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Sustainable energy solutions

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Electrification of rural Mozambique

Sustainable energy solutions

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FACULTY OF ENGINEERING | LUND UNIVERSITY

Electrification of rural Mozambique

Sustainable energy solutions

Miguel Meque Uamusse

LUND UNIVERSITY

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Abstract

The UN Sustainable Development Goal (SDG) 7 states that access to affordable, reliable, sustainable, and modern energy should be provided for all by 2030. The effects on socioeconomic development by access to safe, affordable, and clean electricity stands out as educational benefits, income improvement, and health progress. However, the electrification rate has been slow for sub-Saharan Africa and Mozambique. Mozambique is one of the poorest countries on earth but has abundant supply of energy resources. The reason for the slow progress in rural electrification is not clear. Possible causes may be lack of basic infrastructure, institutional barriers, and low ability and willingness to pay for energy services. Consequently, there is a general gap between electricity supply and demand. In view of this, the thesis investigates ways to supply sustainable electricity to rural Mozambique. A possibility is to use mini-grid systems connected to small hydropower plants. Other possibilities are photovoltaic systems, and combustion of agricultural waste (such as gasification of cashew nut shells). A reason to use agricultural waste is that a large part of the population, and some 90% of the households, still use this as the main energy source for cooking and heating. It appears that the most promising energy sources at present for rural Mozambique are renewables such as solar power and small-scale hydropower. The solar power used at present is very small. However, there are strong incentives and good opportunities to increase the solar power in remote rural areas. Small-scale hydropower is also a good alternative for off-grid or mini-grid solutions. This study investigates the sustainability of different types of energy sources. This is especially important for solar power systems in view of the use of batteries, heavy metals, and accessibility for theft. Results show that legislation needs to be adapted to the suggested sustainable energy sources. There is a need for better institutional coordination and electrical mini-grids' regulation. One of the conclusions is that there is an urgent need of taking adequate account of climate change since this will affect both existing and future hydropower projects in Mozambique. There is thus a risk for the future hydropower potential especially small-scale hydropower since these often operate with small or no storage.

Key words: Renewable energy, hydropower potential, rural electrification, mini-grid, biomass, climate change effects

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Abstract

The UN Sustainable Development Goal (SDG) 7 states that access to affordable, reliable, sustainable, and modern energy should be provided for all by 2030. The effects on socioeconomic development by access to safe, affordable, and clean electricity stands out as educational benefits, income improvement, and health progress. However, the electrification rate has been slow for sub-Saharan Africa and Mozambique. Mozambique is one of the poorest countries on earth but has abundant supply of energy resources. The reason for the slow progress in rural electrification is not clear. Possible causes may be lack of basic infrastructure, institutional barriers, and low ability and willingness to pay for energy services. Consequently, there is a general gap between electricity supply and demand. In view of this, the thesis investigates ways to supply sustainable electricity to rural Mozambique. A possibility is to use mini-grid systems connected to small hydropower plants. Other possibilities are photovoltaic systems, and combustion of agricultural waste (such as gasification of cashew nut shells). A reason to use agricultural waste is that a large part of the population, and some 90% of the households, still use this as the main energy source for cooking and heating. It appears that the most promising energy sources at present for rural Mozambique are renewables such as solar power and small-scale hydropower. The solar power used at present is very small. However, there are strong incentives and good opportunities to increase the solar power in remote rural areas. Small-scale hydropower is also a good alternative for off-grid or mini-grid solutions. This study investigates the sustainability of different types of energy sources. This is especially important for solar power systems in view of the use of batteries, heavy metals, and accessibility for theft. Results show that legislation needs to be adapted to the suggested sustainable energy sources. There is a need for better institutional coordination and electrical mini-grids' regulation. One of the conclusions is that there is an urgent need of taking adequate account of climate change since this will affect both existing and future hydropower projects in Mozambique. There is thus a risk for the future hydropower potential especially small-scale hydropower systems since these often operate with small or no storage.

Keywords: rural electrification, renewable energy, min-grid hydropower, biomass gasification, climate change effects, Mozambique.

Papers

This doctoral thesis consists of a summary and four appended papers. The papers are referred to as Paper I to IV in the summary text and are appended at the end of the thesis:

Paper I. **Uamusse, M.M**., Tussupova, K., Bengtsson, L., Persson, K.M. & Berndtsson, R. (2019). Access to sustainable electrification: possibilities for rural Mozambique (*in review* ***International Journal of Sustainable Engineering***).

Paper II**. Uamusse, M.M**., Tussupova, K., Persson, K.M. & Berndtsson, R. (2019). Mini-grid hydropower for rural electrification in Mozambique: meeting local needs with supply in a nexus approach, ***Water***, 11, 305.

Paper III**. Uamusse, M.M**., Tussupova, K., Persson, K.M. & Berndtsson, R. (2019). Climate change effects on hydropower plants in Mozambique (*in review* ***Energies***).

Paper IV**. Uamusse, M.M**., Persson, K.M. & Tsamba, A.J. (2014). Gasification of cashew nut shell using gasifier stove in Mozambique, ***Journal of Power and Energy Engineering***, 2, 11-18.

Author´s contribution to appended papers

The co-authorship of the papers reflects the collaborative nature of the underlying research. The contribution of Miguel Meque Uamusse (MMU) to the appended papers is as follows:

Paper I. MMU planned contents, performed data collection and literature summary, and wrote major parts of the text. The co-authors participated in discussions and final manuscript editing.

Paper II. MMU designed and executed the survey in Mozambique by creating, distributing, and collecting the questionnaires, analyzing the initial results, and writing the first draft of the paper. The co-authors contributed by adding comments and writing parts of the final paper.

Paper III. MMU planned the paper, carried out the review of the literature, and collected the data in Mozambique. The co-authors added comments and helped write the final part of the paper.

Paper IV. MMU planned the contents, collected material and performed the laboratory work. The third co-author help to design the model and participated in discussions, while the other co-author contributed to writing of the text and to editing of the language.

Related publications not included in this dissertation

Uamusse, M.M., Ndalila, P., Tsamba, A.J., Carvalho, F.O., Persson, K.M. (2015). Monthly stream flow prediction in Pungwe River for small hydropower plant using wavelet method, *Intern.* ***J. Energy Power Engin****.,* 4, 280-286. doi: 10.11648/j.ijepe.20150405.17.

Uamusse, M.M., Aljaradin, M., Nilsson, E. & Persson, K.M. (2017). Climate Change observations into hydropower in Mozambique. *International Conference on Alternative Energy in Developing Countries and Emerging Economies*. Bangkok: ***Energy Procedia***.

Abbreviations

ADB	African Development Bank
BADEA	Arab Bank for Economic Development in Africa
BID	Islamic Bank of Development
CapEx	Capital Expenditure
CO	Carbon Monoxide
CNELEC	National Council of Electricity
DANIDA	Danish International Development Agency
EDENR	Strategy for renewable energy development
EDM	Electricidade de Mocambique
ESKOM	South Africa Electricity Supply Commission
FUNAE	Fundo de Energia
GDP	Gross domestic product
GIZ	Gesellschaft für Internationale Zusammenarbeit
GNI	Gross National Income
HCB	Hidroeléctrica de Cahora Bassa
LED	Light Emitting Diode
MIREN	Ministry of Energy and Mineral Resources
MOTRACO	Mozambique Transmission Company
MOZAL	Mozal Aluminium Company
NGO	Non-Governmental Organisation
PV	Photovoltaic System
SAPP	Southern Africa Power Pool
SEB	Swaziland Electricity Board
SHS	Solar Home System
SIDA	Swedish International Development Cooperation Agency

1. Introduction

1.1 Background and problem description

Mozambique is one of the poorest countries in the world. About 54% of the population are below the poverty line and about 70% of approximately 30 million people (2018) live and work in rural areas (World Bank, 2018). Subsistence agriculture occupies about 80% of the labor force (Cuvilas et al., 2010; Mozambique Forest Information and Data, 2011). Mozambique has, however, experienced a strong economic growth during the last two decades. During this period, the average annual GDP growth was 7.4% due to trade, manufacturing, extractive industries, transport, communication, and electricity production (World Bank, 2017). The rapid growth, however, has not resulted in significant poverty reduction. The general electrification rate increased from 5% in 2001 to about 26% in 2016 (Energypedia.info, 2018). The electrification as well as the domestic power generation are uneven both socially and spatially (Power and Kirshner, 2018). Access to electricity is mainly focused to urban areas (67%) while only 5.7% use electricity for lighting in rural areas. Forest resources, in general, satisfy more than 95% of energy requirements in rural areas.

The UN Sustainable Development Goal (SDG) 7 states that access to affordable, reliable, sustainable and modern energy for all people throughout the world should be achieved by the year 2030 (UN, 2018). This "requires expanding access to electricity and clean cooking fuels and technologies, as well as improving energy efficiency and increasing the share of renewable energy", for those in need of this. Three positive socio-economic effects of electrification stand out (Uamusse et al., 2019; IEA, 2017; Mulder and Tembe, 2018). Positive effects of full access to electrification are often stated as being, in particular, educational benefits, improvements in income, and decrease in respiratory diseases (World Bank, 2018). Electrification and SDG Goal 7 have also been related to several other important SDG goals, among these the following: 1) overcoming poverty, 3) achieving good health and well-being, 4) providing education of high quality, 6) providing clean water and good sanitation, 8) providing decent work and economic growth, 9) promoting industrial development, innovation, and improvement in infrastructure, and 13) supporting actions regarding climate matters. Thus, electrification and SDG

7 can be seen as enabling factors for achieving an adequate degree of sustainable development (UN, 2018; Uamusse et al., 2019).

The primary present energy supply in Mozambique is biomass, providing about 80% of the energy produced, followed by hydropower providing about 13%, fossil fuel providing about 7%, and solar and wind energy providing the rest. Biomass is typically used in a marginal way, without use of basic technologies, such as gasification (gas), pyrolysis (coal), and fermentation (biogas). The population uses combustion directly, which has serious health consequences, since the burning of biomass releases soot, particles, and carbon monoxide (CO), which is a toxic gas dangerous to health. The urban population in Mozambique often uses charcoal while the rural people use fuelwood. The use of biomass has implications for the environment, through releasing carbon dioxide in the combustion process, which increases global warming because of greenhouse gases being released. Another negative implication of the use of biomass is deforestation. On the other hand, the country produces large quantities of agricultural crop residue that are still not being appropriately and integrally used as additional source of energy, especially for rural communities where these residues are generated. Cashew nut shells are among those residues. This kind of feedstock is said to be of high energy content.

Mozambique has considerable potential non-renewable energy reserves. Coal reserves are estimated at more than 23 billion tons (Power and Kirshner, 2018; Bucuane and Mulder, 2007). Total natural gas reserves correspond to 100 Tcf and the potential of renewable energy (hydro, solar, wind, and biomass) being approximately 23,000 MW (hydro corresponding to 12-18,000 MW) (Hussain, 2015). Despite the large amounts of energy resources that exist in Mozambique, less than 3,000 MW are at present being exploited for electricity production. To drive the societal buy-in for the goal of 100% electrification by 2030, the demand for and use of electricity must be increased. Currently, there is a strong contrast between the production and the consumption of electricity. Mozambique produces large amounts of hydropower and has several hydropower projects underway besides the Mphanda Nkuwa such as the North Bank project (1,245 MW), the Lupata project (600 MW), the Boroma project with a capacity of 200 MW, and the Lurio project (120 MW) (Hussain, 2015). Mozambique can also use non-renewable fossil-based energy resources, such as coal reserves in Tete, and natural gas in Temane-Inhambane to speed up the electrification of the country. Some of these resources are at present destined for export. However, to meet the increased demands for electricity, the country continues importing energy rather than using its local resources in a more economic fashion (Schut et al., 2010).

As mentioned above, the general electricity access in Mozambique is low and mainly concentrated to urban areas. The national electrification strategy has been to supply 20 million Mozambicans by electricity the next 12 years. To achieve this,

and universal electricity access by 2030 to fulfill its SDG, Mozambique would need to add 4 million homes and 300,000 to 400,000 new connections per year (Power and Kirshner, 2018; Mulder and Tembe, 2008; Nhamire and Mosca, 2014). The government´s target was to have 50% access by 2023 (Hussain, 2015). However, it seems that this target may be relaxed to 50% achieved by 2030 instead of 2023 (Hussain, 2015).

In general, energy poverty and lack of energy in rural areas are seen to exacerbating the poverty of developing countries (Javadi, 2013). Thus, access to electricity, either by grid or off-grid systems could be a means to achieve better economic growth and equitable distribution of income and development (Rahman Mohamed and Lee, 2006; Sovacool and Valentine, 2011). In general, solar, biomass, hydro, wind, and wave may be viewed as renewable energies (Javadi et al., 2013). Research indicates that these types of energy may be good alternatives for off-grid solutions in rural areas. In this way, even remote areas can be reached by electricity.

Climate variation impacts the use of hydropower and represents high challenges to the water resources sector in Mozambique. In Africa in general, and especially in Mozambique, water supply systems are poor and the government is already strained to deliver this resource to the population. Climate change will further complicate management of most of the systems in the future. In southern African nations where Mozambique is located, a decrease in annual discharge will significantly affect the amount of surface water in large parts of the south of the continent by the end of the century (Mozambique Forest Information and Data, 2011). Hydropower being a renewable energy source is dependent on a predictably steady precipitation pattern. The use of hydropower plants in the country of Mozambique is therefore fraught with potential risks associated with its geographical location, as it is identified as being a vulnerable country in terms of climate change. Located along the coast of the Indian Ocean, being a downstream country and being associated with low technology, poverty and a weak capacity to adapt to societal changes, hydropower use in Mozambique is expected to be negatively affected by climate change in the future (World Bank, 2017). However, Mozambique is one of the southern African countries that depends almost completely on hydropower as a main source of electricity as an on-grid system and this change in the water resources availability will result in significant changes in electricity supply (Energypedia.info, 2018).

In view of the above, Mozambique needs to urgently supply its rural population with energy to fulfill its SDG goals. The complexity of electrification of rural areas in Mozambique, however, is formidable. To solve this complex situation, Mozambique needs to develop a rural electrification policy that can improve rural electrification in a sustainable manner considering all the above constraints and choices. In this process, scale of solutions as well as temporal aspects in view of climate change need to be considered. Along this line, the thesis presents an analysis

of the current situation of rural electrification in Mozambique and ways forward. Different energy alternatives at different scales are considered as well as the climate change aspect.

1.2 Objectives and scope

The general objective of this thesis is to achieve a better understanding of how renewable energy based on use of off-grid systems in rural Mozambique can be used to combat poverty. Thus, the general scope of the thesis is to study sustainable rural electrification by off-grid systems in Mozambique. The study focuses on three basic research questions connected to the above general objective:

A. What is the status of Mozambiques´s energy sector and what is the potential for off-grid sustainable energy solutions in rural areas (Paper I)?

B. To what extent can mini-grid hydropower systems be efficient in improving rural electrification and meeting local needs in energy supply (Paper II) and to what extent can the climate change affect the efficiency of electricity generation from hydropower plants? (Paper III).

C. Could other alternatives in household energy sources such as biomass waste (cashew nut shells) be complementary energy source when implementing hydropower plants? (Paper IV) and what is the joint effect in using both energy sources?

1.3 Thesis structure

The thesis is a compilation of four appended papers and a summary. The summary contains an introductory state of the art regarding the energy system of Mozambique. Paper I continues the analysis of the energy system for the rural areas and examines the sustainability of rural electrification in Manica Province, Mozambique, focusing on different alternatives for mini-grid and off-grid power supply. Paper II and III, examine mini-grid hydropower systems and effects of a future climate change on the efficiency of electricity generation. Finally, Paper IV, investigates the possibility of biomass waste as a complementary energy source for rural electrification.

2. Materials and methods

2.1 Experimental area and data

The general area of interest is the country of Mozambique, but the specific study area is located in the Chua Village along the Chua River, Mozambique. Chua is a small village with about 3,000 inhabitants located in Maridza administrative post close to Manica City in the District and Province of Manica. Chua River Basin is located in the uppermost part of the Pungwe River Basin just at the border to Zimbabwe in the central western part of Mozambique (21°34-16°24 latitude S and 34°01-32°42 longitude W) (Fig. 1). The average annual rainfall is about 1,340 mm and runoff about 477 mm (Uamusse et al., 2019). An experimental catchment was chosen so as to represent a typical small hilly rural basin close to the Chua Village. The selected basin is a hilly branch of the Chua River covering about 9.6 km^2. The surface use is mixed grazed areas with groves along the river. A few homesteads are included in the catchment area. Typically, families live at homesteads quite remote from each other. The main economic income is from agriculture, livestock, and artisanal gold mining.

Chua area has previous experience of donor-assisted small-scale hydropower (Sebastião, 2013). Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ) is active in the area for capacity building, technical, and economic assistance. Existing micro-hydropower plants are often privately owned while grid systems are usually owned by communities (Mulder and Tembe, 2018; Sebastião, 2013).

The area of Manica District is about 4,391 km^2 and it has a population of about 215,300 inhabitants, with a density of 49 inhabitants/km^2. The Manica Province covers 61,661 km^2 (7.7% of Mozambique) and borders the Tete Province to the north, by the Luenha and the Zambezi Rivers, the Provinces of Gaza and Inhambane to the south, by the Save River, Sofala to the east, and the Republic of Zimbabwe to the west. The climate is tropical and modified by the altitude with a tendency of hot and humid weather. The rainy season is from September to March and the dry season from April to August. The average summer temperature for about half of the province is about 20°C, occurring most of the time in about half of the province. However, the warmest temperatures (about 25°C) occur in the Save and the Zambezi Valleys. The coolest temperatures (15 to 20°C) occur in the districts of Gondola,

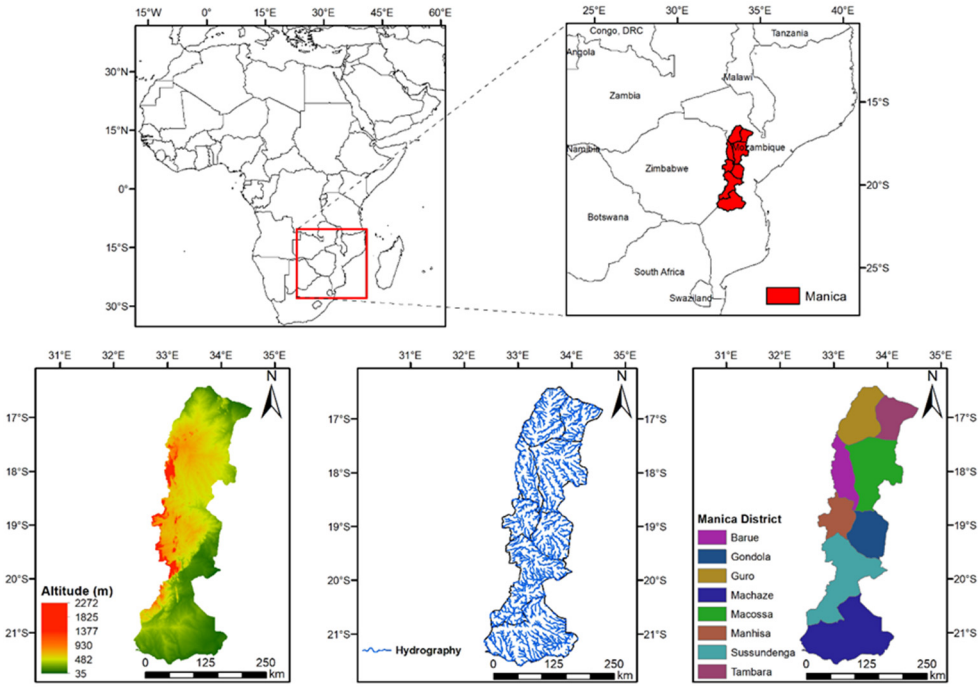

Figure 1. Manica Province physiography, administrative borders, and location of Chua Village. Source: own illustration.

Manica, Mossurize, Báruè, and in the mountainous western parts. Average annual rainfall is about 1,400 mm. In dryer regions, the annual rainfall is up to 700 mm and can reach 1,800 mm in the interior highlands (Wate and Mika, 2007). The mountains are located mainly in the far west, at an altitude of more than 1,000 m, near the border to Zimbabwe. This area has the highest altitudes up to 2,436 m (Mount Binga).

Western Manica Province has many rivers and streams with perennial flow and suitable conditions for construction of micro-hydropower plants. Several locations for implementation of potential small hydropower projects have thus been identified such as Honde, Bárue District, Rotanda, and Sussundenga District (EDM, 2017). The total power potential of these projects is about 2,000 kW. One area with a high potential for hydropower production is the Chua region along the Chua River, which has been partly exploited already, through the construction of five small hydropower plants. These have a total power of 1,200 kW and an annual electricity production of 10,500 MWh (EDM, 2017; FUNAE, 2015).

Due to the abundance of water resources, Manica Province has good agricultural potential. More than 90% of the about 2.4 million population are engaged in subsistence agriculture (2017). The area has a high poverty level, however, and the population suffers from recurrent high degrees of malnutrition. Staple food crops are maize, sorghum, pulses, and groundnuts. The province was severely affected by the 16-year civil war that ended in 1992. More or less all social and economic infrastructure was destroyed and this is still gradually being rebuilt (Sebastião, 2013). Health and medical service is scarce and of poor quality. Access to education is unsatisfactory, especially for girls. The literacy level is about 56%. About 77% of the area are covered by forest and forest resources plus charcoal constitute 80-90% of the energy consumed (INE, 2018). The electrification level is about 8% in Manica (IEA, 2016; INE, 2018).

About 51% of the Chua Village population are illiterate, men are often more illiterate due to that women are more involved in economic and social activities (INE, 2018; Sebastião, 2013). Chua Village covers two valleys and surrounding mountains. Households are generally located at far distance from each other. Average household size is 5.5 persons. About 74% had access to radio, 25% television set, and 30% mobile phone in 2003 although without grid connection (Wate, 2007). Electricity access is often done by solar panels, car batteries or diesel generators. About 25% suffer from malaria and 20% from respiratory diseases. An average of 15% of the villagers use solar panels and car batteries as power for radios and some even for television. This is an indication of already existing demand for electricity. In a study from 2007 (Zana, 2007), most of the villagers (75%) stated willingness to pay for the electricity. However, they were reluctant to express what amount of their disposable income that they could use for these additional expenses.

2.2 Methods

Data and information collection were performed during two monthly study visits to Manica Province and Chua Village in July 2015 and June 2016. Data scarcity and lack of information regarding rural conditions are general problems in Mozambique. A law to provide free access to information, however, was approved in 2014 (Law on freedom of information) (freedominfo.org, 2018). For this reason, data and information used in the present paper could partly be collected from official documents. Initial literature surveys and qualitative document analyses were combined with semi-structured interviews in Chua Village and Manica Province during the study visits. Literature surveys and document analyses gave important insights on national electrification policies of Mozambique that could be compared to at-site conditions and interview results with different stakeholders such as experts from different ministries and authorities, national and international organizations,

energy companies, local power plant managers, and potential local energy consumers in Chua Village and Manica Province. Study visits and interviews were made with key professionals at the GIZ offices in Chimoio the capital of Manica Province (Uamusse et al., 2019). As mentioned above, GIZ is responsible for financing projects concerning renewable hydropower energy produced in this region of Mozambique. Other institutions that provided us with information were EDM (Electricidade de Moçambique), UNIDO (United Nations Industrial Development Organization), Ministry of Energy of Mozambique, and FUNAE (Fundo de Energia). Five local hydropower operators in Manica Province were interviewed during the study visits. In each interview, questions were asked to elucidate institutional and organizational conditions, economic aspects, environmental conditions, and socio-cultural features. Deeper literature surveys on sustainability gave input to the methodology that was used to understand relationships between electrification and sustainability goals (Ritchie, et al., 2013).

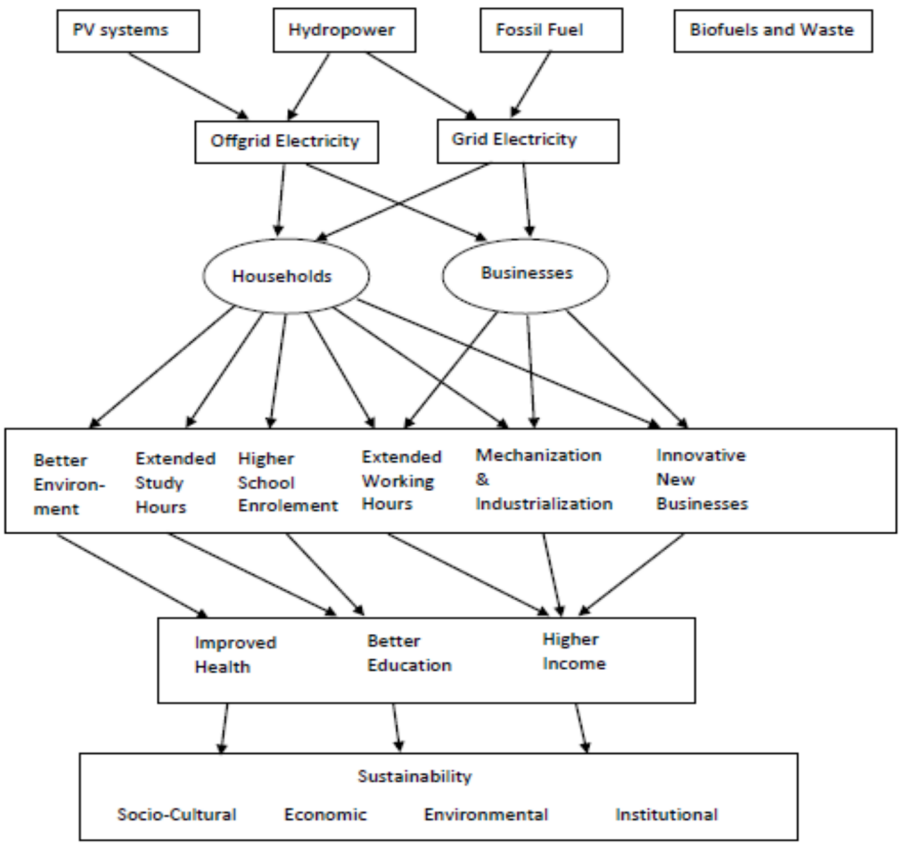

Figure 2. Links between electrification in Mozambique and possibility for improved sustainability. Source: own illustration partly after Peters and Sievert (2016)

Households and businesses may be interested in connecting to the grid or off-grid system to receive safe electricity for a fee. The potential impact of electricity, may as schematized in Fig. 2, improve school results, simplify the work in the household, improve environment, and lead to development of other industrial sectors than the traditional agriculture. In turn, this could have positive effects on health, education and career opportunities, and income often noticed in South America and Asia (Fisher-Vanden et al., 2015; Gibson and Olivia, 2009; Grogan and Sadanand, 2013; Groh, 2014; Kanagawa and Nakata, 2008; Khandker et al., 2014). With the objective to investigate if similar improvements could be expected for the Manica Province in Mozambique, the above schematized methodology (Fig. 2) was used.

Specific interviews were made with villagers in Chua Village. The objective was to analyze local needs of electricity and how these match possible supply. Totally, 50 face-to-face interviews with mixed electrified/non-electrified household representatives were conducted in order to understand local sustainability of different electricity alternatives in the area. The results, gave insights on five key demand areas in the village namely, households, public infrastructure, small trade, small industry, and leisure activities. The village head was interviewed to get an overall assessment of village functions and public electricity needs. Interviews were recorded by taking handwritten notes during the interviews, supplemented by further notes after the interview events. A checklist was used to find answers concerning household structure and basic needs of electricity such as how lighting is used, health status, general water use, washing and cleaning, refrigerator needs, cooking requirements, leisure activities, and appliances uses. Enquiries were also made regarding public lighting, local hospital use, village administration, primary school conditions, and business opportunities.

The information gathered through document analyses and interviews were used to address the four dimensions of sustainability according to Table 1. The assessment is based on the group of indicators (Table 1) that were evaluated relative to an ideal situation. Particularly, we wanted to assess the sustainability of rural mini-grid and off-grid solutions using different possibilities to supply rural Manica Province with electricity from renewable energy sources.

Table 1. Indicators of four sustainability dimensions used in this study, partly adapted from Feron et al. (2016).

Environmental	Socio-cultural	Economic	Institutional
Environmental awareness	Accessibility	Cost effectiveness	Decentralization
Environmental impact	Social acceptance	Reliability	Adaptability
Resilience to climate change	Cultural justice	Funding	Stability

The methodology to assess the sustainability of rural electrification in Manica Province followed four main dimensions of sustainability, namely environmental, socio-cultural, economic, and institutional (Feron, et al., 2016). Environmental indicators reflect awareness of the population and impact of applied technology on environment. An important environmental aspect of applied technology is the ability to contribute to societal resilience against climate change. Socio-cultural indicators show the degree of equity regarding energy provided to different societal groups partly through accessibility. Social acceptance implies a participatory and inclusive approach. Cultural justice refers to justice through participation, mutual learning, and knowledge sharing (Feron, et al., 2016). Important aspects regarding economic sustainability are indicated by cost effectiveness, reliability, and funding. Cost effectiveness is a measure of how efficiently monetary resources are spent on a certain technology. Reliability is a measure for how operational the technology is in time. Funding depends on both investment costs and operation and maintenance costs. In turn, this is determined by both public and private spending. Institutional sustainability provides a stable and dependable framework through which individuals and organizations can interact. Decentralization is important as it gives legacy to, e.g., national policies to be implemented at a local scale. Adaptability is

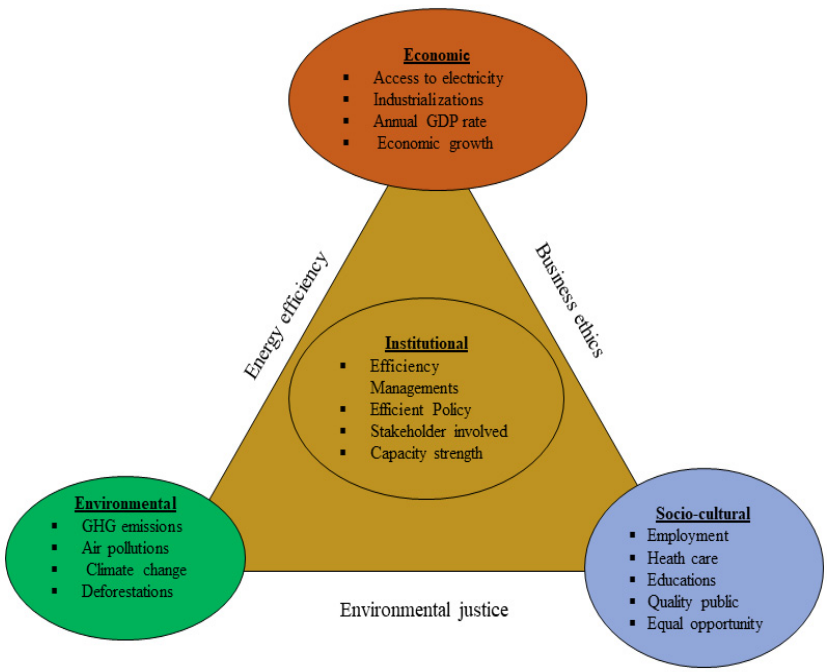

Figure 3. Methodological framework used to satisfy the objectives of the dissertation and sustainability analysis.

is also a measure of institutions´ ability to adapt to needs of a population in terms flexibility and decentralization. Stability or durability defines the strength of the institution and related to the general reliability (Barnes et al., 2011).

The theoretical framework of the thesis, in which possibilities of achieving all four main indicators of sustainable rural electrification in Mozambique is based on the sustainable development model shown in Fig. 3. According to Tussupova (2016) sustainable development here refers development that is economically viable, environmentally friendly, and socially acceptable. The quality of life in a community is closely connected to sustainability. The model presented in the figure shows the focus on sustainability analyses in the thesis and the outcome indicators directly relevant to the degree of the universal access to electricity. In view of the above, the objective of the dissertation was to investigate possibilities of achieving access to electrification in rural Mozambique and to critically assess the sustainability of rural grid and off-grid electrification programs. We are especially interested to analyzing different ways of supplying rural electrification through use of renewable energy sources.

Other studies have previously indicated that future hydropower development in Mozambique needs to be nexus-oriented (Nielsen et al., 2015). However, to the best of our knowledge, this has previously not been shown for Mozambique using a bottom-up approach. We see the economic drivers for sustainable development of rural electrification as especially important. Since the rural population is very poor, the willingness to pay for energy services is low. Thus, also other incentives for financing small-scale hydropower have to be considered. At the same time, hydropower development and the use of water are intrinsically linked to water supply and food production.

Cashew nut shell samples used for the gasification study were obtained from a waste cashew nut shell dumping site in Gaza Province of Mozambique. The collected samples were grounded to about 1 mm particle size prior to characterization. Traditionally, extraction of the kernel from the shell of the cashew nut is a manual operation. The nut is roasted making the shell brittle and loosens the kernel from the inside of the shell. By soaking the nuts in water, the moisture content of the kernel is raised, reducing the risk of being scorched during roasting and making it more flexible to avoid cracking. Subsequently the shells are released when the nuts are roasted. The energy, water, ash, and carbon content were measured in samples prior to thermal gravimetric analysis with TGA type NETZSCH STA 409 PC Luxx (Netsch Gerätebau, Germany).

3. Results and discussion

3.1 Review of energy sector and rural electrification in Mozambique

Total primary energy available in Mozambique is about 408.9 PJ (FUNAE, 2013; Chambal, 2010). Mozambique´s potential for power generation is to a major extent hydropower (85%) and more than 80% of the hydropower potential are located in the Zambezi River Basin. Governmental policies in Mozambique promote different renewable energy solutions, such as small hydropower generators, solar panels, and biomass plants in off-grid systems, with the objective of decentralizing the energy system.

Energy use in Mozambique during the latest decades is shown in Fig. 4 (IEA, 2017). Firewood and charcoal are estimated to represent about 22 million tons per year (Cuvilas et al., 2010; Sitoe et al., 2008; Ellegård et al., 2002). Imported primary and secondary oil represent an annual consumption of about 700,000 m^3 (Cuvilas et al., 2010). Significant amounts of hydropower are produced by the Hidroeléctrica de Cahora Bassa (HCB) plant along the Zambesi River. The dam was completed in 1974. However, during the Mozambican 16-year civil war, power transmission lines were sabotaged until the end of the war in 1992 (Sebitosi and da Graça, 2009). Most of the 2,075 MW capacity plant generated electricity are, however, exported (1,500 MW or 65%) (Power and Kirshner, 2018). At present, hydropower supplies about 95% of the electricity in Mozambique (Cipriano et al., 2015). Another large hydropower project downstream of HCB, the Mphanda Nkuwa Dam (1,500 MW) is under construction (Electricidade de Moçambique, 2018).

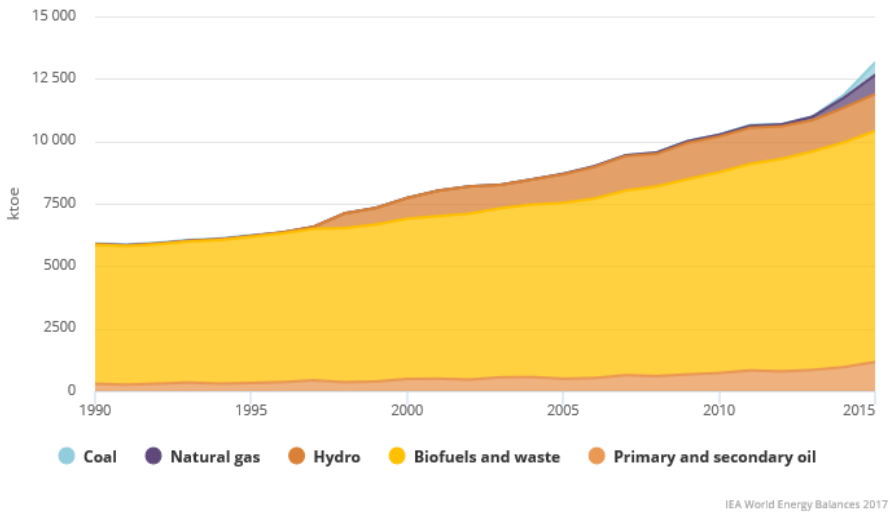

Figure 4. Total primary energy supply by source for Mozambique. Source: data from (IEA, 2017).

This hydropower plant is planned to become the second largest energy producer in Mozambique. However, also here, a significant part (90%) is planned for export (Power and Kirshner, 2018). As seen from Fig. 4, coal and natural gas use has increased significantly during the last few years. Even so, non-sustainable biofuels and agricultural bio-waste remain the major part of energy use in Mozambique.

In Mozambique, electricity can be provided for through the use of three different systems, namely (1) on-grid systems in urban areas, supplied by Electricidade de Mocambique (EDM), (2) mini-grid systems located in rural areas and supplied by National Energy Fund (FUNAE) and EDM, and (3) off-grid systems using PV solar home systems supplied by FUNAE. Rural electrification in Mozambique started by the establishment of EDM on August 27, 1977, just two years after Mozambique's independence. EDM is the national electricity company, responsible for the production, transportation, distribution, and commercialization of energy in the entire Mozambique. In 1977, the energy sector supplied only three capital provinces (Maputo, Beira, and Chimoio), whereas by 2010 it had increased to encompass all 11 capital provinces. The evolution of electrification in the various districts was such that in 2005 only 55 districts were electrified, whereas by 2011 the total had nearly doubled to encompass 107 districts. Currently, in total 147 districts have at least one town or village electrified. However, much of the grid system requires restoration (Power and Kirshner, 2018; Cipriano et al., 2015; Baptista, 2015). Mozambique´s electricity system is constituted by three separate systems with no interconnection; a southern, a central, and a northern system (Fig. 5) (Cipriano et al., 2015). Electricity supply is usually intermittent and large parts of the rural areas

are not covered (Broto et al., 2018). Connecting rural people to the national grid appears cost-prohibitive. The rural customers are typically very poor and distances to be covered are large (Broto et al., 2018). It is thus, not likely that the national grid can be extended to cover major parts of the rural landscape in a foreseeable future (Ahlborg and Hammar, 2014).

Power sector reforms have addressed private sector involvement in rural electrification (Karekezi and Kimani, 2002; World Bank, 2007). However, due to the limited payment capacity of the rural poor, it is not likely that private actors will significantly contribute to rural electrification in Mozambique. Consequently, the remaining option is off-grid systems of various power source and design (Ahlborg and Hammar, 2014; Akella et al., 2009; Karekezi, 2002; Kaundinya et al., 2009) and involvement of donors, NGOs, and development banks. The Ministry of Energy and Mineral Resources (MIREN) is responsible for all energy programs in Mozambique (Fig. 6). MIREN basically supervises all resources connected to the production of electricity including alternative and renewable energy, oil fuel products, natural gas, coal resources, and mineral resources (Energypedia.info, 2018; Cipriano et al., 2015). The National Council of Electricity (CNELEC) is an independent electricity regulator for Mozambique. Its main objectives are to resolve financial issues, ensure administrative autonomy safeguarding that mandates and responsibilities are carried out in accordance with the law, and to secure public interests. Mozambique Transmission Company (MOTRACO) was created as a joint venture transmission company encompassing ESKOM (South Africa Electricity Supply Commission), EDM, and SEB (Swaziland Electricity Board). The 2,075 MW HCB power is transmitted to South Africa, Mozambique, Zimbabwe, and Botswana. Mozambique is guaranteed 200 MW from HCB at a low cost. The cost of the seller energy from Cahora Bassa to ESKOM is only US$3.6/kWh, and in 2012 the energy produced was about 8,351 GWh, whereas during the same period of time EDM imported energy from ESKOM at the higher price of US$30/kWh. MOTRACO is a partnership between public and private entities. The goal of MOTRACO is to provide reliable electricity to industrial companies based in Maputo. The MOTRACO is owned by the South African ESKOM as a majority owner and EDM and the Swazi utility as minority owners. EDM participates in the Southern Africa Power Pool (SAPP) activities, but is in a weak position vis à vis neighboring South Africa and its strong power utility, ESKOM. Figure 6 shows how the different main sectors of Mozambique´s electrification partnership is related and main responsibilities.

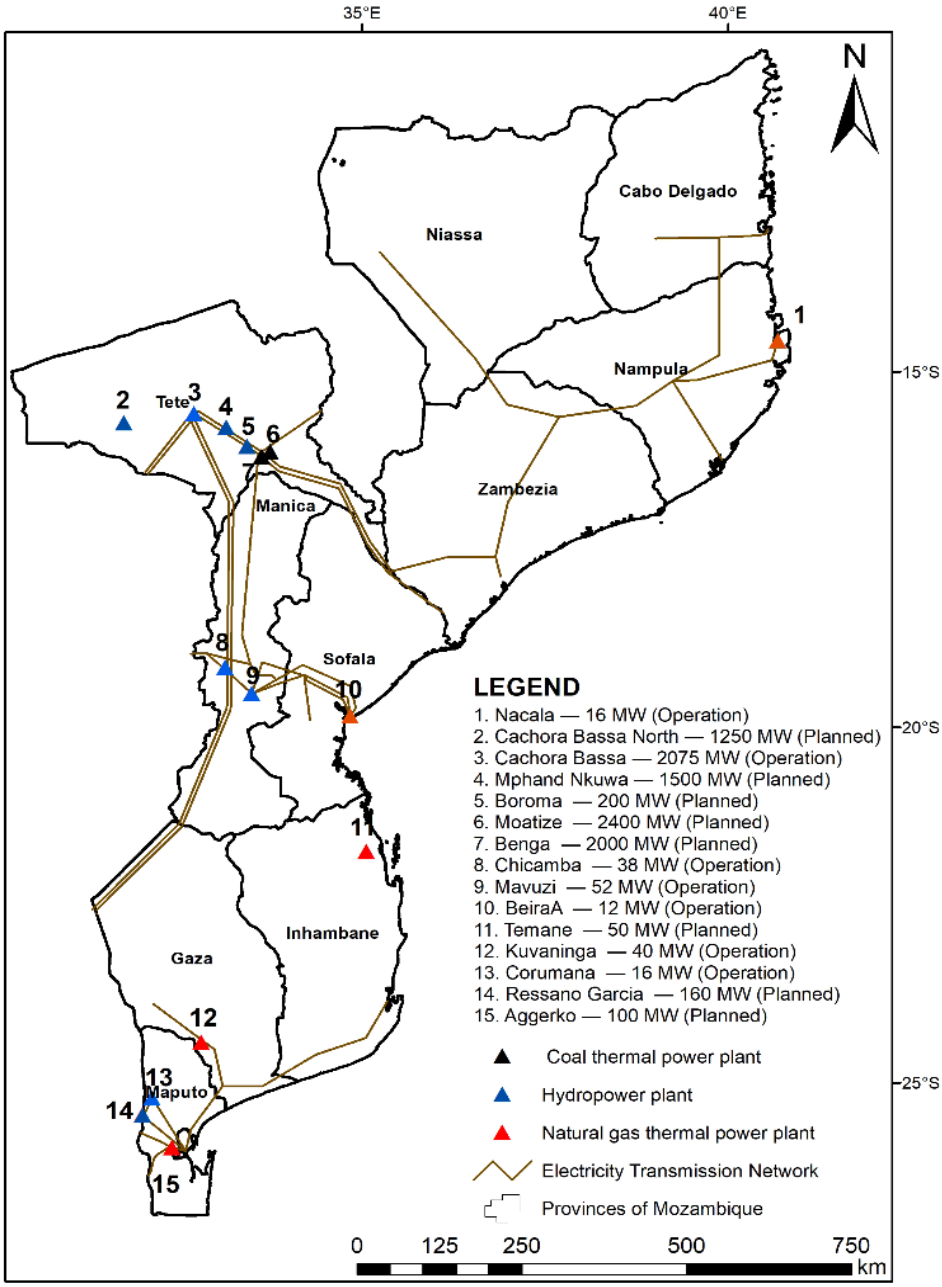

Figure 5. Grid electricity extension with power type in Mozambique. Source: own illustration with data from (Energypedia.info, 2018; UN, 2018; IAEA, 2015).

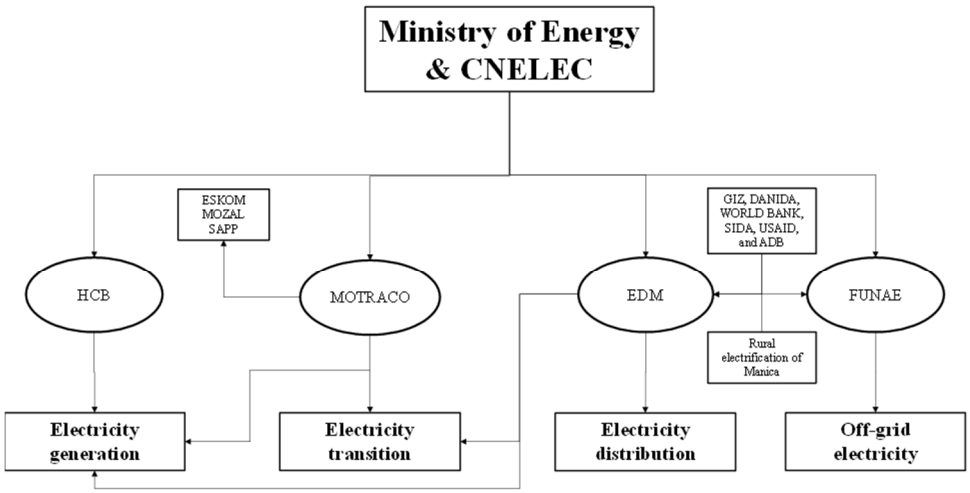

Figure 6. Schematic of organization of the energy sector in Mozambique with its different stakeholders. Source: own illustration with information from (Energypedia.info, 2018; Cipriano et al., 2015).

The FUNAE (Fig. 6) was established as a public institution in 1997 by the Decree 24/97 (van der Plas et al., 2012). Its basic aim is to promote access to mini-grid system energy for rural areas and to produce and distribute different forms of renewable energy to off-grid systems so as to further improve rural electrification. Thus, the FUNAE complements EDM by promoting rural electrification where EDM does not provide service by the national grid due to too high costs. The consortium as regards the rural energy initiative is the EDM, HCB, and MOTRACO (Hankins, 2009). In addressing rural electrification, the Mozambique government adopted the Policy for Renewables in March 2009 (IEA, 2017). The objectives of the FUNAE are (FUNAE, 2013; FUNAE, 2015; BRFR, 2016):

- Advance social programs involving use of renewable energy to meet the needs of rural communities,
- Develop, produce and make use of different forms of renewable energy, such as solar energy, energy produced by small hydropower plants, and wind energy to supply low-cost power,
- Since all renewable energy technologies are endorsed, FUNAE is to promote the use of clean renewable energy sources that have a lesser impactful on the environment than traditional energy production does,
- The financing of renewable energy research and technology is to be provided jointly with the financing of university research.

Due to the low density of rural population, rural electrification by a national grid is cost-prohibitive. This has led the government to adopt a strategy making use of FUNAE so as to create (local) mini-grid systems when these are called for. Governmental and non-governmental organizations (NGOs) such as the Swedish International Development Cooperation Agency (SIDA), the Danish International Development Agency (DANIDA), the World Bank, and the African Development Bank (ADB) are working with EDM and FUNAE to help solve access problems in connection with rural electrification (Fig. 6).

EDM has adopted a hydropower strategy for rural Mozambique (Sebastião, 2013). This plan involves the use of a number of small-scale hydroelectric power projects that require only 5-10 km of grid extension in order to connect different areas. The Mozambique government has introduced a code of grid connections. FUNAE and their partner GIZ have in turn begun a rural electrification program making use of small-scale off-grid energy production systems (Sebastião, 2013; IRENA, 2012).

The government has continuously strengthened legislation for rural electrification so as to ensure access to electricity for the entire country (see Table 2) (Cuamba et al., 2013). In 1977, 80% of the population were living without access to electricity. This led to the creation of the government run EDM, with the purpose of producing, transmitting, and distributing electricity to the country. Since then, the government has introduced reforms and regulations into law and declared policies for increasing the access to electricity of the population. Through these instruments, the government is able to dictate how the energy sector is managed, pushing the program towards the goal of supplying electricity to each person for the betterment of society. The major reforms in the energy sector started in 1995 with Decree 28/95, defining the role of EDM and establishing its bylaws, as shown in Table 2. In order to more efficiently carry out rural electrification, the government needs to continue to strengthen the institutional framework and work in partnership with stakeholders to provide reliable, sustainable, and affordable electric power.

In Mozambique, solar energy should be given a high degree of attention since the country has very strong solar radiation and the sunshine involved is always available and free, at the same time as there is a lack of access to electricity in most parts of the country. Solar energy can very much change the present situation of poverty and of market inequality between rural and urban areas, another advantage being that solar energy also contributes to the reduction of greenhouse gas emissions, which contribute strongly to global warming (Cuamba et al., 2013).

Table 2. Mozambique energy policy and reforms of the sector. Source: Cuamba et al. (2013).

Year	Name of legal instrument promoting electrification	Objective
1995	Decree 28/95	Government giving EDM a degree of independence, administration, and financial support.
1997	Electricity law (Decree 21/97)	Increasing efficient energy use, increasing use of electricity in households and increasing energy demands for export purposes. Adopted by CNELEC and FUNAE.
1997	Municipal legislation	Giving municipalities the opportunity of planning investments in accordance with their needs of electricity.
2000	National energy sector strategy (Decree 24/2000)	Established to implement national energy policy.
2005	Decree 42/2005	Establishing rules and regulations for planning, financing, construction, production, and transportation, purpose involving use of electricity in ownership projects and the grid system used to centralize EDM.
2009	Strategy for conservation and sustainable strategy for use of biomass energy	Promoting use of biomass energy through use of jatropha as biomass for biodiesel production. Reducing the import of fossil fuel for electric lighting in rural area.
2009	Renewable energy policy	Promoting modern and sustainable rural electrification.
2011	Renewable energy strategy	Strategy for renewable energy development (EDENR) adopted 2011-2025.

3.2 Access to sustainable electrification: possibilities for rural Mozambique (Paper I)

Governmental electrification policies and programs are implemented at the local scale. Hence, it is of specific importance to evaluate effects on the local user-scale when addressing sustainability. For this reason, special emphasis of the interview work was allotted to the Chua villagers. The Chua Village is in many respects representative of socioeconomic and physiographical properties of Manica Province (Bensch et al., 2010). In general, villagers with access to electricity agreed upon that electricity had done much to change their lives for the better. The rural household representatives were pleased to have electricity to light their homes, watching television, listening to radio, and different leisure activities, as well as for cooking and making life in general easier. Most villagers, however, are still not connected to safe and reliable power. Candles, kerosene, batteries, and wood are still to a main extent used as energy sources. Many families have a solar panel or a generator sometimes in combination with a car battery. According to the village head, about 520 households are in need of safe and reliable electricity. Other important communal infrastructure is a hospital, a primary school, and a church. Besides these, there are 4 small shops, one administrative office, 2 grain mills, and 2 bars. The village head, emphasized prioritizing the hospital, primary school, and church besides the households. The shops, administrative office, grain mills, and bars have access to electricity through solar panels, batteries or diesel generators. One of the grain mills is an old hybrid type used for both electricity generation and grain milling. The identified main potential uses of electricity in Chua Village are providing lighting of houses at night, as well as for television, charging small appliances and mobile phones, water supply, refrigeration, and food conservation.

Environmental sustainability and electrification of rural areas in developing countries are strongly connected to several SDGs (UN, 2016). At present there are some 1.75 million people in Manica who still do not have access to safe and reliable electricity (about 8% supplied by modern electricity) (IEA, 2017). Besides household uses of electricity, services such safe water supply and sanitation, lighting in schools and public spaces, and health care are important considerations for improved quality of life in rural Manica.

Interviews indicated that environmental awareness is quite limited in Manica Province and Chua Village. Weak implementation of environmental laws was given as a main reason in interviews with experts. As the illiteracy level is high in Manica Province and poverty is widespread, environmental issues are generally of secondary concern. In Chua Village, as in many other places in Manica Province, deforestation and illegal logging are major problems. Deforestation is related to biomass burning but also to artisanal gold mining. Small-scale and informal artisanal gold mining is the second largest sector of employment after agriculture in

Manica Province (UniZambeze & Mining Development Fund, 2012). In Chua Village, 30% of all male adults are involved in gold mining as a primary occupation (Bensch et al., 2010). This gives households an important extra income to the subsistence agriculture. However, it also creates erosion of sediments causing siltation in downstream reservoirs. The inappropriate use of mercury in the gold amalgamation process, causes serious pollution of soils, crops, and downstream water (UniZambeze & Mining Development Fund, 2012). Authorities and environmental organizations need thus, to set up framework for these activities that are obviously not sustainable.

FUNAE is giving priority to solar home systems (SHSs) for the production of household electricity in rural areas (FUNAE complements EDM by promoting rural electrification where EDM does not provide service by the national grid due to too high costs). The SHSs consist of a PV panel, charge controller, wiring, and a battery (FUNAE, 2015; BRFR, 2016). This can, e.g., provide sufficient electricity needed for a television set, mobile phone, refrigerator, and some LED lamps. The overall solar power use is quite small at present but growing steadily in rural areas due to general affordability, ease of use, and simple installment. Solar power systems, however, contain hazardous constituents and batteries such as, e.g., heavy metals. There is no system or infrastructure for re-use or collection of old batteries and other parts of used solar panels in rural areas of Mozambique. This, in combination with low environmental awareness and the rather short lifespan of solar panel components, will likely result in used batteries and solar panel parts ending up in the general waste deposits of rural villages.

The renewable energy potential in Manica Province has been identified as 1,941 MW from hydropower, 25 MW from solar, and 187 MW from biomass (FUNAE, 2013). It is the region that is best suited for small-scale hydropower. However, so far only few small and micro-scale hydropower projects have been implemented in Manica. The reason for this is lack of capacity to implement small-scale hydropower projects, lack of clear process, and lack of focus of the sector (Hankins, 2009; Wolfgang Mostert Associates, 2006). Medium-sized hydropower plants may be defined as 10-100 MW. Some research defines renewable hydropower as less than 10 MW due to the fact that large reservoirs often carry negative environmental impact (Hankins, 2009). Up to now, large-scale hydropower projects have been prioritized due to the fact that consumers have primarily been industry and export to SAPP. However, in order to supply rural consumers with electricity, small-scale hydropower may be necessary through off-grid or mini-grid solutions. Off-grid systems such as solar PV and small hydropower plants represent renewable solutions to the needs at hand that display cost-efficient power supply with better developmental, social, health, and environmental performance as compared to traditional centralized power supply.

An example of transition to sustainable rural electrification is the 40.5 MW solar power plant under construction by the Norwegian energy producer Scatec Solar in

Mocuba in the Zambezia Province (Broto et al., 2018; FUNAE, 2018). The potential power production is 77,000 MWh per year that is equivalent to delivering power to 175,000 households. The total investment is US$76 million of which 55 million come from the International Finance Corporation (ICF) and the remaining funds from EDM (Broto et al., 2018; Frey, 2017). Generally speaking, solar energy development in Mozambique as a whole encourages the use of renewable and clean energy production to reduce dependence upon fossil fuels, as well as reducing deforestation and emission of greenhouse gases. Figure 7 shows examples of rural electrification in Manica developed by EDM in an on-grid system with use of electricity from hydropower and an off-grid system developed by FUNAE for rural water supply making use of the PV solar system.

Figure 7. Examples of electrification of rural areas in Mozambique using on-grid system in (a) and (c) by EDM and using an off-grid PV system for water supply by FUNAE (b) (photo by Miguel M. Uamusse).

From 2006 to 2017 FUNAE was in charge of installing 63 solar powered water pumps in the provinces of Inhambane, Gaza, Zambezia, Sofala, and Manica (ALER, 2017). The projects meant that, the inhabitants did not need to travel far for safe water for both drinking and sanitation uses. Thus, the water pumps improved the lives of the communities reached. The water pumps continue to work as planned. However, maintenance and theft threatens the sustainability of the projects. Absence of fees also threaten the sustainability in the long-term perspective (ALER, 2017).

Figure 8 summarizes the potential in terms of renewable energy in Mozambique. It is evident that the supply of renewable energy is huge. Even though large hydropower projects may be seen as non-sustainable with negative environmental impact (Hankins, 2009), there is ample energy to be supplied from small-scale

projects. Renewable energy potential in Manica is dominated by hydropower as mentioned above (EDM, 2018).

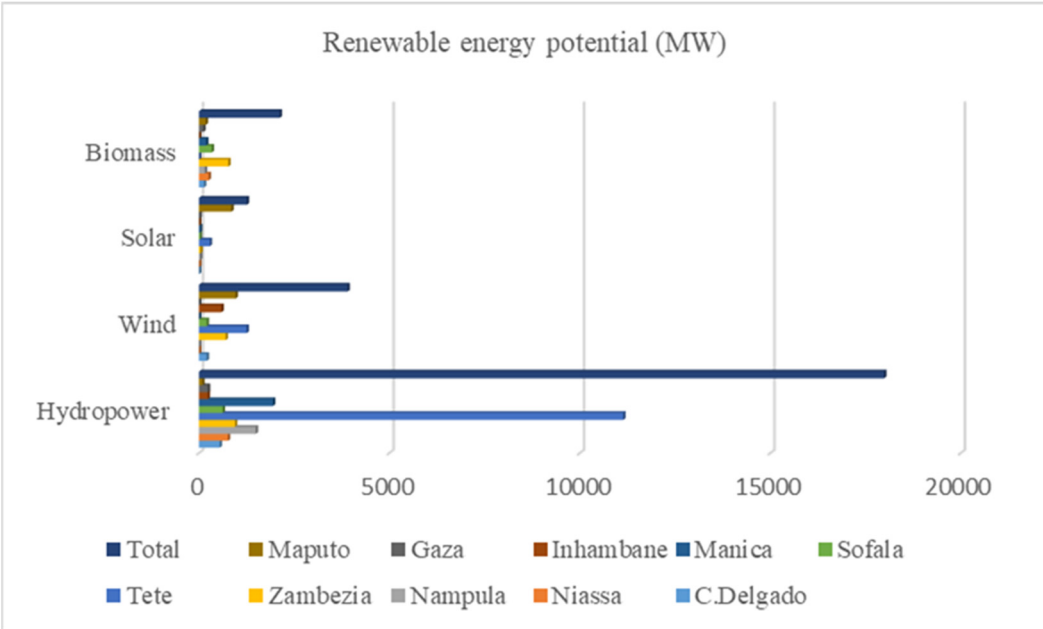

Figure 8. Renewable energy potential in Mozambique. Source: own elaboration.

About 40 Million metric tons of carbon dioxide equivalent (about 60% of national release) are released from emissions from land-use change and forestry (USAID, 2017). These emissions stem from agricultural expansion, wild fires, and harvesting for wood fuel including for firewood and charcoal. Emissions from other energy use represent about 6 million metric tons of carbon dioxide equivalent (about 9% of national release). These figures reveal that a substantial part of the CO2 emissions can be reduced by increasing the share of renewable energy.

PV systems pose specific advantages and the technology is developing quickly with continuously decreasing cost per produced kWh. Solar energy systems are especially suited for off-grid solutions and do not compete with the central grid, instead with the system that uses fuelwood, charcoal, and kerosene (Broto et al., 2018). It is estimated that about 2.2 MW solar power capacity has been installed in the country (Hussain, 2015; Broto et al., 2018). The focus of FUNAE is on solar PV systems even though it has also developed micro-hydro and pilot wind projects.

PV systems have, however, as well some disadvantages compared to other options. Batteries are usually required to store the electricity to maintain power during dark hours (Lahimer et al., 2013; Raman et al., 2012; Phuangpornpitak and Kumar,

2007). These batteries are often expensive and need replacement every 3-5 years. Due to batteries and other components, PV systems have large losses (Lahimer et al., 2013). At the same time, PV systems and batteries contain chemical hazards that need to be treated in a safe way.

Climate change will probably affect future river flow caused by less annual rainfall, increasing inter-annual variability, and less dry season river flow (Andersson et al., 2011). There is a close correlation between climate change and hydropower generation. With higher temperature, evapotranspiration will increase and reduce runoff in rivers and thus, reduce water levels in reservoirs. From this background, small-scale hydropower is probably more vulnerable due to less storage volumes (less ability to store water from one season to another) and less resilient as compared to large-scale hydropower and other renewables such as PV systems. To increase the resilience against climate change, it would probably be better to have a regional and national mix of renewable energy sources. However, also large hydropower plants such as the HCB are likely to be affected. The electricity output of HCB may be reduced with 20% until 2100 (Uamusse et al. 2019).

Figure 9 summarizes the outcome of the four-dimensional sustainability assessment for the rural electrification process in Manica Province. In the graph, the wider each point to the outside, the better the performance. It should be noted that the indicator values are merely indicative and should be interpreted in the relative context of other indicators. In general, the indicators reflect the situation at present for the electrification in Manica Province. Thus, even though renewables like PV systems and small-scale hydropower are suggested in rural electrification programs, the implementation is still in its establishment phase. In view of the interviews in Chua Village, the social acceptance stands out. The interviews with villagers indicated a potential demand of electricity in Chua Village corresponding to approximately twice the average actual consumption of electricity in Manica Province. The communal needs from hospital, school, and church would need to be added to the household demand. Environmental sustainability indicators are somewhat better than average, except for awareness. The potential here for the future is much larger than what is shown in the graph. Institutional sustainability indicators are better than average. Mozambique is a young country that has gone through a prolonged civil war. Thus, institutions and legislations are as well recently established. There appears, however, to be a political will to improve the state of affairs and rural electricity is underway. Economic sustainability is below average. The general funding of rural electrification is a conundrum. Efficient rural electrification has to consider scale and institutional strengthening. Donor organizations such as the GIZ work efficiently at the local scale. A national framework to support small and independent power producers would be necessary. However, at present, there is a lacking capacity for this.

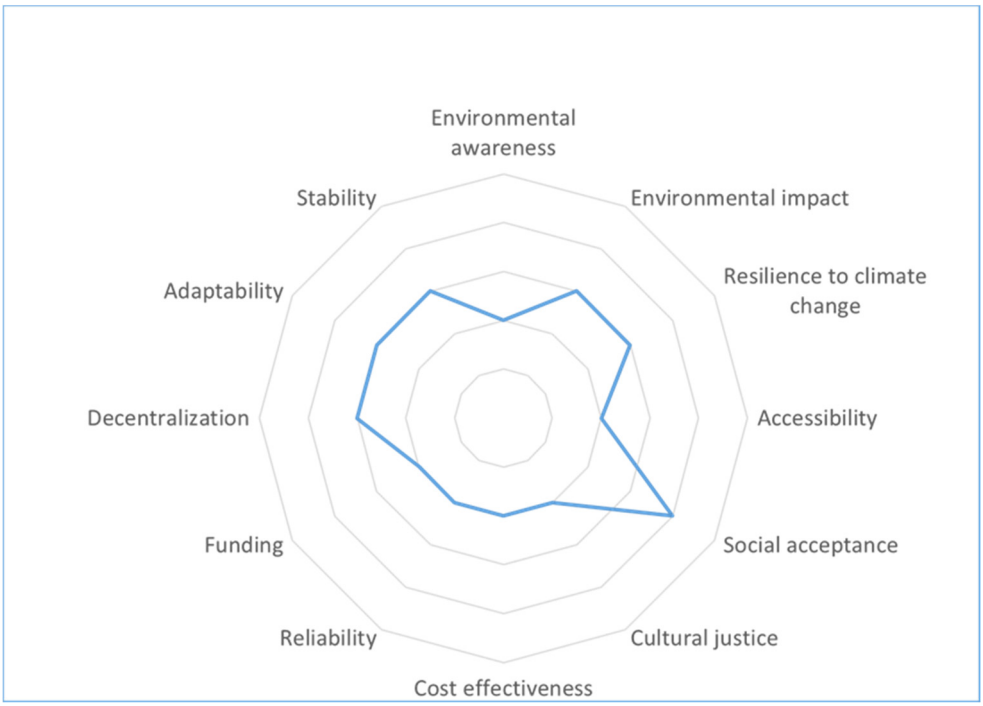

Figure 9. Summary of sustainability indicators for the investigated four sustainability dimensions. Source: own elaboration.

Cook (2011) and Estache and Fay (2007) argue that the following prerequisites need to be fulfilled to achieve access of electricity for rural poor, namely 1) instruments to ensure service operators providing access, 2) instruments to reduce connection costs using, e.g., tariff design or direct subsidies within payment plans to favor poor, and 3) instruments to increase the range of suppliers thereby giving alternatives for lower quality service providers. Providing electric power is one of the most dominant resources that the government has for catalyzing societal development within the country. Through electrification, it is possible to provide better services and job opportunities resulting in an improvement in the quality of life in rural areas (Ahlborg and Hammar, 2014).

The most promising energy sources at present for rural Mozambique have been considered as solar power and small-scale hydropower. Small-scale hydropower is a well-tested technique but needs to be adapted to local conditions and size of grid. The potential is huge, especially for the Manica Province. Interviews with household representatives in Chua Village show that there is a strong social acceptance to electrification. Simple small-scale hydropower for a community in a village or group of houses can be implemented using knowledge from villagers. Simple turbines and other parts of the generator can often be maintained or repaired

by the village smith. Cultural justice is therefore high especially for small hydropower schemes. Even though solar power represents similar advantages, the negative environmental impact from used batteries and parts and less durability, are not favorable. In order to speed up the rural electrification process, legislation needs to be improved, and there is a need for better institutional coordination for hydropower mini-grids' regulation (ALER, 2017). An obvious pre-requisite for successful implementation must always be strong local connection and participation. Mistrust between government and the rural population will inevitably lead to failed projects.

Other Sub-Saharan countries are struggling in a similar manner as Mozambique. However, on the positive side, Rwanda, with substantial rural poor population, has displayed positive effects of electrification (Bensch et al., 2011). Similar results have been achieved by South Africa (Dinkelman, 2011) and Cape Verde (Ranaboldo et al., 2014). As well, these countries have displayed creation of new job opportunities for the people, a clear growth in their economy, improved agricultural technology, educational facilities, and health conditions. In general, the access to electricity reduces the level of poverty and is important for sustainable development. As well, Tanzania has displayed a positive case study for prosperous mini-grid-focused policy measures. Tanzania now has over a hundred operating mini-grids, and is one of the leading African countries in this capacity (SEforALL, 2017). Between 2009 and 2015 a standardized 15-year power purchase agreement program for under 10 MW projects was continuously replaced by a feed-in-tariff, which mitigates high inflation and local currency fluctuations. Tanzania has as well waived connection costs for poor customers supplied via Rural Energy Agency projects.

Sub-Saharan countries like Gabon, Swaziland, and Kenya have all experienced a rapid growth in electrification. Access rates have increased by more than 50% between 2000 and 2016. Kenya is in the forefront in renewable energy in Africa. It has more than 40% of its electricity coming from non-hydro renewable resources (World Bank, 2018). Thus, there are several good examples of African developing countries where electrification pace is picking up. In a not too far future, hopefully they will be joined by Mozambique.

3.3 Mini-grid hydropower for rural electrification in Mozambique: meeting local needs with supply in a nexus approach (Paper II)

In the late 1990s, when peace came to Mozambique, a decade of marked development in the Chua area began. The German organization GIZ modernized parts of a system employed for milling corn. A hybrid system was developed for producing electricity to approximately 50 families, and a school and a hospital were built. Today, the area has five small hydropower plants, including the Tomás Wiston Ngurai plant that supplies 36 houses; the Gimy Pondo plant supplying 30 houses, as well as a hospital, twenty small shops, and four public lighting posts; and the Stephen Benjamim Mucheca plant supplying 30 houses, a school, a hospital, fifteen small shops, and four streetlights. Nevertheless, only a small portion of the Chua Village population is yet supplied by electricity. To motivate the societal buy-in to reach the SGD goal of 100% electrification by 2030, the demand for and use of electricity must be increased. At present, there is a marked difference between the production and the consumption of electricity. Mozambique produces large amounts of hydropower and has several hydropower projects underway besides the Mphanda Nkuwa such as the North Bank project (1,245 MW), the Lupata project (600 MW), the Boroma project with a capacity of 200 MW, and the Lurio project (120 MW) (Hussein, 2015). A major part of this is, however, destined for export.

To contribute meaningfully to the electrification ambitions of 2030, two important pre-requisites need to be fulfilled. The first is to work with the local population so as to engage these in the ambitions. Careful mapping of the local needs is very important. The second concerns the cost and ability of the locals to pay connection and operation fees. Figure 8 shows a comparison between the capacity of existing major hydropower plants in Mozambique and the cost per MW (FUNAE, 2013; EDM, 2018). The largest plant is obviously constituted by the HCB. Even though there is no simple relationship between size and cost, several of the smaller hydropower plants have similar low cost as the large HCB plant. It is thus, reasonable to expect that larger hydropower plants would be more economical due to higher efficiency at large-scale vs small-scale (Koutsoyiannis, 2011). A further advantage of large-scale vs small-scale hydropower systems is that large-scale systems can efficiently store energy and thus, they are more resilient against both climate variation and climate change.

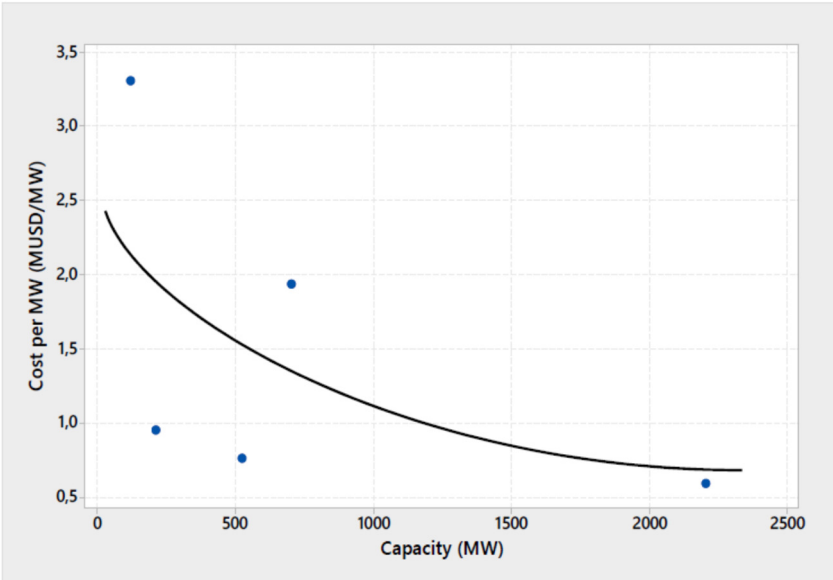

Figure 10. Relation between capacity of existing hydropower plants in Mozambique and their investment cost per MW. Source: own illustration with data from (FUNAE, 2013; EDM, 2018).

In general, the investment cost for small-scale hydropower in Mozambique has been estimated to about 570 USD/MWh while for large hydropower plants about 230 USD/MWh (FUNAE, 2013). Regarding the possibility of investing in wind energy, most of the projects of this kind identified by FUNAE have an investment cost of between 50 and 100 USD/MWh, whereas the solar energy facilities have an investment cost of about 100 to 150 USD/MWh (FUNAE, 2013; Branco, 2012). The investment cost of biomass-fueled plants in Mozambique is about 100 USD/MWh (FUNAE, 2013). The production cost of electricity in a hydropower plant can be rather low as compared to other forms of renewable energy, partly due to that the fuel involved is freely available water supplied by sun energy. The cost of electricity that is generated by large-scale hydropower ranges from 20 to 190 USD/MWh (Kaunda, 2012).

The interviews in Chua Village identified potential consumers of electricity according to Table 3. In general, interviewed people with access to electricity were quite unanimous in their belief that electricity had done much to change their lives for the better. Examples were given such as the creation of many small businesses and possibilities to communicate with distant family members. The rural household representatives were happy to have electricity for lighting their homes, watching television, listening to radio, and for different leisure activities, as well as for cooking and making life in general easier. According to the village head, about 520

households are in need of electricity. Other important public infrastructure is a hospital, a primary school, and a church. Besides these, there are 4 small shops, one administrative office, 2 grain mills, and 2 bars. According to the village head, besides households, prioritizing the hospital, primary school, and church is important. The shops, administrative office, grain mills, and bars have electricity access through sun panels and batteries or diesel generators. One of the grain mills is an old hybrid type used for both electricity generation and grain milling.

The electricity use that the households most often stated was lighting, ironing, television/radio, and mobile phones. Occasionally refrigeration was mentioned. For most villagers, however, a refrigerator implies a too high investment and energy consumption. For the hospital, primary school, and church, lighting was the first choice. Hospital representatives mentioned sterilization as an important use of electricity. Identified needs for each person in Chua Village households would approximately correspond to 3.0 kWh/day or 1,100 kWh per capita and year. Assuming that each household consists of 5.5 persons, Chua Village total needs would correspond to about 3,100 MWh (Table 4). The communal needs for the hospital, primary school, and church, would be added to this figure (75 MWh/year). Thus, total needs would correspond to 3,175 MWh/year (Table 4).

In general, the stated needs for electricity are more than twice the average consumption of electricity in Manica Province (1,100 as compared to 453 kWh per capita and year) (Public Private Infrastructure Advisory Facility, 2003). Using the lower figure for the total needs corresponds to about 1,300 MWh per year for the Chua Village (Table 4). Thus, stated needs appear to be much larger than existing average use. This would also mean that needs are real and exceeding supply. After adding communal needs, the total would add up to about 1,375 MWh/year (Table 4).

Table 3. Potential consumers of electricity in Chua Village.

Type	Consumer	Total
Private home	Households	520
Small business	Shops	4
Public infrastructure	Hospital	1
	Primary school	1
	Church	1
	Administrative office	1
Small industry	Grain mills	2
Leisure	Bars	2

In total, about one year of discharge records exist for the Chua River close to the village. The average discharge during the one-year observation period was about 0.15 m^3/s. The head for the potential diversion type run-of-river small hydropower plant was identified as about 50 m. This would yield an output power of about 60 kW (~80% efficiency) (BHA, 2012; ESHA, 2004; Kaunda, 2012). Consequently, a turbine would give a possible energy of about 500 MWh per year. In turn, this would

imply that about 80 households could be supplied by energy for the documented need of 3,100 MWh per year. On the other hand, if the lower rate of needs (average for Manica Province as a whole) equal to 1,300 MWh per year is accepted, this would mean that about 200 households could be supplied by electricity.

Table 4. Total energy needs and payment capacity of Chua Village assuming a) 1,100 (results from interviews) and b) 453 (average for Manica Province) kWh per capita and year, respectively.

Number of Households	Household Needs (MWh/year)	Communal Needs (MWh/year)	Total Needs (MWh/year)	Payment Capacity (USD/MWh)
(a) 520	3100	75	3175	8
(b) 520	1300	75	1375	19

The payment capacity of poor rural villagers in Mozambique has been estimated in several studies. Rural households without access to electricity have been estimated to potentially be willing to spend about 50 USD annually (out of 300 USD annual income) on substitute products like kerosene and batteries (Nielsen et al., 2015; Nhamire and Mosca, 2014). Another study estimated the willingness of 93% of rural households to spend about 48 USD per year on electricity (Zana, 2007). Since both results are fairly close, about 50 USD per household and year appear to be realistic. Thus, the payment capacity for households would correspond to 8 and 19 USD/MWh for the two cases in Table 4. It is interesting to note that the payment capacity in Table 4 (assumed average of 453 kWh per capita and year) is close to the lower limit of cost for generated large-scale hydropower as discussed above (20 USD/MWh). Thus, it appears that there are real economic incentives to supply rural Manica with hydropower. To further improve economy, small-scale hydropower schemes can be planned to be connected to small-scale business initiatives to further promote profitability. An example of this is shown below.

The above case study example shows that the investigated diversion type run-of-river small hydropower plant (500 MWh per year) is not enough for the total needs of Chua Village). The supply from the plant would give energy for 80-200 of totally 520 existing households. Including all electricity needs according to Table 4, the village would need 2-5 more similar-sized plants to fulfill all energy needs. The example shows the inherent difficulties involved in supplying remote rural areas in Mozambique with electricity. However, the example also indicates that the villagers have a real payment capacity of between 8-19 USD per MWh and year. Adding capacity for pumping surface or groundwater for domestic use or irrigated agriculture would further add to the above electricity needs. Thus, it is important that each small-scale hydropower project identifies local needs and economic drivers such as payment capacity and possibilities for connecting local small-scale business.

Figure 11 shows the return flow to the river from the powerhouse for one of the existing electricity generators in the area. The generator is a diversion type run-of-

river small hydropower plant that gives about 12 kW for an average flow of about 0.08 m^3/s. The powerhouse contains a Pelton turbine, transformer, generator, and milling equipment. This is a typical hybrid system used for grinding grain. The turbine receives water from a small reservoir through a penstock and then leaves the powerhouse through a draft tube back to the river. The head is about 75 m and the turbine gives electricity to about 130 households. The mill and turbine are part of a small-scale business that generates return to private investors. In a similar manner, to increase the economic profitability of the above suggested mini-grid hydropower system, small-scale industry would need to be included. For the studied Chua Village, this would preferable be constituted by a small-scale factory for milling of corn and other cereals. Rural electrification in Mozambique, would therefor also be part of the important water-food-energy nexus. This means that rural water management in a sustainable manner would contribute to energy, food production, and processing.

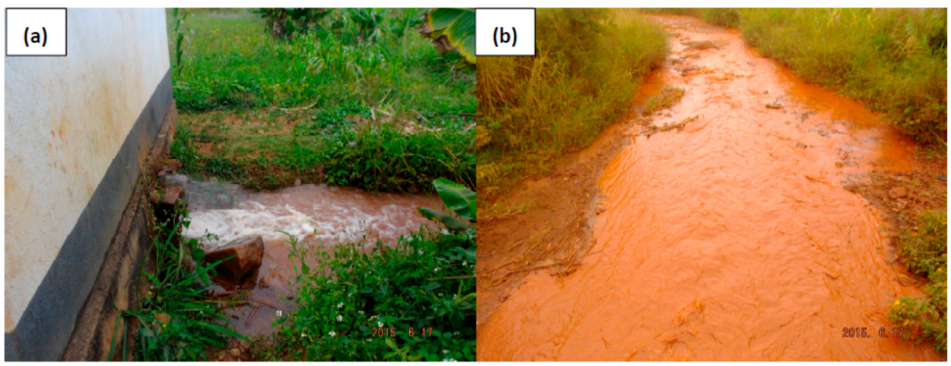

Figure 11. a) Outside of the powerhouse for one of the area´s hybrid generator for electricity and grain milling with return flow to the river. b) Example of sediment transported by the river water as a result of upstream deforestation and artisanal gold mining (photo by Miguel M. Uamusse).

Mozambique´s electrification challenges are common to many sub-Saharan countries (Nielsen et al., 2015). The situation for Mozambique, however, is unique in that it has huge hydropower resources that can be commonly developed between many sub-Saharan countries. The challenges include developing new infrastructure, develop institutional framework, and increase ability to pay for energy. The solution is complex and scale dependent. At the largest scale, national grids need to connect regions across country borders to support large-scale economic development (Nielsen et al., 2015). This is likely only realizable in the longer time scale. Developing an institutional framework for small-scale power allowing for increasing willingness pay for energy services is a goal that probably can be reached in the short-term. A nexus approach founded at the local scale involves as well economic drivers and security by connecting small-scale hydropower to local

industrial enterprises. Access to electricity will spur improved water supply that can improve health and food production. There are, however, also environmental challenges. Figure 11b shows an example of sediment transport in a nearby small river as a result of upstream deforestation and artisanal gold mining. Small-scale gold mining gives households an important extra income to the subsistence agriculture. However, this also leads to destroying the natural forest, serious erosion problems, and siltation in downstream reservoirs. Due to inappropriate use of mercury in the gold amalgamation process, serious pollution problems occur both in soil and downstream water (UniZambeze & Mining Development Fund, 2012). It is thus, important that authorities and environmental organizations set up framework for small-scale gold mining.

Small-scale hydropower presents some general advantages over other renewables such as solar power for rural Mozambique at locations like Chua Village. Total solar power use is at present very small but growing steadily in rural areas due to general affordability, ease of use, and simple installment (Uamusse et al., 2019). Solar power systems, however, contain hazardous constituents and batteries such as, e.g., heavy metals (Lahimer et al., 2013). There is no system or infrastructure for re-use or collection of old batteries and other parts of used solar panels in rural areas of Mozambique. Consequently, especially regarding the rather short lifespan of solar panel systems, used parts and old batteries are likely to end up in the general waste deposits of the rural villages. Solar panels are as well accessible for theft. Small-scale hydropower is a simple and well-proven technique with simple parts. Faulty or worn parts can often be manufactured or repaired by the village smith or other handy villagers. Since there is a long tradition to use small-scale hydropower in many rural areas in Mozambique, rural villagers often have a good understanding of how to plan, build, and maintain small hydropower plants. Small-scale hydropower, as it is used in hilly areas of rural Mozambique, has a greater net capacity (ratio of actual electrical energy output to maximum possible electrical energy output over time) than, e.g., solar power. In general, hydropower also represents greater efficiency as compared to solar power. Due to that small streams in rural Manica hilly areas often drain groundwater (or springs), the seasonal variation in flow may be rather small due to that a large part of the discharge is base flow that gives a rather stable mean discharge rate.

Small-scale hydropower, on the other hand, requires larger investment cost and available capital as compared to family-based solar panel systems. However, small-scale private businesses may be benefit from investing in hydropower and enjoy a stable economic return. As well, small-scale hydropower, linking a group of households together in a mini-grid system, may improve the socioeconomic cohesion of the scattered rural homesteads. Climate change is likely to affect the future river flow by less annual rainfall, increasing inter-annual variability, and smaller dry season river flow (Andersson et al., 2011). In this context, small-scale hydropower is more vulnerable and less resilient as compared to large-scale

hydropower and other renewables. In view of this, it would be better to have a national mix of renewable energy sources for a greater resilience against climate variation and climate change.

3.4 Climate change effects on hydropower plants in Mozambique (Paper III)

Climate change is projected to alter the frequency of precipitation, floods and drought events in Mozambique. Regional studies have been made for the largest river basin Zambezi River, where estimates point at an output from major Zambezi hydropower plants to decline by 10–20% under a drying climate (Spalding-Fecher et al., 2017). To mediate the potential reduction, Spalding-Fecher et al. (2017) argue for an increased cooperative governance arrangement to manage shared water resources in the entire southern African region, which could be enhanced by targeted political initiatives.

The Zambezi River has two of the largest dams in the world, Kariba and Cahora Bassa, which both will be substantially affected by increased evapotranspiration and decreased precipitation. The Kariba dam forms Lake Kariba, which extends for 280 km and holds 185 km^3 of water (Spalding-Fecher et al., 2014). The Cahora Bassa dam forms the Cahora Bassa Lake, which extends for 292 km and holds 56 km^3 of water. The flow of the Zambezi River may decrease by 40% or more due to climate change (Hamududu and Killingtveit, 2016). The precipitation is estimated to be reduced by 15% and the evaporative losses increasing up to 25%. This may to a large extent be applicable for all major river basins in Mozambique. A decrease in runoff reduces the economic benefits of a hydropower plant fed by the river, increasing the need for careful investment analysis of new hydropower plants.

The demand for electricity in Mozambique, where 15% more households have been connected to the grid the last 5 years, is expected to increase rapidly. In addition, the need for electricity in industry and public work further increases each year in Mozambique, meaning that the demand for electricity will continue to increase in the coming 30 years. Spalding-Fecher et al. (2017) argue for a policy development in the energy sector, not only in Mozambique but within the entire region of southern Africa. A combination of excessive use of reservoirs and low precipitation directly reduces the electricity output from hydropower. Future changes in climate could reduce the performance of the plant and reduce the economic output, as well as the power production. This may decrease the economic growth in southern Africa, particularly in hydropower depending countries like Zambia and Mozambique. To mediate these risks from climate variability and long-term climate change, there is a need for strong and cooperative governance arrangements to manage shared water resources with the help of integrated water resource management tools. The probable expansion of irrigation and construction of new dams and hydropower stations will intensify the need for cooperative governance between the countries sharing the trans-boundary rivers. Not least is an economic viable structure necessary which can cover costs and support additional investments,

such as larger storage of water and additional alternative power supply sources to guarantee the future delivery of power.

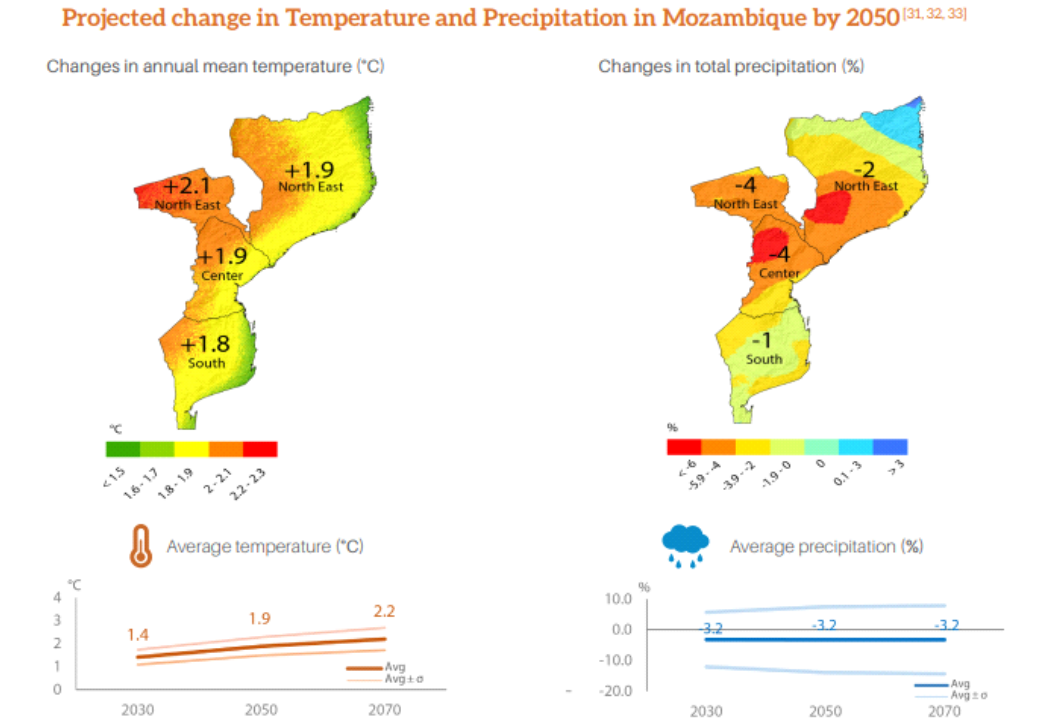

Figure 12. Projected increase in temperature and precipitation in Mozambique by 2050. Source: Irish Aid (2016).

Mozambique is extremely vulnerable to climate change and climate variation because of the location and geographical conditions and large areas of the country are exposed to tropical cyclones and droughts. Every three to four years, the phenomenon is repeating and river, coastal area suffering of flooding. This vulnerability is heightened by the country's 2,470 km of coastline and socioeconomic fragility. More than 60% of the population live in low-lying coastal areas, where intense storms from the Indian Ocean and sea level rise put infrastructure, coastal agriculture, key ecosystems and fisheries at risk. Increased frequency and severity of intense storms, droughts and floods are likely to exacerbate these development challenges. For example, the Idai Tropical Cyclone which hurtled into the Mozambique´s coastline on March 14 2019 flooded 2,515 km^2 of the low lying plain in the central of the country. It caused more than 500 deaths, the final figure will maybe never be known since many bodies were washed out to the sea. In total the floods caused by Idai are thought to have affected the lives

of some 1.8 million Mozambicans. About 90% of Beira Municipalities was devastating or destroyed by the cyclone. In 2000, a large-scale flooding in the south-central part of Mozambique killed almost 700 persons (Economist, 2019).

Figure 13 shows the trend in temperature for October to March in the Ara-Centro region. There is clear statistical positive temperature trend during the last four decades from 1973 to 2012.

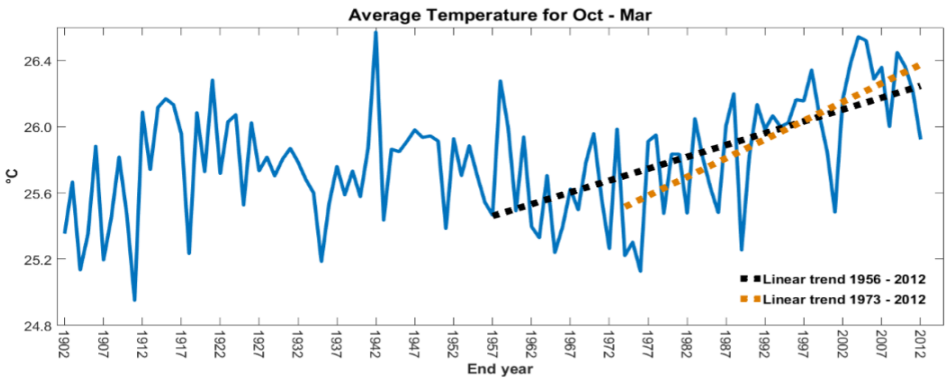

Figure 13. Trend in temperature for October to March in the Ara-Centro region.

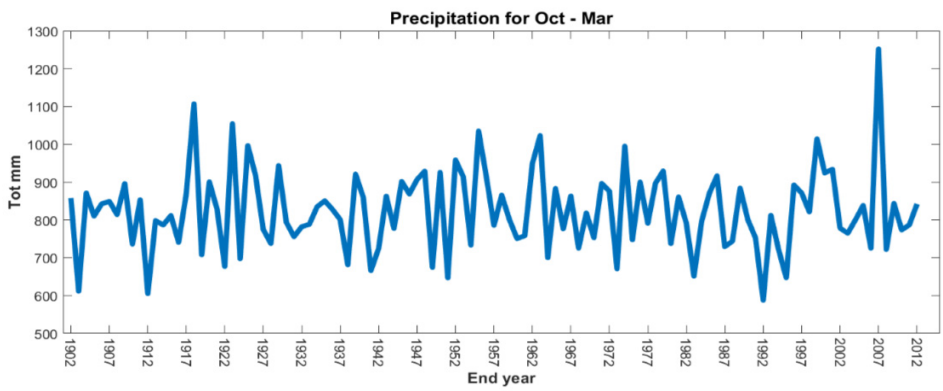

Figure 14. Time series of October to March precipitation for the Ara-Centro region.

For October to March precipitation, as seen in Figure 14, no significant trend is visible. Climate change scenarios do suggest an increase in precipitation due to warmer climate, yet with a faster increase in temperature. The evapotranspiration will increase faster than precipitation. The evaporation will continue to reduce the available water in the river basins and alter the runoff for the hydropower plants.

In the climate scenarios projected by GCMs (CSIRO 3.0, CGCM3.1, ECHAM5, CCSM3.0, HACDM3), a 10% decrease in runoff during the rainy season and a 12% decrease during the dry season is estimated for the coming 10 years. Until 2100 the runoff may decrease even further, down to -18% in the rainy season and -20% in the dry season. A lower runoff will immediately affect the hydropower production. The total electricity generation will decrease in accordance with the available flow to the reservoirs. Taking Cahora Bassa as an example, the total capacity of the plant is at present 2,075 MW and the yearly standard/normal generation of electricity for the plant is almost 19 TWh. The Zambezi River flow is, however, never that high all year round. For instance, the electricity generation in 2016 was 15.6 TWh and due to drought in 2017, the electricity generation decreased that year with 11.5%, down to 13.8 TWh. A further reduction in flow to the Cahora Bassa dam with 20% would decrease the electricity generation further, maybe down to 12.5 TWh per year. Assuming a steady growth of electricity consumption in Mozambique requires a continuous development of hydropower stations.

Mozambique has a large number of economically suitable rivers and gorges that could be exploited for hydropower generation. What is notable from a power supply point of view is that with reduced runoff to the hydropower stations, their maximum capacities cannot be utilized all year around. Instead, the total power generation available during a year will be cut with 10-20% in the 21st century due to climate change, increased evapotranspiration, and decreased runoff.

Depending on growth assumptions and economic development, the southern African regional power generation capacity will increase from 52 GW to about 1,000 GW in 2070, a 20-fold increase (Spalding-Fecher, 2018). This is approximately the same growth rate as for Mozambique itself. The capex cost for a large hydropower plant is in the range of US$50 per MWh. To build a new plant like Cahora Bassa (with an annual generation of about 15 TWh) could be estimated to cost US$750 million. Assuming that all hydropower potential in Mozambique would be utilized, the total investment cost for additional 16,000 MW would be in the range of US$8-10 billion. Capital is generally difficult to raise in southern Africa, yet the need for electricity and the willingness to pay is high in the region. Increased sustainable power generation will benefit all countries in the southern part of Africa. Therefore, one important step to facilitate an expansion of the hydropower generation in Mozambique is to increase the economic collaboration with neighboring countries and increase the electricity transmission capacity within and between the countries. The joint European electricity market may possibly be one inspiration for the southern African countries on how to organize the supply and transmission. Central for the southern African countries is probably to continue collaboration and develop mutual organisations to utilize the important hydropower potential of the watersheds.

When investigating potential hydropower projects in Mozambique, it is necessary to take into account that the climate change effects on river runoff will decrease the

annual capacity of the plant with 10-20% and reduce the electricity generation. Particularly, in the investment calculations, the long-term pay-off of investments should be noticed. The need for sustainable and renewable electricity generation is, however, urgent in southern Africa and investment projects should therefore be considered carefully in the feasibility phase considering that they may need to operate for a longer period before delivering profit to the owners.

3.5 Gasification of cashew nut shell using gasifier stove in Mozambique (Paper IV)

Gasification is a thermo-chemical process at high temperature that converts carbon containing fuels, such as coal and biomass, into a combustible gas containing mainly carbon monoxide, hydrogen, methane, and inert gases, through incomplete combustion and reduction. In the beginning of the 1800's, gasifiers were used for industrial power and heating applications until in the 1920's, when oil-fueled systems gradually took over the systems fueled by producer gas. It is also noted that unreliable supplies of petroleum gas revitalized gasifiers during World War II and it was intensively used in transportation and on farm systems. Gasification is appealing since:

1) Combustible gas can be used in internal combustion engines or gas turbines (enabling high efficient power generation), burned directly or used in the production of methanol or hydrogen.

2) Gaseous fuel needs little excess air in combustion and has low levels of contaminants.

3) Enables solid fuels to replace oil, considering the rising oil price and climate change effects.

Eventually, gasification technology is currently identified as a sustainable renewable alternative for energy generation with zero impact to the environment.

Moisture content is one of the most significant properties of any biomass that are known to affect the gasification process. Moisture constraints any gasifier fuel and are dependent on type of gasifier used. Upper limit acceptable for a downdraft reactor is generally considered to be about 40% on a dry basis specified that moisture content of feedstock should be below 33% for generating a burnable, good quality gas. Moisture contents higher than 67% make the product gas too lean for ignition.

The cashew nut shell is about 0.3 cm thick, having a soft feathery outer skin and a thin hard inner skin. Between these skins is the honeycomb structure containing the shells. Cashew nut shells are high energy content residues from cashew nut processing. It can potentially replace fuel wood for thermal application in a factory. However, direct combustion of cashew nut shells is troublesome due to low combustion efficiency and high smoke emission.

Cashew nut shell samples (see Fig. 15) used for this study were obtained from a waste cashew nut shell dumping site in Gaza Province of Mozambique. The collected samples were grounded to about 1 mm particle size prior for characterization. Traditionally, extraction of the kernel from the shell of the cashew

nut is a manual operation. The nut is roasted making the shell brittle and loosens the kernel from the inside of the shell. By soaking the nuts in water, the moisture content of the kernel is raised, reducing the risk of being scorched during roasting and making it more flexible and avoid cracking. Subsequently the shells are released when the nuts are roasted.

Figure 15. Example of cashew nut shell waste.

The approximate analysis of cashew nut shell revealed suitability of the fuel for gasification. It is observed that, the average moisture content of cashew nut shell waste was about 4%. The moisture content of the fuels under study is in the acceptable limit to ensure free flow and good quality gas production. The average of volatile matter content in Cashew Nut Shell was found to be 73%. The higher

amount of volatile matter revealed the suitability of the fuel for gasification, since the recommended minimum value is 73%. Also the data indicated that, the average ash content of the cashew nut shell was about 8% which revealed their suitability for the gasification since the maximum allowed is 26%. Fixed carbon is a most desirable component, which governs the suitability of the fuel for gasification. The average fixed carbon was found to be about 15% in cashew nut shell while the heating value of was found to be 24.2 MJ/kg.

The main findings of this study was:

1) The fuel properties of the cashew nut shell waste revealed its suitability for gasification. The sampled cashew nut shells had low moisture content (4.2%), low ash content (7.5%), and a heating value of 24.2 MJ/kg against the recommended values 6.7%, 26.2%, and 21.5 MJ/kg, respectively.

2) Thermo-gravimetric analysis showed that the shells have about 94% volatile matter which is suitable for gasification. The minimum required value is 73.2%. The average residue content of the cashew nut shell was found to be about 2%, which reveal the suitability for the gasification with minimum blocking of flow of air and fuel against the minimum recommended value of 35%.

Proper utilization of the cashew nut shell waste through gasification will conserve the biomass fuel and make its use self-sustainable for thermal energy. The shells can be used for domestic cooking and heating instead of relying on fossil fuel and gas.

4. Conclusions and recommendations

Poverty is characterized by a decline in human conditions, lack of food, lack of safe drinking water, lack of adequate sanitation, lack of adequate health care, lack of adequate educational opportunities, and finally lack of readily available information that people should have access to. A central element in the alleviation of poverty is providing people with access to reliable electricity. The general lack of electricity for the majority of the people living in the Manica region is the most serious obstacle for poverty eradication. About two million people here, still have no electricity available in their homes. Yet for the population in of Chua, where some of the field studies took place, agriculture was improving through electrical pumping of water. These activities are generating small job opportunities, and by supplying the much needed energy for small industries, small businesses are being established, together with possibilities for health care and education.

The general objectives of this thesis, as stated in chapter 1.2, was to achieve a better understanding of how renewable energy, based on use of off-grid systems in rural Mozambique can be used to combat poverty. In view of this, the study can conclude the following on the three basic research questions connected to the above general objectives:

A. What is the status of Mozambique´s energy sector and what is the potential for off-grid sustainable energy solutions in rural areas (Paper I)? The current energy development policy is centralized. It would be preferable to give external investors in the electrical sector better independence in rural areas where problems of electricity availability are critical. There are clear advantages in decentralizing the energy sector through use of mini-grid systems. For these, the initial investment costs are low in comparison to extending the national grid. national grid. Paper I indicates difficulties in evaluating the general sustainability of different off-grid systems. However, at present it appears that a mix of grid and off-grid systems with a mix of energy sources may be advantageous.

B. To what extent can mini-grid hydropower systems be efficient in improving rural electrification and meeting local needs in energy supply (Paper II) and to what extent can the climate change affect the efficiency of electricity generation from hydropower plants? (Paper III). To speed up and build rural electrification in a sustainable manner, off-grid and mini-grid solutions should constitute parts of the

important water-food-energy nexus. Successful existing local applications of off-grid and mini-grid systems build on a combination of energy provision, water supply (safe sanitation), and food production or processing. Climate change is likely to affect the future energy sector in the future in Mozambique. Climate change will probably decrease the future river flow, increase inter-annual variability, and lead to smaller dry season river flow. In this context, small-scale hydropower may be more vulnerable and less resilient as compared to large-scale hydropower and other renewables. In view of this, it is likely better to have a national mix of renewable energy sources for a greater resilience against climate variation and climate change. An important step is to facilitate an expansion of the hydropower generation in Mozambique by increasing the economic collaboration with neighboring countries and increase the electricity transmission capacity within and between the countries.

C. Could other alternatives in household energy sources such as biomass waste (cashew nut shells) be complementary energy source when implementing hydropower plants? (Paper IV) and what is the joint effect in using both energy sources? Proper utilization of existing biomass waste has a great potential to generate energy in Mozambique. Since most of the population already use biomass to produce energy, the next step would be to introduce simple and sustainable gasifiers to produce self-sustainable thermal energy. The study on cashew nut shell waste shows, which is a common bio-waste in Mozambique, that shells can be used for domestic cooking and heating instead of relying on fossil fuel and gas. Thus, cashew nut shell waste fits into the above mentioned national mix of renewable energy sources for a greater resilience against climate variation and climate change.

In addition to the research objective C above, future work is needed to select biomass types with high energy content to be included in the priority list of biomass waste for energy. Examples of such biomass are coconuts shells and other agricultural residues. For this purpose, as well, it is important to study possible types of gas turbines that may be suitable for connection to gasifiers to produce electricity. In my dissertation work, I focused on electrification and analyzing mini-grid systems based on hydropower. However, biomass can as well be useful for rural electrification. I would suggest that also other types of technologies such as biogas production could be studied. Examples of this is efficient bio-digesters that can be used in rural areas. I recently participated in a pilot project on this carried out in the town of Boane near Maputo together with a group of researchers from Eduardo Mondlane University. It shows promising results.

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Miguel Meque Uamusse is a chemical Engineer from Eduardo Mondlane University (Mozambique). He started his career in 2009 as an Assistant Lecturer at Faculty of Engineering at Eduardo Mondlane University. He graduated with a Master's degree in Renewable Energy from the University Dar-es-Salaam in Tanzania in 2012. In 2014, he was awarded a PhD scholarship in Sweden funded by the Swedish International Development Agency (SIDA) through the Integrated Water Resources Management (IWRM) Program for Sustainable Development in Southern Mozambique. Accordingly, he carried out a PhD thesis study at Lund University through a bilateral cooperation between the governments of Mozambique and Sweden. Dr. Uamusse's research focuses on renewable energy technology and water resources. In connection with renewable energy he specializes on biomass, solar and hydropower energy as solutions to problems of rural electrification in Mozambique.

In the thesis, he investigates possibilities of hydropower and biomass energy as solutions to rural electrification needs in Mozambique. Improving the access to electricity can significantly contribute to alleviation of poverty. His work provides a strategy for researchers, policy makers, and electrification stakeholders, in gaining a clear understanding of how the national energy policy in Mozambique can improve in providing universal access to electricity in rural areas.

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