts and generator size were diesel price, battery price and the possibility to sell excess energy to the grid.

5 Discussion

This thesis aims to contribute to improving technical and social feasibility of PV and PV hybrid micro-grids for the purpose of providing access to electricity to people in rural areas of countries with low levels of electricity access. This broad and general aim can be addressed in several ways. As elaborated in Section 2.2 and Section 3.1, the majority of related scientific studies focus on issues of rather technical nature, though social scientific studies are increasingly available as well as multi-disciplinary ones. In addition, a range of reports, particularly from international organizations, discuss technology implementation, electrification, and construction and operation as well as financing and policy issues related to PV and PV hybrid systems. Throughout the research preceding this thesis, special attention has been given to the interaction between social and technical aspects of technology and electrification. The way technical systems influence social systems, situations, power relations, activities, etc has been investigated. How the functionality of a technical system and its ability to support the intended development and change is affected by the social context has also been studied. Focus has been set on three different questions in three different phases of electrification.

The first research question, "*How can social aspects become better integrated into practice in rural electrification projects?*" has primarily been addressed in connection to the planning and implementation phase. One answer to that question is to increase the extent to which scholars and project implementers with a technical background regard social aspects in electrification studies and implementation projects. This thesis is contributing to that by making available the Three-perspectives-approach presented in Paper I. The presented methodology has been used in the research preceding this thesis, and it is presented for others to use.

The Three-perspectives-approach carries with it several advantages. It is flexible, and can thereby be used in limited as well as in more extensive investigations. Within this research, it has been used in the main case study, comprising a study over several years with multiple field visits. It has also been applied during visits to other power systems which only have lasted a few days. The approach can be applied in a rather broad sense, or to investigate something rather specific. In this case, it has been used for investigations on a very local scale. Though it has not been a part of this study, national political interests, institutional requirements, global aid related aspects and economic incentives and financing methods are topics which deserve increased attention [36] and the Three-perspectives-approach could be used for such investigations.

The Three-perspectives-approach is not a substitute for in-depth social scientific studies. It should be regarded as a way to facilitate multi-disciplinary investigations complementing these. It can also be used to facilitate communication between researchers from different disciplines, by providing a common way of using terminology and presenting results from different fields of research. An important application of the suggested methodology is to give a technology implementer a tool which facilitates increased understanding of local conditions, and of what complementary competences are necessary. For example, knowledge about local power structures and hierarchies related to the use of an introduced technology and its services may result in adjustments in project administration, local involvement and decision-making processes. The ability to estimate the consequences in a society of introducing a technology increases the possibility of shaping a project so that it successfully contributes to fulfill overall aims which may be to improve study results, support gender quality, or reduce child mortality, as examples.

As a response to the second research question "*How can operation and management of small PV-diesel hybrid systems become improved when financial and personal resources are limited?*" a guide is proposed in Paper II. The guide offers support to *monitor*, *evaluate* as well as taking *action* based on the outcomes of the evaluation, and suggests a methodology which is *easy to use* and implementable at *low cost*. The identification of criteria as well as the resulting guidelines are based on results from using the Three-perspectives-approach presented in Paper I, together with measurements and evaluation of measurement data.

The originality in the proposed guide is that it offers early detection of changes in PV-diesel hybrid system operation and performance, direct feedback to the user, as well as guidance on how to take actions based on gained information. This is all obtainable at low cost and is easy to use without experience from similar tasks. Obviously, different tools, guides, methods and equipment are suitable for different contexts and purposes. Among the guides and tools already available and applicable to PV-diesel hybrid systems, none has been found which fulfills all the identified criteria. Most tools instead offer much more detailed evaluation and information than the suggested guide, for example the IEC 61724 standard [21] and the 'Guidelines for Monitoring Stand-Alone Photovoltaic Power Systems, Methodology and Equipment', developed by IEA PVPS Task 3 [22]. The level of gained information is however also reflected in the required data acquisition equipment and the amount of data to analyze. Equipment for sophisticated data collection can be a financial challenge for owners and users of small systems. To retrieve and analyze extensive amounts of data is another challenge, especially for a person with limited experience of similar tasks. Products developed specifically for system monitoring, and equipment offering automatic energy management carry with them similar challenges.

The simplicity in an approach for power system performance evaluation proposed by Swingler [23] has been a great source of inspiration to the proposed guide. The two methods have many similarities and can easily be combined. The major difference between the two is that the guide proposed in Paper II offers instant feedback to the system user whereas Swingler's approach supports more periodical evaluation, such as yearly.

Though simplicity is one of the major advantages of the guide, it is also one of its major challenges. The way the assumed daily minimum battery voltage is obtained carries with it significant uncertainty, on which the major evaluation is then based. The way data collection is proposed makes the guide sensitive to human factors. If applied as intended though, the guide offers a way to carry out comparative analysis for each particular power system, despite the fact that measured values might have significant uncertainty and that comparison to other power systems thereby is of limited value. In the process of defining the content of the guide it was concluded that a simple and indicative evaluation is better than no evaluation. In most situations where the guide would presumably be used, no evaluation is the current alternative. In situations where a more extensive data collection and evaluation procedure is or can be used, the guide can act as a complement in order to facilitate evaluation based power system operation.

The guide has been introduced at a few locations using off-grid PV-diesel hybrid systems, including the main case study and the hospital presented in the example in Section 4.2.2. Unfortunately though, the use of the guide has not yet been evaluated. It hence remains to investigate whether the guide is perceived by its users as applicable and useful, and to what extent it leads to changes in power system operation.

The third research question, "*How can an existing off-grid PV-diesel hybrid system be utilized when the national grid becomes available?*" has been addressed in the simulation study presented in Paper III. The study is rather unique by providing a case study of alternatives of how to retrofit an existing off-grid power system to a central grid. The study shows clearly that an important aspect to consider, which has been disregarded in nearly all related studies, is the extent to which blackouts occur in the national grid. Depending on the extent of blackout hours, different system configurations are feasible.

An unexpected result from the study was that if the grid was not subjected to any blackouts, the financial viability of only using the national grid and to connect the existing off-grid power system to the grid without using any batteries resulted in similar financial savings. One could have expected it to be financially beneficial to utilize the possibility to generate electricity from the existing (and paid-off) PV panels, and thereby reduce the amount of electricity from the grid. The simulations however show that these savings were in this particular case compensated by replacement costs for inverter and charge controller.

As can be concluded from the variation of parameters and the sensitivity analysis in this simulation study, it is not possible to draw any general conclusions regarding how to connect an existing PV hybrid system to a national grid. Each power system and situation is unique, and must be investigated and simulated in order to find the most optimum solution. The study however shows how such an investigation can be carried out, and it clearly points to the importance of including the extent of blackouts in the investigation.

It should be noted that the results in Paper III are presented from the perspectives of a power system owner. In the definition of costs associated with the grid, significant subsidies on grid connections apply in Tanzania. Potential subsidies for other technologies affecting the market price for grid electricity have not been taken into consideration. From a national economic perspective, PV may be a more financially viable than this study indicates, in a similar way as concluded in [121].

The particular case has been used in different ways in all the included papers, which has enabled investigations of three different aspects in one context. Despite being a product of a case study, the results in Paper I and Paper II are generalizable methodologies, which can be applied to other cases and studies as well. Paper III shows the importance of including certain parameters in electrification studies, which could, and should according to the results, be regarded in any similar study. All three included papers contribute to fill knowledge gaps in their own, rather diverse, ways. This is elaborated more in the respective papers and earlier in this thesis. Yet, they all contribute to the overall aim of this thesis: to contribute to improved technical and social feasibility of PV and PV hybrid micro-grids for the purpose of providing access to electricity to people in rural areas of countries with low levels of electricity access.

The general aim of this thesis as well as its context is obviously much broader than the main case study and the three included papers. The included studies all focus on very local perspectives of rural electrification; a focus where there is a significant gap [15, 36]. As mentioned earlier, interesting aspects which also deserve attention, and have not been covered in this work, include political interests, national regulations, institutional requirements, economic structures, structural formats for different actors to participate and collaborate easily. This thesis has taken a local and multi-disciplinary shape extensively due to the researcher´s personal interest in technology in the local context. Successful collaboration with the Tanzanian partner and a multi-disciplinary environment at Dalarna University has enabled fruitful field studies and good possibilities to shape the study in line with these interests.

5.1 Ethical and methodological reflections

The overall aim of this research project has not only been to study and evaluate technical and social feasibilities of micro-grids, but also to work to improve them. Within social scientific research, a general opinion is that one should not intervene nor try to change what one is studying [100]. In the definition of the overall project aim there is hence an embedded potential conflict of interest. Not only are these double interests an issue for the research as such, but also in respect to the collaboration partner who has agreed to participate in the research project with the expectation to benefit from the expertise and to improve their access to electricity. Although it would on some occasions have been beneficial for the research not to report identified issues, the researcher has throughout the study chosen to take an active role in pointing out aspects to improve the feasibility of the micro-grid.

In all the studies, the presence of a person studying a specific topic contributes to emphasize that topic, and hence alters people's perception of it [100, 101]. This is however often less reflected upon in technology implementation projects than in social scientific studies. Investigations and related technical system improvements can certainly have a positive effect on the long-term feasibility and sustainability of a power system. The presence of a technical expert may however also alter established responsibilities and roles and may affect the sense of local ownership associated with the power system [101]. This in turn can have negative effects. In order to minimize the risk of affecting the social context negatively in this project, the researcher has taken on a rather theoretical role and has given suggestions for improvements in matters concerning the micro-grid, but left all decisions and practical work to the partner organization and their appointed electrician. Decisions and practical work related to the data collection system have been the researcher's responsibility. Despite clear divisions, a data collection system and a person working practically adjacent to the power system may pose a risk for the power system owner/user. Throughout the project, the researcher and Dalarna University has strived to minimize the risks for the partner organization, and covered all costs incurred as a result of the project.

As with any other skill, carrying out research successfully is a matter of training. The researcher in this study has a background in technology and limited previous experience in social scientific studies. Any studied situation is seen through the lens of the observer and is influenced by his or her culture, personality and prior experiences [100, 101]. It is a matter of training and experience to understand how one's own personal views and actions can affect a study. In order to understand how the researcher has influenced the outcomes of the study, a reflection upon the person and personality behind the researcher is necessary.

In order to gain knowledge about the insiders' perspective of a situation, it is necessary to be close enough to people to make them feel comfortable with one's presence. This is partly a matter of how well people enjoy each other's company on a personal level. However, the personal identity of the researcher also has a large impact on which domains that researcher can gain access to [101]. In this case, the researcher is a woman in her thirties, not native to the place of the research. Being non-native to the area has resulted in a seemingly large acceptance among people for the researcher to take on tasks and habits outside the traditional gender roles. Examples include to climb roofs to inspect solar panels, to wear trousers, to socialize in a bar, to drive a car, to do carpentry work, etc. At the same time, the researcher has been accepted in traditional female domains, which has created opportunities for conversations and relationships which would presumably not have been possible for a man regardless of origin. Young people have tended to show less formal respect to the researcher, and men and elderly have tended to treat her more like one among themselves than local people of the same age and gender. The researcher has also perceived it as easier to socialize with people from different social classes than what seems to be the case for people already having a more defined place in the social structure. At the same time as being an advantage to have access to different social groups, these personal characteristics also limit the possibilities to immerse completely into any one of them.

To speak about topics which are of interest to the recipient is an appreciated human trait, and a researcher typically has interest in a specific topic. The respondent's interpretation of the researcher's interests in combination with her or his (intentional or unintentional) wish to communicate what she or he thinks the researcher wants to hear is another factor influencing the information that a researcher has access to [100, 101]. In this study, for example, the researcher has interpreted some descriptions of maintenance procedures associated with the micro-grid in the major case study as corresponding more to the respondents' understanding of proper maintenance than to actual practices. A respondent might exclude or include certain information depending on how associated personal advantages and risks are estimated. On some occasions in this study, for example, respondents tended to (over)emphasize the importance of electricity and PV - something that the researcher interpreted as a way to seize the possibility of accessing a PV system via the researcher. This is not to be confused with respondents lying, but influences the information which the researcher has access to and reaffirms that received information is filtered through the lens of the researcher. In this multi-disciplinary study, the rendered focus on the studied topic has potentially been more significant than in a purely social scientific study. This may have implied that the researcher received the impression that the topic of research is more important to people than it actually is, compared to other things in life.

Although the research does not contain any information which is regarded as sensitive, concern has been taken on the level of information about respondents necessary for each specific context. To carry out participant observation and to become close to people for research purposes poses an ethical dilemma. Respondents may express things that they possibly would not tell a researcher, as they perceive the researcher more as a friend. For sensitivity reasons, interesting information has sometimes been excluded from publications. When of particular value to the context, special efforts have been made to present information in a way which does not place a possibly identifiable respondent in a bad light or in a difficult situation. At times, the respondents have emphasized that certain things "should be written in the report". They have been keen to share their opinion, and want their opinion spread. In such cases, the same careful consideration of the necessary level of information about the respondent has been taken.

The applied multi-disciplinary approach has posed some challenges, and has limited the possibility to dive deep into technical or social research questions. It has however provided an opportunity to combine methods and insights from different disciplines and to discover aspects which would have remained hidden between fields in a non-multi-disciplinary study. Being an engineer giving attention to social aspects within a field which is primarily regarded as technological has highlighted ways of viewing socio-technical systems through the eyes of an engineer. It has also facilitated better trans-disciplinary understanding between the fields of technology and social sciences.

6 Conclusion

This thesis contributes to a more holistic view of technology implementation, beyond the traditional scientific fields. It explores the mutual effects of technical and social aspects, while not forgetting the economic and financial implications. A general conclusion from the research preceding this thesis is that each case of rural electrification is unique. What can be generalized, however, are the used methods and the investigation parameters. This thesis is centered around three papers, all presenting methodologies or investigation aspects in rural electrification projects and studies in general, and for PV-diesel hybrid micro-grids in particular. Each part of the thesis, each in its own way, thereby carries with it potential to contribute to increased feasibility of PV and PV hybrid micro-grids and increased electricity access on a global level.

The research presented in this thesis has made clear that technical and social aspects of off-grid electrification projects and studies are not and cannot be regarded and treated as separate issues. In order to achieve successful and long-term impact, these aspects must be regarded together. This is valid for all stages of any off-grid electrification project, from the initial idea stage until a system is eventually decommissioned. For successful implementation other aspects such as legal matters, political interests and economic incentives also need to be considered. These topics are outside the scope of this thesis, but deserve attention and would complement this thesis in a valuable way.

7 Acknowledgements

This thesis has been made possible thanks to support from a number of people. I would like to express my gratitude towards my supervisors Annette Henning, Frank Fiedler and Ewa Wäckelgård for guiding me through this work, for encouraging me to try and implement ideas that I have had, and for the flexibility you have given me. I also wish to thank my other colleagues at the research profile Energy, Forest and Built Environments at Dalarna University for valuable comments on my work and fruitful discussions.

Special thanks goes to everybody who has contributed to my research during my field trips in Tanzania. Without you, who let me explore your world, patiently responded to my questions, and trusted me to fiddle with your power systems, this thesis would not exist. I also wish to thank those of you who have welcomed me to your homes, hosted me, been my friends and made my times in Tanzania memorable and full of joy.

To the International Energy Agency Photovoltaic Power Systems Programme (IEA PVPS) and the members of IEA PVPS Task 9, thanks for sharing your extensive knowledge and interesting experiences with me, and for support in the process of writing and publishing the guideline. Thank you Corinna Fritz for your work towards the guideline. Thanks to Engineers Without Borders Sweden for providing a place where I can implement things I have learnt during this research, and for the valuable knowledge and experience I have gained. Thanks to the master students in solar energy engineering who I had the privilege to supervise for interesting discussions and for contributions to my work. Thanks to SIDA for funding the majority of my work, and the Anna Maria Lundin stipendium fund for travel grants.

To colleagues both in Borlänge and Falun, thank you for enjoyable lunches and coffee breaks and for being a part of my every-day life. To my family and friends, thank you for believing in me. Last but definitely not least, I want to thank my husband David Bastholm. Thank you for moving with me to Dalarna, for following me to Tanzania, for bringing perspective to my troubles that I am too narrow-minded to see, and for supporting me in the choices I make. David, Kerstin and Ingrid, thank you for being the best parts of my life.

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