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End-user evaluation of Solar Home System as a viable energy system for rural development in South Africa

Sluttbrukerevaluering av Solar Home System som et vellykket energisystem for rural utvikling i Sør Afrika

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Preface

This thesis marks the end of my Master´s thesis degree in Renewable Energy at the Norwegian University of Life Science (NMBU). It has been two great years surrounded by amazing classmates and friends.

The thesis subject was introduced to me by Engineers Without Borders, NMBU, in cooperation with Solar Energy without Borders w/ Tommy Fernandez. Being able to visit and learn about the Solar Home System arrangement in South Africa have opened my eyes for the challenges and opportunities for electrification of rural areas.

I am grateful to Solar Energy Without Borders for giving me this assignment and Engineers Without Boarders for sponsoring my fieldwork.
The work would not have been possible without the great help from Rotary Polokwane and Rotary Climate Change Group for arranging my stay in Polokwane. Further, all the assistance from Solar Vision during my fieldwork and for answering all my questions through the whole process have been valuable.

I would also thank my supervisor Muyiwa Samuel Adaramola for taking on this work and helping me through this process.

Finally, I want to thank friends and family for support and help through this process, it would not have been possible to do this without your help!

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Monika Mannes

Abstract

In 2001, South Africa's government initiated an electrification programme with ambitions to improve its rural electrification access rate. Therefore, the government provided remote and rural areas without access to the grid with Solar Home Systems (SHSs). This study has evaluated whether the SHS has contributed to improved welfare for the users, and in which ways. The success of the fee for service arrangement and electricity demand beyond the given amount from the SHS has also been investigated. Two alternative solutions consisting of two mini-grid systems have been examined to evaluate if they had the potential to be a better solution for South Africa's rural electrification in the future.

Qualitative interviews were carried out in the Limpopo province to gather information directly from the SHS users. Data on consumption and demand beyond the energy provided by the SHS was also collected. Mini-$grid_1$ was dimensioned for the same energy production as the SHS, while mini-$grid_2$ was dimensioned to provide users with additional power to cover their demand for fridges found during the research. The systems were dimensioned using equations provided n chapter three and using the methods described in chapter four.

The results showed that the end-users were pleased with the SHSs due to various reasons. The SHS resulted in reduced spending on lighting and phone charging. Furthermore, the interviewees experienced increased level of safety when candles were replaced with electric lights. The electric lights quality improved the possibility for children to study after dark.

Mini-$grid_1$ was estimated to have a LCOE of 1.3 ZAR/kWh, Mini-$grid_2$: 1.4 ZAR/kWh and the SHS: 28 ZAR/kWh. The payback period for both mini-grids were 15 years, while the SHS had 41 years. This indicates that a mini-grid system could be a more economically viable solution.

There are concerns attached to mini-grids regarding ownership and payment. There are also benefits due to the possibility of connecting the mini-grid to the main grid and supply electricity should be included in such a decision. Further, future investment in solar PV has the potential to provide cheaper electricity than the grid in South Africa. These are factors that need to be considered before changing the systems.

Sammendrag

Sør-Afrikas myndigheter startet i 2001 et program med ambisjoner om å øke andelen elektrifiserte rurale områder. Dette gjorde de ved å tilby Solar Home Systems (SHS) til områder med tilgang til det nasjonale strømnettet. Denne studien har evaluert dette programmet i et sluttbruker-perspektiv med fokus på i hvilken grad programmet har bidratt til økt velstand og på hvilke måter. Det har også blitt sett på hvordan den nåværende betalingsordningen med månedlige avgifter for vedlikehold av systemene fungerer. Videre ble det undersøkt hvilke behov brukerne har utover den energimengden SHS gir dem. To alternative mini-grids ble skalert og vurdert som alternativ til den nåværende ordningen. Disse alternativene er evaluert opp mot SHS med tanke på energiforsyning og økonomi.

Kvalitative intervjuer ble gjennomført i Limpopo provinsen for å hente inn informasjon direkte fra brukerne. Forbruksdata og etterspørsel utover nåværende energimengde ble hentet gjennom de samme intervjuene. Mini-$grid_1$ ble dimensjonert for å dekke lik produksjon som SHS, og mini-grid2 ble skalert opp for å produsere nok mengde energi til at alle husholdningene kunne koble til kjøleskap, som i følge intervjuene var det folk ønsket fra systemet.

Resultatene viste at sluttbrukerne var fornøyde med dagens system. Overgangen fra tradisjonell belysning og betaling for telefonlading til SHS medførte en månedlig sparing på ZAR 137. Brukerne opplevde økt trygghet i hjemmet ved bruk av elektriske lys, og mulighetene for lekselesing økte. LCOE for systemene ble funnet til følgende: mini-$grid_1$: 1.2 ZAR/kWh, mini-$grid_2$: 1.4 ZAR/kWh og SHS: 28 ZAR/kWh. Tilbakebetalingstiden for begge mini-gridene var 15 år og SHS 41 år. Dette indikerer at mini-grid løsningene er mer lønnsomme løsninger.

En overgang til bruk av mini-grid innebærer noen utfordringer angående eierskap og betaling. På den andre siden er muligheten for å koble mini-gridet til det nasjonale strømnettet når det blir bygget ut til området noe som også må tas med i en slik evaluering. Fremtidige investeringer i solcelle teknologi har potensialet for å produsere elektrisitet til en lavere kostnad enn prisen på strøm fra strømnettet i fremtiden.

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Acronyms and abbreviations

BoS: Balance of System components

FBE: Free basic electricity ESKOM: South African electricity supply company

ESCO: Energy service company

IEA: International Energy Agency

Irradiation: (kWh/m^2/day)

INEP: Integrated National Electrification Programme

kW: kilo Watt (effect)

kWh: kilo watt hour (energy)

LCOE: Levelized cost of energy

Mini-grid$_1$: Mini-grid system providing the same amount of energy as the SHS

Mini-grid$_2$: Mini-grid system providing additional energy

NPV: Net present value

O&M: Operation and maintenance

PV: Photovoltaic

Radiation: (kW/m^2)

SHS: Solar home system

$W_{p:}$ Watt peak

1 Introduction

Access to modern energy is fundamental for both sustainable and economic development to improve standard of living. This has been common knowledge for years, nevertheless more than 1.1 billion people are still without access to electricity (IEA, 2016; WEO, 2016; WEO, 2016). The lack of modern energy services hampers the basic services provision like education and health care. Smoke from pollution, heating devices and inefficient cooking are estimated to kill about four million people globally each year (World Health Organization, 2016). These local pollutions also impact the global effect of climate change. Therefore, most countries are implementing policies that encourage energy systems development based on renewable energy resources (Panwar, 2011; Osusu, 2016).

Electricity access varies between continents, countries and among citizens within a country. Globally, most non-electrified communities are found in rural areas (especially in the Sub-Saharan region). In 2014, Sub-Saharan Africa had an overall 19 % rural electrification rate (see Table 1-1) (WEO, 2016). South Africa, however, stood out, with its 85 % rural electrification rate (see Table 1-1). This can partly be explained by South Africa's Solar Home System (SHS) programme that started in 2001. This thesis examines this programmes´ success in an end-user perspective, and provides two alternative mini-grid systems to evaluate whether these have potential to become a better techno-economic solution in the future.

Table 1-1: Urban and rural electrification rates in Africa (WEO, 2016)

	Population without electricity (millions)	Electrification rate (%)	Urban electrification rate (%)	Rural electrification rate (%)
Africa	634	45 %	71 %	28 %
North Africa	*1*	*99 %*	*100 %*	*99 %*
Sub-Saharan Africa	*632*	*35 %*	*63 %*	*19 %*
South Africa	*8*	*86 %*	*87 %*	*85 %*

1.1 Previous studies

The SHS as a viable technology for development in South Africa has turned out to be a controversial issue. Some researchers support the SHS while others questions these systems as a contributor to development. Researchers and organizations have reviewed the SHS in aspects like economy, social impact, different technology problems and the fee for service arrangement. According to studies (Laufer, 2011; Azimoh, 2015), the fee for service approach can be a good way to sustain the SHS arrangement. However, to make it efficient and sustainable, most studies agree that some preconditions need to be in place (Azimoh, 2016; Energy & Development Research Centre, 2003; Lemaire, 2011). Only a few studies (e.g. Azimoh et al. (2015) and Laufer & Shäfer (2011)) based their research on direct conversations with end-users.

Results from previous studies provided the outline for this research. It was interesting to investigate if the preconditions for a successful operation and maintenance (O&M) arrangement using fee for service were followed in the Limpopo province and how the SHS affected peoples daily life.

1.2 Objectives and limitations

This study is based on fieldwork conducted from SHS users in five villages in the Limpopo province in South Africa. It examines how the system owners evaluate the arrangement. It also provides possible ways of reducing observed shortcomings to improve future systems in order to meet the users need. Therefore, the thesis objectives are:

- Investigate the Solar Home System programme´s success in an end-users perspective
- Consider two mini-grid systems as alternatives to the current small scale SHSs and compare the economic viability of the options

The evaluation of the programme´s success in end-user perspective was assessed using following criteria:

- Have the SHSs contributed to improved welfare for the users?
- How well are these systems functioning in meeting the villagers electrical needs
- Have the SHSs impacted the users economy?
- How well is the fee for service arrangement working?

Further, data collected from the interviews were used to construct the average daily load profile. This was used as a base to evaluate the two alternative mini-grid solutions for 50 households. The first mini-grid (mini-grid$_1$) covers the daily supply received from the SHS.

The second mini-grid (mini-$grid_2$) was extended to cover the additional needs discovered during the research. These mini-grid solutions and the current SHS solution were compared using the following economic criteria:

- Investment cost
- Levelized cost of energy
- Payback period

Finally, solar technology and battery price trends, and development in South Africas grid price toward 2025 were examined and used to discuss solar technologies profitability in the future.

2 Background

2.1 General electrification process

Electrification processes are generally divided into two phases. The first phase involves establishment of institutions responsible to regulate and facilitate the electricity systems (Bekker, 2008). This phase focuses on electrification of the economy as whole, primarily urban areas. The second phase includes electrifying areas omitted in the first round, typically rural areas. This phase is more complicated and more expensive. Distances between settlements and households are longer and people living in these areas have, in general, less income to pay for the electricity services in comparison to people in urban areas. Therefore, electrifying rural or remote areas is considered last priority in most countries, especially developing countries. However, there are two main motivations for carrying out electrification in these areas. First, electrification of remote areas has potential for promoting local economic development which reduce or prevent rural-urban migration. Secondly, it can reduce or remove problems concerning energy poverty and improve standard of living.

2.2 Electrification process for South Africa

There has been an expansion in homes with access to electricity since the 1990s in South Africa. Prior to 1990, the electrification rate was 56 % (The World Bank, 2017). In 2000 this number had reached 70 %. However, the rural electrification rate in 2001 was below 50 % (The World Bank, 2017), which was a problem to address.

In 2001, the government of South Africa initiated the Integrated National Electrification Programme (INEP). This programme included a broad set of development criteria. The free basic electricity (FBE) for poor households where introduced, and an off-grid PV-programme for remote and rural areas were implemented. This was the Solar Home System (SHS) programme. The government is responsible to pay the investment cost for the SHSs for people without access to the grid (Eskom, 2016). Through the INEP programme, electricity access rate have tremendously increased, and in 2014, the rural electrification rate in South Africa had reached 85 % (WEO, 2016).

2.3 Installed capacity in South Africa

The total installed capacity in South Africa was 46 million kW in 2014 (Central Intelligence Agency, 2017). The energy mix for 2013 is shown in Figure 2-1. Fossil fuel, mainly coal, was the main energy resource. Renewable energy sources stood for only 5.2 %.

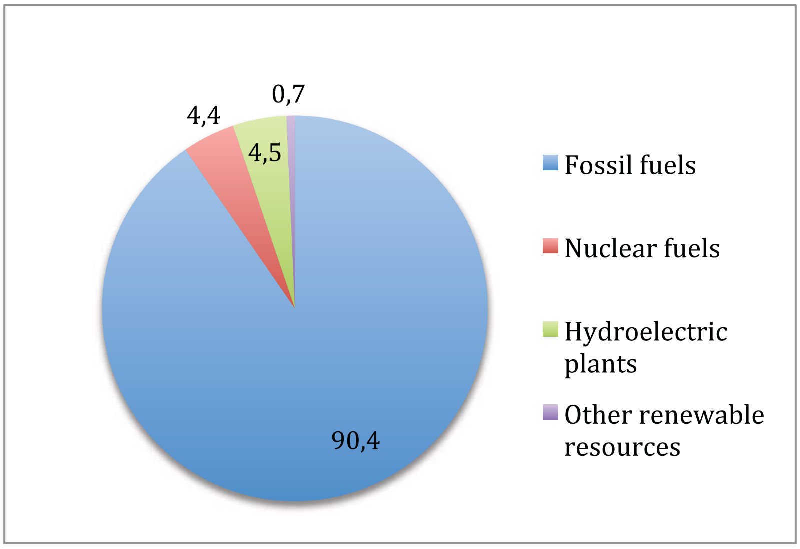

Figure 2-1: Installed capacity in South Africa (2013) divided on energy resources (Central Intelligence Agency, 2017)

2.4 The Solar Home System (SHS) Project

Due to challenges related to topography, South African authorities decided the non-grid Solar Home Systems (SHS) could be a good temporary alternative, while awaiting the grid extension to the whole country (Africa, 2012). The Solar Home System is considered an environmentally friendly technology with low operation and maintenance costs.

2.4.1 Description of a Solar Home System

Figure 2-2 illustrated the main components of a SHS. The radiation from the sun hits the PV module and energy is sent through the charge controller and further on to the battery or directly to the appliances.

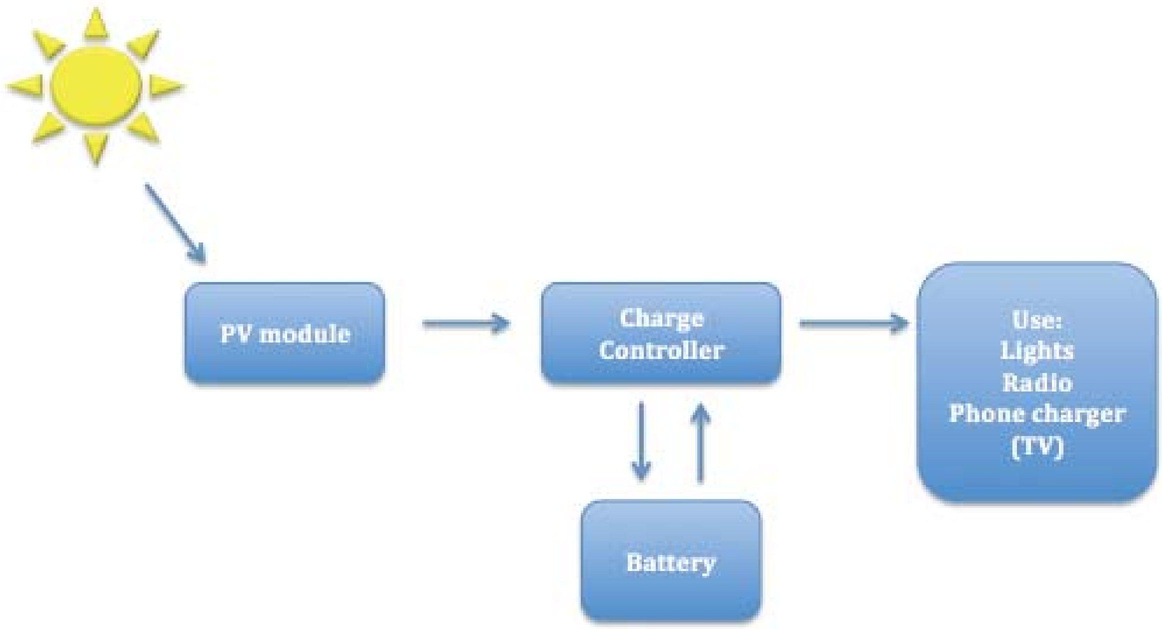

Figure 2-2: Main components of a SHS

Each SHS serves one household and gives a limited energy output. It provides the basic electricity needed for essential services such as lighting and electronic media.

A typical solar home system package in South Africa include (Republic of South Africa, 2012):

- One photovoltaic (PV) module
- Charge controller
- Wiring and outlets for small appliances
- One 102 Ampere-hour battery

In the programs beginning, the distributed module had a rated capacity of 50 W_p. However, due to recent reduction in solar modules prices, current packages deliver modules with rated capacity of 90 W_p for approximately the same price as the old 50 W_p modules (Solar Vision, 2017). Furthermore, the new standard package includes four interior LED lights, two LED spotlights, radio, connection for a phone charger and TV.

2.4.2 Fee for service

The SHSs in South Africa are given out through a leasing agreement (fee for service) between the users and the energy service companies (ESCOs). The concessionaries own the systems and the end-users pay a monthly fee to lease the system. There have been found some criteria needed to be fulfilled for a fee for service approach to be efficient and suitable (Lemaire, 2011; Azimoh, 2016; Energy & Development Research Centre, 2003). These preconditions are:

- High quality user education for the end-users to maintain the SHS and avoid excessive system usage
- Continuous interactions between the end-user and the ESCOs
- Manage the end-users expectations before installing the system considering it´s limitations
- Precise agreements with the municipalities who are willing to subsidise the fee
- Access to good enough infrastructure and trained people, so repairs can be done within a short period

2.4.3 The concessionaries

In order to address the poverty and electrification issues, South African government created private-public partnerships for the service delivery. This was done by involving concessionaries in 2001 (Republic of South Africa, 2012). Concessionaires are holders of a concession for commercial premises and trading rights. In this case, the concessionaires were responsible for evolving the SHSs in the province. Six concession areas were identified, and Solar Vision acquired responsibility for the Limpopo province (Africa, 2012). Solar Vision was registered in 2000 (Solar Vision, 2017) to provide basic electricity to people living in rural and remote areas and they have entered the commercial market with solar products.

Initially, the concessionaries received exclusive rights to provide the off-grid electrification in the province for five years, and the service contract was binding for 20 years. However, to this date, the rights last for two years at a time and service contracts for 20 years (Solar Vision, 2017).

The Municipality applies to the Department of Energy to request approval and support for providing non-grid electrification in their area. Eskom, the South African electricity supply company, must confirm the area being more than 2 km from the national grid, and the area is not included in any grid extension plans within the next three years.

If the end-user fails to pay the fee in due time, the system is removed (Solar Vision, 2017). Furthermore, when the grid infrastructure reaches the area where SHSs are provided, the service workers are responsible to de-install the SHS.

2.4.4 Challenges with the arrangement

In NuRa, one concession area in South Africa, there were found some issues with the fee for service approach (Lemaire, 2011). The problems included lacking subsidies from the government for the capital costs and fee from the municipalities. It has been argued that the operation and maintenance (O&M) arrangement does not work in a satisfying way due to the risk of end-users not paying their fee, operators having a fading interest, currency flow and a lack of continuity in the arrangement (van Der Vleuten, 2007). Poor end-user education resulted in losses from both technical design problems and usage patterns due to wrong battery usage, shading and wrong angles on the PV modules (Azimoh, 2014).

2.4.5 Impact from SHS on economic development and satisfaction from the end-users

The SHS does not seem to contribute to economic development in a substantial way (Azimoh, 2015; Wamukonya, 2007; Ellegård, 2004). Low energy output is the main reason for this. The Solar Home System only provides consumer goods like lights and radio. The system might give one shop economic development due to longer opening hours, but this will decrease income for shops without the SHS. Therefore, it will not result in economic development for the entire village (Laufer, 2011). There are studies with different outcome concerning satisfaction with the system. Azimoh et al. (2015) claimed the end-users were unsatisfied. This was because they were expected to pay the fee when the system was not working. The systems limited capacity was also an issue. On the contrary, (Gustavsson, 2004) found that consumers were pleased with the system because the electric lights quality was better than candles and they had the opportunity to use other electrical devises.

2.5 The Limpopo province

The initial agreement for Solar Vision was to install 5000 SHS annually for 10 years. The development in installed systems has not followed this initial plan. The grid has been extended faster than expected and the concessions have been characterised by a start/stop character, meaning that the government runs the concept for one or two years followed by 2-4 years without allocating installations to existing concessionaires (Solar Vision, 2017). Figure 2-3 shows the development in installations in the province from 2003-2016. The data in Figure 2-3 is lacking information for certain years, and excludes de-installations. However, the figure is gives an idea of the development. In 2017 the total number of systems in the province had reached 16 000.

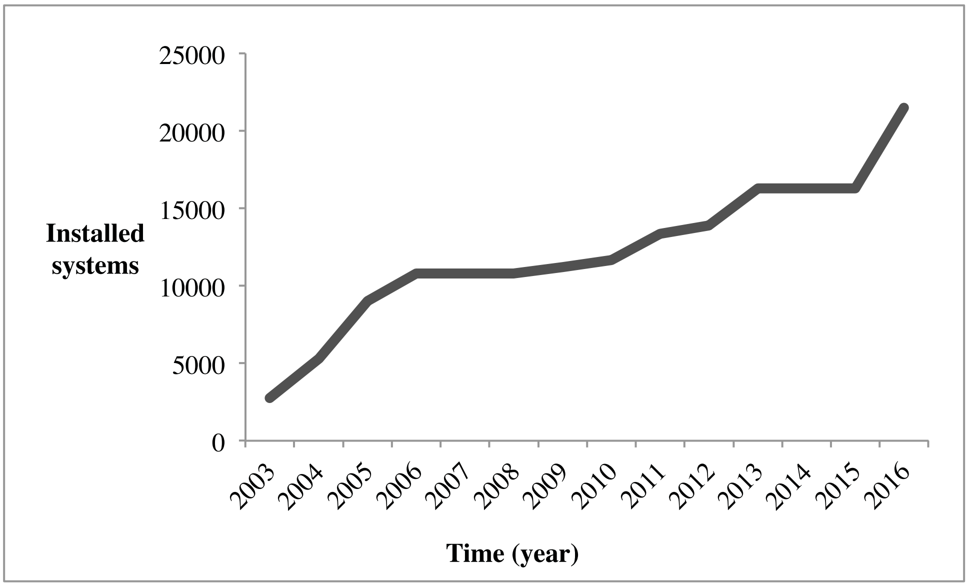

Figure 2-3: Development in installations of SHS in Limpopo from 2003-2016 (Solar Vision, 2017)

In addition to basic benefits from the SHS to each end-user, the project also created local jobs within the Limpopo province. As of January 2017, there were 18 full time workers and one representative who collected the fees in each village (Solar Vision, 2017). Furthermore, there were two helpers in each village when the systems were being installed.

Fee for service in the Limpopo province

The end-users pay an application fee of ZAR 110 (ca. 73 NOK (DNB, 2017)) when applying for the SHS and a monthly fee, currently fixed at ZAR 90 (ca. 60 NOK (DNB, 2017)). This cover operation costs, customer service and system support and management (Solar Vision, 2017). People needing the SHS are expected to have a low income and incapable to pay the whole fee. A low-income household was in 2011 defined with a total annual income of less than ZAR 19 200 (ca. 12 758 NOK (DNB, 2017)) (Statistics South Africa, 2011). Due to the "Free basic electricity" (FBE) policy, the fee is subsidized with up to 80 % (Republic of South Africa, 2012). The municipalities are responsible to pay this subsidy (Solar Vision, 2017). In the Limpopo province, end-users pay the ZAR 30 while the municipalities pay ZAR 60 per month.

2.6 Description of a mini-grid solution

A mini-grid can be defined as a set of electricity generators and storage system interconnected to a local distribution grid as depicted in Figure 2-4. In such a system, the electricity is generated centrally and provides all connected households with power, opposed to each household having their own generator, as with the SHS. This creates the opportunity to use bigger and fewer modules and batteries, which can lead to cost reduction.

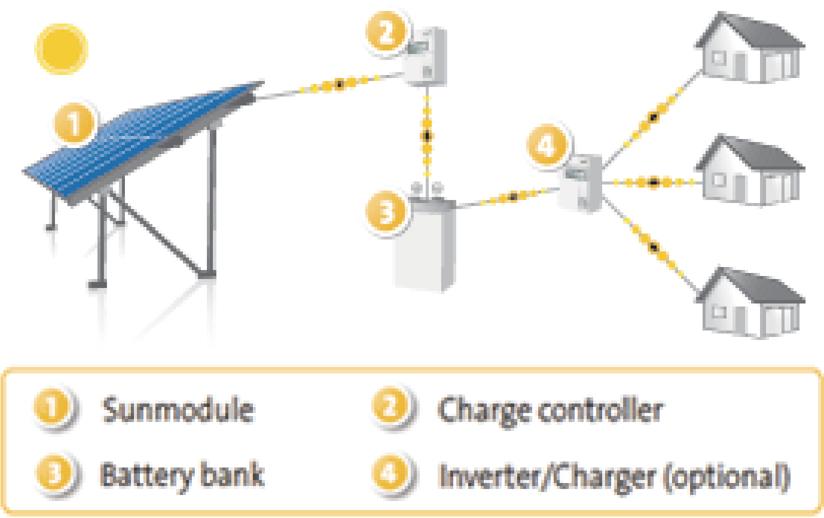

Figure 2-4: Mini-grid arrangement (SolarWorld)

3 Theory

This chapter describes the different theories used for this study. This thesis consists of qualitative and quantitative data. The chapter's first part describes the different types of data. Next, solar resource assessment, predicting system performance and possible production from the systems, are explained. Finally, methods for comparing the projects in an economic view are presented.

3.1 Qualitative research and phenomenology

Qualitative research interviews were used in this thesis to gather information from SHS users. The qualitative research interview can be defined as a conversation with a structure and a purpose (Arntzen, 2010). Within the qualitative research there are several approaches. One is a phenomenological approach (Johannessen, 2011). Phenomenology means the researcher tries to understand the respondents daily life to better understand their needs (Gripsrud, 2010).

The quality of qualitative research can be assessed using some criteria, such as reliability and trustworthiness (Johannessen, 2011). Reliability relates to the research data. What data has been used, where it was collected and how it was processed. The method used to increase reliability is for the researcher to describe the procedure used and explain all choices taken through the process.

Trustworthiness regards to which degree the researchers´ procedure and findings reflect the studies aim and represent the reality. It includes information about the method used when collecting the data, during the interviews and for analysing the data. It is impossible to be unbiased because the interviewer being represented will influence the informant. However, it is important to avoid influencing the objective as much as possible.

3.2 Quantitative research

Quantitative research has been used for collection of energy consumption data to estimate the average daily load profile. Quantitative research include methods to systematically investigate social phenomena using statistical or numerical data (Watson, 2015).

In order to find the daily energy (E_i) amount per end-user, information about rated power (W) and the daily amount of hours (h) used for the different appliances were needed and used in equation 2.1 and 2.2.

$$E_i = W(i) * h(i) \tag{2.1}$$

$$E_{daily} = \sum_{i=1}^{N} E(i) \tag{2.2}$$

3.3 Solar resource assessment

A solar energy conversion systems performance depend on available solar radiation. The solar radiations are classified into direct radiation and diffuse radiation. When the sunrays hit the atmosphere a part of the light is scattered. The cloud cover at the time decide the amount of scattered light (Boyle, 2012). The direct radiation is the light portion that comes straight from the sun. When the weather is clear the direct radiation can reach a power density of 1 kW/m^2, which is called “1 sun” (Boyle, 2012).

3.3.1 Solar irradiation at a horizontal surface

The total global irradiation, H, is a measure of how much solar energy that falls at a location over time, and is represented in kWh/m^2/day. The total global irradiation on the horizontal surface is given as: (Duffie, 2013)

$$H = H_D + H_B \tag{2.3}$$

where H is the sum of the direct beam irradiation (H_B) and the diffuse irradiation (H_D).

3.3.2 Optimal angle for the PV module

The SHS module´s inclination angle can be changed on daily basis because it is placed on the ground. However, for the mini-grid array installation, it will be assumed, in this thesis, that the modules are inclined at a fixed angle throughout the year. For equator tilted solar PV modules, the optimal surface inclination angle at noon depends on the sites latitude and the declination angle. The declination angle is the angle between the equator and a line drawn from the earth centre to the sun centre (Kharo, 2015). Assuming a constant daily declination angle, the optimal inclination angle is a function of the site´s latitude. For a fixed installation, the optimal inclination angle is given as:

$$\theta_{optimal} = L - \delta \tag{2.4}$$

where $\theta_{\mathrm{optimal}}$ is the optimal surface inclination angle (same as tilt angle), L is the site latitude and δ is the declination angle. The declination angle can be calculated from the following equation (Mukherjee, 2004):

$$\delta = 23.45 * \left(\frac{360}{365}(284 + N)\right) \tag{2.5}$$

where N is the day number of the year.

3.3.3 Solar irradiation on inclined surface

The total irradiation need to be changed from the horizontal surface to an inclined plane (Duffie, 2013). The total global irradiation on the inclined surface, H_{p}, is given as:

$$Hp = H_{B,p} + H_{D,p} + H_{R,p} \tag{2.6}$$

where $H_{\mathrm{B,p}}$ is the direct beam component on the inclined surface, $H_{\mathrm{D,p}}$ is the diffuse radiation component and $H_{\mathrm{R,p}}$ is the reflected irradiation component (see Figure 3-1). Equation 2.6 can be rewritten as (Kharo, 2015):

$$H_p = \frac{Sin(\beta+\theta)}{sin(\beta)} * (H - H_D) + H_D * \left(\frac{1+cos(\theta)}{2}\right) + \rho * H * \left(\frac{1-cos(\theta)}{2}\right) \tag{2.7}$$

where β is the sun's altitude angle, θ is the collectors tilt angle and ρ is the albedo factor.

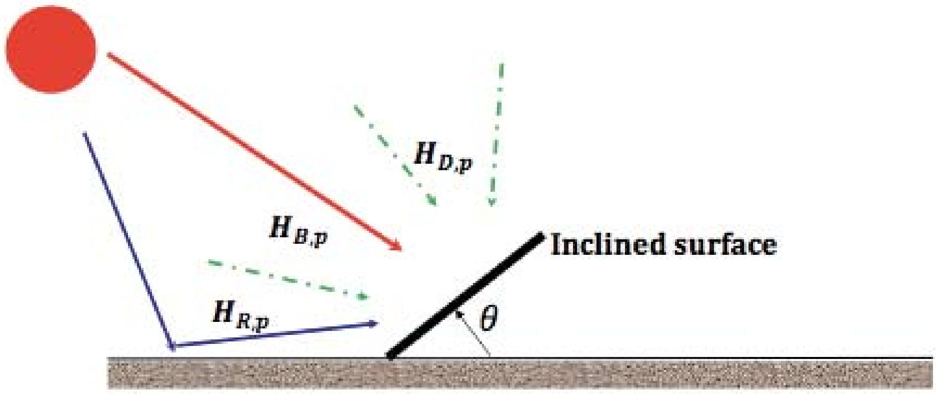

Figure 3-1: Irradiation types on the inclined surface. $H_{B,p}$: the direct beam component, $H_{D,p}$: the diffuse radiation component , $H_{R,p}$: the reflected radiation component and θ: inclination angle.

3.4 Dimensioning the PV system

The PV arrays´ size or capacity (kW) depend on the sun peak hour (S_h), daily energy needed and the derating (overall losses) factor (Boyle, 2012). The sun peak hour is given as:

$$S_h = \frac{H_p}{1\ kW/m^2} \tag{2.8}$$

where H_p is the total global solar irradiation on the inclined PV module (see equation 2.7), $E_{daily,}$is the daily energy and (f_d) is the derating factor. The capacity needed is calculated from:

$$P_{array}(kW) = \frac{E_{daily}}{f_d * S_h} \tag{2.9}$$

3.4.1 Derating factor

The derating factor, f_d, is the product of temperature related losses, $f_{temperature}$, and non-temperature related losses, $f_{non\text{-}temperature}$ (Roberts, 2017).

$$f_d = f_{non-temperature} * f_{temperature} \tag{2.10}$$

The non-temperature related derating factor is the product of individual derating factors from the system. These factors are PV module name-plating DC rating, module mismatch, soiling, system availability shading and the degradation rate from the PV systems aging.

$$f_{non-temperature} = product\ of\ the\ individual\ derating\ factors \tag{2.11}$$

The temperature related derating factor affect the production when the module temperature is different from 25 °C (STC). STC is the standard test conditions with a 1 kW/m^2 solar radiation, 25 °C cell temperature and 1,5 air-mass ratio (Tsai, 2012). Wind, temperature and the solar radiance affect the module temperature. The temperature related derating factor is calculated from:

$$f_{temp} = 1 + \Delta P \tag{2.12}$$

where ΔP is the change in P_{max} (max effect) and can be found from:

$$\Delta P = \beta_{P\,max} * (T_{cell} - 25\ °C) \tag{2.13}$$

where $\beta_{P\,max}$ is the power temperature coefficient (%/°C). T_{cell} is the temperature on the PV cell and is calculated by equation 2.14 (Duffie, 2013):

$$T_{cell} = T_{amb} + \left[\left(\frac{9{,}5}{5{,}7+3{,}8*w}\right) + \left(\frac{NOCT-20°C}{0{,}8}\right) * G_p\right] \tag{2.14}$$

where $NOCT$ is the module normal operating cell temperature, G_p is the solar radiance (kW/m^2) on the module plane, w is the wind speed and T_{amb} is the ambient temperature.

3.4.2 Module arrangement

In a situation where only multiple modules can meet the load requirement, the modules can either be connected in series or in parallel, or a series and parallel combination, as shown in Figure 3-2 (Manna, 2014). Connecting modules in series increases the voltage (equation 2.15) and the parallel wiring increases the current (equation 2.16).

$$V = nV_d \qquad (2.15)$$

$$I = nI_d \qquad (2.16)$$

V_d is one module's voltage, I_d is one module's current and n is the number of modules connected (Manna, 2014). The above equations are valid for only electrically identical connected modules. However, if the modules are non-identical, the one with lowest current and voltage decides the arrays voltage and current output.

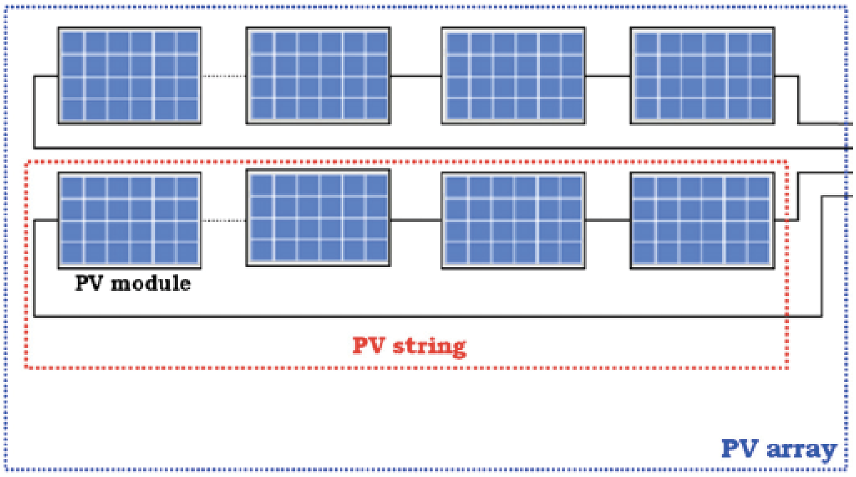

Figure 3-2: PV array arrangement (Manna, 2014)

3.4.3 Inverter

Because the PV module generates DC electricity, there is need for an inverter in cases where the applications or the grid are based on AC electricity. However, with the SHS, an inverter is not used because all appliances use DC electricity. In addition, for the proposed mini-grid solutions, inverter is not added because the same DC appliances is assumed to be used.

3.4.4 Dimensioning battery capacity

For off-grid solar energy systems, a storing facility, such as battery, is needed to store excess energy and make it available when needed. The solar modules produce most energy during the day, while the consumption is mainly during the evening. The battery capacity is given in ampere hours, *A*h, at a nominal voltage and specified discharge rate. The formula for battery size is: (Bhuiyan, 2003).

$$Battery\ size, Ah = \frac{Ah_d * T_c * DA * DM}{\eta_{battery} * DOD} \tag{2.17}$$

where Ah_d is daily ampere-hours, *DM* is design margin safety, *DOD* is depth of discharge, $\eta_{battery}$ is overall battery efficiency, T_c is temperature correction factor and *DA* represents the days of autonomy. The design margin of safety is included to account for changes in the electrical load and recommended to be 1,10. Depth of discharge represents the energy amount drawn from the battery bank and should be in the range of 20-90 %. The daily ampere-hours is defined as:

$$Ah_d = \frac{E_{daily}}{Nominal\ battery\ voltage} \tag{2.18}$$

The days of autonomy is the number of days the battery bank last without recharging it, typically due to clouded days. This is found by equation 2.18 (Messenger, 2010):

$$DA = 0.1071 * S_{h(min)}^2 - 1.869 * S_{h(min)} + 9.4286 \tag{2.19}$$

3.4.5 Battery arrangement

The batteries have to be arranged when there is more than one battery needed. The arrangement in series, parallel or combination will have an impact on the system's voltage and capacity output. The parallel arrangement increases the system capacity while the series connected increase the system voltage.

Batteries in series:

$$System\ voltage = \sum_{i=1}^{n} V \tag{2.20}$$

$$System\ capacity = \ Battery\ capacity\ of\ one\ battery, Ah \tag{2.21}$$

Batteries in parallel:

$$System\ voltage = Voltage\ of\ one\ battery \tag{2.22}$$

$$System\ capacity = \ \sum_{i=1}^{n} Ah \tag{2.23}$$

If the batteries combined are of different size, the lowest Ah in series and voltage in parallel combinations is used. Combining batteries in parallel and series the voltage and capacity output from the system increases. The number of batteries is decided by the following equations:

$$Number\ of\ batteries\ pr\ string = \frac{System\ nominal\ voltage}{Voltage\ one\ battery} \tag{2.24}$$

$$Number\ of\ strings = \frac{Total\ battery\ system\ size\ (Eq.2.17)}{Size\ one\ battery} \tag{2.25}$$

$$Total\ number\ of\ batteries = Number\ of\ strings * Batteries\ per\ string \tag{2.26}$$

3.4.6 Sizing the battery charge controller

It is important to have a battery charge controller for the system to protect the battery from being overcharged. To find the right charge controller for the system, three factors are taken into consideration. The maximum controller current output, I_{coc}, the charge controller´s maximum voltage limit, $V_{c\text{-volt}}$, and the input current from the array, $I_{c\text{-input}}$, showing the minimum controller input current (Ebaid, 2013).

$$Charger\ Current, I_{coc} = \frac{1.25 * PV\ capacity}{Nom\ battery\ voltage} \tag{2.27}$$

$$V_{c-volt} = 1.10 * number\ of\ modules\ pr\ sting * V_{oc} \tag{2.28}$$

$$I_{c-input} = 1.25 * I_{sc} * Number\ of\ strings \tag{2.29}$$

where V_{oc} is the open circuit voltage and I_{sc} is the open circuit current. The numbers 1.25 and 1.10 are safety factors.

3.5 Predicting system performance

The energy output is a product of the modules rated power $P_{pv,\ rated}$, the overall derating factor and the sun peak hours using following equation:

$$E_{DC} = S_h * f_d * P_{PV,rated} \tag{2.30}$$

There are several ways to look at how well the PV is performing. Capacity and load factor are two useful factors. The annual capacity factor is the ratio of actual energy production in a year to the hypothetical maximum production possible. This factor can be determined from:

$$C_f = \frac{E_{annual\ production}}{8760 * P_{\text{PV,rated}}} \tag{2.31}$$

The load factor is the ratio of average load to maximum load from the system. If the load factor is low, it indicates that the system may be oversized, which results in economic losses as a result of investing in too high capacity.

$$L_f = \frac{Average\ load}{Maximum\ load} \tag{2.32}$$

3.6 Economic evaluations of projects

Investments in solar PV systems are characterised by high investment costs and low operation, maintenance and fuel costs. To prioritize projects, economic evaluations are important and two methods used for this research are levelized cost of energy and payback period.

3.6.1 Levelized cost of energy

In order to compare the life-cycle costs of alternative solutions, the levelized cost of energy (LCOE) is introduced. The LCOE measures the unit cost of energy (per kWh) over the investments lifetime (Boyle, 2012). It uses the total life-cycle costs net present value (equation 2.35) divided by the total life cycle energy production from the power system:

$$LCOE = \frac{Life\text{−}cycle\ cost\ (ZAR)}{Life\text{−}cycle\ production\ (kWh)} \tag{2.33}$$

Calculating todays investment value with annual cash flow, it is necessary to calculate the net present value (NPV) (Boyle, 2012). The NPV uses a discount rate to discount future cash flows. To decide the discount rate the investor should use the minimum rate of return expected from other investment projects with lower risk, typical inserting the money in a bank. Inflation is also an important factor to include. The real interest rate or discount rate is found by:

$$r = (1 + d) * (1 + j) - 1 \tag{2.34}$$

where *r* is the real discount rate, *d* is the discount rate and *j* is the inflation rate.

When the correct real discount rate is in place the net present value can be calculated using the following equation:

$$NPV = -I_0 + \sum_{n=1}^{i} \frac{C_n}{(1+r)^n} \tag{2.35}$$

where I_0 is the initial cost, C_n is the net cash flow in year n, *i* is the projects economic life-time and *n* is the year number.

3.6.2 Payback period

Another method for evaluating projects is the payback period. The payback period is the time required to recover the investment cost (Richter, 2013). This is an easy method to determine whether the investment should be done or not. If the payback period is shorter than the projects expected lifetime it indicates a profitable project. It is found by dividing the capital investment cost on the value of annual output.

$$Payback\ time = \frac{Capital\ cost}{Value\ of\ annual\ output} \tag{2.36}$$

The annual outputs value is the energy amount produced multiplied with the expected energy price in the area:

$$Value\ of\ annual\ output = annual\ energy\ produced * energy\ price \tag{2.37}$$

4 Method and analysis

This chapter present the area where the fieldwork was conducted. Further, methods used for this research is presented and explained. Figure 4-1 shows the process´ main steps, and a more detailed description is presented below.

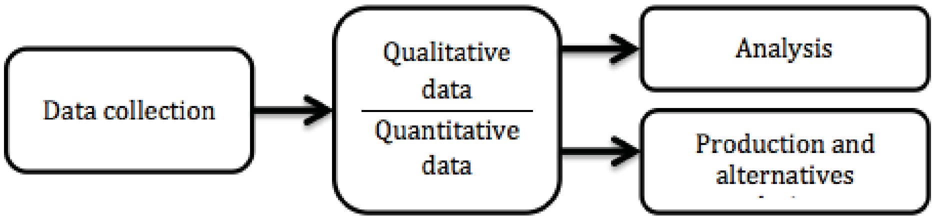

Figure 4-1: Method layout used for this thesis

4.1.1 Description of the Limpopo Province

The research was narrowed to one concession area. The Limpopo province was chosen because of contact with Solar Vision who function as the areas concessionaire. The Limpopo province is located in the northeast part of South Africa, marked red in Figure 4-2, at Latitude -23.8°S and Longitude 29.45°E. The interviews took place in five villages and town ships; Thlangalanya, Mogaladi, Nobody New Stand, Songozwi and Khambe. Driving around to the different villages was time consuming. Nevertheless, it was considered important for the research to be carried out in different areas to receive a broad research foundation.

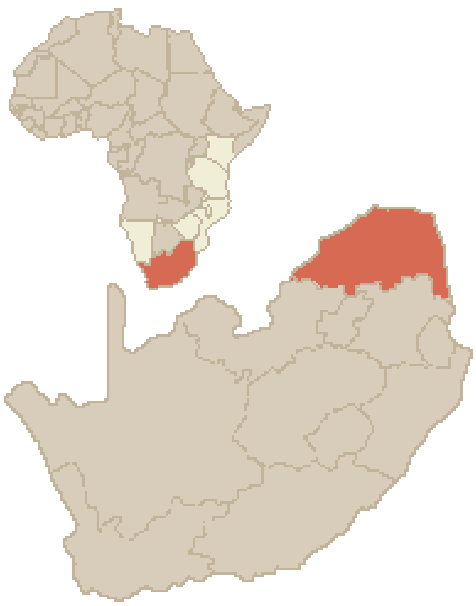

Figure 4-2: Map over South Africa and the Limpopo province in red (Gamelodges)

The chosen area for the mini-grid solution was set to a township named Nobody New Stand. This area was expanding, and there were constantly new residential areas being developed. The grid had not reached the area, and was not planned to approach the area for the next three to five years. Therefore, people in this area were able to apply for the Solar Home Systems.

The area was flat and the houses were arranged with approximately 20 m between them as shown in Figure 4-3. The living conditions varied from people living in sheds (Figure 4-4) to having small houses as the ones in Figure 4-3. People in the area had generally low income, if any, and few women were working. The energy demand was low. The demand they had were mostly lighting, radio and phone charging. Most had no access to electricity previous to the SHS. Trucks delivered water to them, and there was not much infrastructure beside the roads as shown in Figure 4-3.

Figure 4-3: Typical small house and road infrastructure in Nobody New Stand

Figure 4-4: Typical shed with a PV module from the SHS in Nobody New Stand

4.2 Data collection

For this study two data types, which are primary- and secondary data, were used.

Primary data are collected for a purpose and are considered new data (Hox, 2005). The primary data for this work was collected through the interviews. Secondary data are already existing data. Many secondary data from previous reports on the SHS, FBE and data from Solar Vision were collected for this research and used as background information.

4.2.1 Methods selection

In this thesis, both qualitative and quantitative data were collected. This was done to receive information directly from the end-users and to collect data for the daily load profile. The data for the daily load profile had to be collected this way because there was no energy output measurement from the SHSs.

4.3 Qualitative method

The phenomenological qualitative method was chosen to understand how the arrangement impact people's daily life and understand their needs. In addition to having conversations with people, understanding their background was valuable.

4.3.1 Research design

Selection of informants

The fieldwork was performed over a five days period. Therefore, accurate preparations were important. There are various opinions on the number of respondents needed for a qualitative research. This research carried out 12 respondent interviews, meaning only people with SHS experience were interviewed (Jacobsen, 2005). Information on how long the SHS had been used, number of people in the household, size of the module and living conditions are shown in Appendix 2. The informants were chosen through variation selection to get different experiences and perspectives. The different premises for deciding whom to interview were:

- People living in rural villages
- People living in townships
- People with higher material standard
- People with lower material standard (living in sheds)
- People who former had the SHS and were now connected to the grid
- People who had used the SHS for more than 10 years.

None interviews were arranged and spot on recruitment was done. All people who were approached were willing to participate.

Eleven out of twelve interview objects were female. This was a natural consequence of the interviews being done during the day, when it is normal for the wife to stay at home with the children while the husband (if there is one) is at work.

Interview guide and the situation

Preparations were done to get knowledge on how to carry out interviews with non-leading questions. Most often the interviews took place outside the person's home. The interviews were semi structured. This was chosen to give everyone approximately the same questions, but at the same time being able to ask for more details and adjust the interview for each informant. Human experiences and understandings are most clear when the informant can impact the interview (Johannessen, 2011). In a research situation where there are no possibility to repeat or carry out more interviews at a later time, semi structured interviews are recommended (Arntzen, 2010). For the interview guide see appendix 1.

Carrying out the interviews

Before the interview started there were introductions, the research was explained, information about how the results would be used, the transcription, anonymity and everyone were asked if it was acceptable for the interview to be recorded. Ten of twelve interviews were recorded, the remaining two were not due to cultural reasons.

The recorded time from the interviews varied from five to 30 minutes. Language difficulties and how much people wanted to share resulted in uneven time lengths. Some interviewees wanted to talk for longer periods, while others only wanted to answer the questions with one-sentence answers and no elaboration. After the interviews, surroundings, living conditions and other impressions were noted.

4.3.2 Qualitative data analysis

Each evening was used to sum up the most important results. The interviews were evaluated and notes on technique and what to investigate further was considered.

The transcriptions from the recordings were written exactly like everything was said. Sounds, laughter and interactions were included to get aware if someone answered a question direct or if they were hassling.

Further, the data was categorical indexed. It started with cross sectional division which help constructing a system to index the data (Johannessen, 2011). The categories were the same categories focused on during the interviews.

Afterwards, the transcripts were studied for interesting answers or stories on a more personal basis. Next the information from the two unrecorded interviews were added. All data were sorted, first in qualitative and quantitative data. The qualitative data was divided into tables, quotas and keywords for the different categories.

At last the sorted, qualitative data was analysed. The interviews were analysed one at the time and including pictures, notes, impressions and thoughts.

4.4 Quantitative Method

To do calculations on the solar home system and mini-grids solutions, it was necessary to collect data on energy consumption.

4.4.1 Daily load profile

Data on consumption were collected quantitatively through the interviews. The energy consumed from each appliance and the total daily energy consumption was determined using equation 2.1 and 2.2. The typical appliances wattage used with the Solar Home Systems in South Africa are listed in Table 4.1. The respondents had modules with different dimensions and the number of lights varied. However, the latest SHSs consist of 90 W modules and six lights. To make the calculations suitable for today´s and future systems, the calculations were normalised to the new SHS.

Table 4-1: Appliances and effect on each appliance (Solar Vision, 2017; WholesaleSolar)

Appliance	Number of appliances	Power each appliance (*W*)
Outdoor lights	2	2,4
Indoor lights	4	3
Radio	1	12
Charging phone	1	4
TV	1	50

4.4.2 Solar resource assessment

Irradiation data and albedo data was collected from NASAs web page (Stackhouse) and adjusted to the inclined surface of 15° and 23.8 ° using equation 2-5 and 2.7.

4.4.3 Energy production

The potential energy production from the SHS was found using equation 2.30. The total average insolation on the inclined surface (H_p) at 15° was calculated using equation 2.7. H_p was then used to find S_h with equation 2.8. The overall derating factor was found using equation 2.10.

4.4.4 Solar Home System derating factors

Non-temperature derating factor

As stated in the theory chapter, the solar PV system overall derating factor consist of non-temperature and temperature related factors. The non-temperature derating factor was assumed to be equal every month. Assumptions were made when information were unavailable. These assumptions where taken from similar studies like (Dobos, 2014; Chaurey, 2010). The degradation was calculated based on information from the PV module producer (SpecializedSolarSystems, 2017) for the SHS. All the individual factors were used in equation 2.11 to find the non-temperature related derating factor.

Temperature related derating factor

For the temperature-derating factor, T_{amb} and average wind speed were taken from NASA website (Stackhouse). This was due to lack of ground measured weather data at the site. The NOCT and $\beta_{P,max}$ were found on the technical specifications on the solar module (SpecializedSolarSystems, 2017). Table 4-2 list all input factors used for finding the temperature derating factor. The monthly average f_{temp} was calculated using equation 2.12.

Table 4-2: Monthly T_{amb}, wind, cell temperature and temperature derating factor for the SHS

	T_{amb} (°C)	Wind (m/s)	NOCT	$\beta_{P,max}$ (%/°C)	T_{cell} (°C)	f_{temp}
January	27.0	4.94	48	-0.5	40.59	0.92
February	26.5	4.81	48	-0.5	40.37	0.92
March	25.8	4.37	48	-0.5	40.71	0.92
April	23.5	4.24	48	-0.5	38.74	0.93
May	19.9	3.93	48	-0.5	36.01	0.94
June	16.4	3.93	48	-0.5	32.51	0.96
July	16.6	4.07	48	-0.5	32.31	0.96
August	20.5	5.29	48	-0.5	33.39	0.96
October	20.5	5.48	48	-0.5	33.04	0.96
September	27.0	5.75	48	-0.5	39.07	0.93
October	27.0	5.66	48	-0.5	39.22	0.93
November	26.5	5.05	48	-0.5	39.86	0.93
December	26.5	4.99	48	-0.5	39.98	0.93

4.4.5 SHS batteries and charge controller

Evaluation on whether the battery and charge controller were correct dimensioned for the SHS was carried out. The battery was 12 V and had a 102 Ah capacity (SpecializedSolarSystems, 2017). The optimal size for a 12 V battery for the system was calculating using equation 2.17. The input factors are presented in Table 4-3.

Table 4-3: Factors used to determine the correct battery size

Parameter	Value
Cell temperature, T_c (°C)	1.0
Design margin safety, DM	1.1
Depth of discharge, DOD	0.8
Days of autonomy, DA	2.16
Battery efficiency, $\eta_{battery}$ (%)	0.85
Daily Ampere-hours, Ah_d	33.8

T_c was set to one because the temperature in the area is around 26 °C (solar-store; TimeandDate, 2017). *DM*, *DOD* were assumptions. If information on the efficiency is not provided, the recommended value for lead acid batteries, like the once used here, is 80 % (Rodrigues, 2017; Svarc, 2016; Solar-store). *DA* was calculated using equation 2-19. The non-critical application was used for this calculation, as the appliances used were not continuously needed. Ah_d was calculated using equation 2.18.

The maximum charge controller current and voltage were found using equation 2.27, 2.28 and 2.29. The input data and the limitations were found in the technical specifications (SpecializedSolarSystems, 2017) and are shown in Table 4-4.

Table 4-4: Input data to decide the charge controller size and limitations

Parameter	**Value**
Open circuit voltage, V_{oc} (V)	22.1
Open circuit current, I_{sc} (I)	6.7
Max power current (I)	5.0
Maximal power voltage (V)	18.0

4.5 Mini-grid

To size mini $grid_1$, the daily energy use from the SHS was multiplied with number of households, which is 50. For mini-$grid_2$, which includes fridges, an additional 240 W to each household were added to the PV array.

4.5.1 Modules

The modules used for the mini-grid systems had a 315 W_p capacity. This module was chosen because it was sold from a South African company at a reasonable price. Price, NOCT, $\beta_{,Pmax}$ and $f_{non\text{-}temperature}$ of the modules are presented in Table 4-5. The price and technical information was found on Art Solars homepage (ARTsolar, 2017). The temperature related derating was found with equation 2.12 using the same monthly T_{amb} and wind average as for the SHS. The number of modules needed to cover the daily demand for the 50 households were found for both mini-grid solutions.

Table 4-5: PV module information

PV module	Value
Power (W_P)	315
NOCT (°C)	45
$\beta_{P.max}$ (%/°C)	-0.41
Price (ZAR/module)	1685.25

4.5.2 Batteries

The right battery size was found using equation 2.17. The battery type were chosen because it was a good match at a good price, and sold in South Africa. Ah_d was calculated by equation 2.18 and DA by equation 2.19. The price per battery, Ah and battery voltage was found on the web page (Sustainable.co.za). DOD, battery efficiency and DM were assumptions. All the factors are presented in Table 4-6.

The number of batteries per string and number of strings were found with equation 2.24 and 2.25. With equation 2.26 the total amount of batteries needed were found. The expected life time for the batteries were set to five years because most of the lead acid batteries are in the range of 3-10 years (Powerthru; Monteiro, 2017).

Table 4-6: Battery information

Battery	Value
Size (Ampere-hours)	95
Battery Voltage (V)	12
Cell temperature, T_c (°C)	1.0
Design margin safety, DM	1.1
Depth of discharge, DOD	0.8
Days of autonomy, DA	2.12
Battery efficiency $\eta_{battery}$	0.85
Daily Ampere-hours, Ah_d	406
Price (ZAR/each battery)	1828

4.6 Project evaluation

This study used several methods to compare the three different projects; SHS, mini-$grid_1$ and mini-$grid_2$. The evaluation methods were chosen because they represent both technical and economic comparisons. The technical comparisons were based on the load factor and the capacity factor. The load factor was calculated using maximum and average load from the solar home system in equation 2.32, and the same numbers were scaled up for the mini-grid solutions. The capacity factors were found using equation 2.31.

4.6.1 Economic comparisons

Payback period and levelized cost of energy were chosen as economic indicators. Both were included because they describe two different projects performance aspects. Finally, the methods used to calculate the expected development in grid price and price trends for PV and battery technology is presented.

Levelized cost of energy (LCOE)

To compare the cost per kWh produced from the different solutions levelized cost of energy was used. Assumed life time for the projects were set to 25 years because of the expected life time for the PV modules (SpecializedSolarSystems, 2017; ARTsolar).

LCOE for the SHS

The compensation Solar Vision received from the government for each system were used as the investment cost (Solar Vision). The investment costs include the cost for battery replacement every third year, adjusted for the discount rate and inflation. This was adjusted for the discount rate of 8 % (8-12 % is normal for PV investment) (Boyle, 2012) and the current inflation rate at 6,3 % in South Africa (economics, 2017). The energy production was assumed to be equal every year. In addition, the LCOE for the energy used, according to the daily load profile, was calculated as well.

LCOE for the mini-grid solutions

Local prices for PV modules and batteries were used for the mini-grid systems. Installation and balance-of-system components (BoS) was set to 40 % of the investment cost for the PV modules (Szabó, 2011; Innovation Energie Développement, 2013). The BoS components include charge controller, distribution cables etc. Annual operation and maintenance cost was set to 2,5 % of the PV modules + BoS investment cost, and adjusted annually for the real discount rate (Ghafoor, 2015; Azimoh, 2014). The batteries were assumed to last for five years, and the cost for the four battery exchanges during the system´s lifetime was taken into the calculation and adjusted for the real discount rate. The energy production was assumed to be constant every year.

The results from the interviews showed that people wanted a capacity high enough to run a fridge. Therefore, calculations on the LCOE for a mini-grid providing enough energy to make it possible for each household to run a fridge were done. The fridge used for the calculations was found at Specialized Solar Systems homepage (SpecializedSolarSystems). To run each fridge there is a need of 240 W and 2*100 Ah batteries. This additional total effect of 240*50 W and 1000 Ah were added to the small mini-grid system. The O&M and BoS costs were found with the same method as for the first mini-grid solution. The same modules type and batteries were used.

Payback period

The method used to find the payback period was based on equation 2.36. The investment cost in year 0 and the cost for battery replacement, adjusted for real discount rate, was included. These investment cost were divided on the value of the annual energy produced. The energy value of was based on the assumption of equal annual energy production, and an electricity price at 124,5 cent/kWh, which was the electricity price for 2017 (Eskom, 2017).

4.6.2 Trends/future forecast

The price for grid electricity was based on the expected commercial price for 2017 (Motiang, 2016). There were no additional connecting costs for households when being connected to the grid, due to the FBE politics (Solar Vision, 2017).

The forecast was calculated using an expected annual prise increase of 13 % in 2017 and 2018, and then 8 % annually until 2022. From 2022 the price is expected to stabilize (Energy partners, 2016; Louber, 2016).

The expected price decrease for PV modules was based upon the PV price in 2017, and IRENAs 59 % expected decrease in LCOE by 2025 (Taylor, 2016; Taylor, 2016). The price was changed from USD to ZAR using the exchange rate for 09.03.17 (XE, 2017). The 59 % decrease was assumed to be linear, therefore the yearly growth factor was found and used to project the final price in 2025.

To demonstrate the future price trend, forecast for the lithium-ion batteries was used. The numbers were used to demonstrate the falling price. The price development was collected from (Vorrath, 2016) and changed to ZAR/kWh. The same trend is shown at Bloomberg, but with an even faster decrease (Randall, 2016).

5 Results

The research results are presented in this chapter. First are results from the qualitative research presented and then the quantitative results.

5.1 Results from the interviews

5.1.1 Education

The improved light quality affected children´s study routines. In South Africa the sun sets between 17.30-19.00 depending on the time of year (TimeandDate, 2017). The children will often come home late from school and have chores to do. This narrows the window of opportunity for when it is possible to read and do homework. After receiving the lights from the SHS this window expanded, and they were able to read after dark. When explaining the lights importance one interview objects said:

"*I wish to help my children read. My kids love to read. We need the education, and Africa has the sun, which is free, so that's what we can use*"

Furthermore, the radio helps people staying informed on local, national and international news, which improves their knowledge and has the potential to provide further education.

5.1.2 Safety

People felt safer with the electric lights. First of all, the fear of fire around their children decreased. One mother said it like this:

"… the other thing that is good is that I can go to sleep without worrying about the children. When the kids were reading or writing with the candles we could not go to sleep… They can switch the lights on or off, or leave them on, but there is no danger and we don´t need to worry as much as with the candles"

Fire was a major concern when candles or paraffin were the used light source. Parents were afraid of leaving the house when their children were at home.

The lights outside also provided the families with a range of benefits, particularly woman and children felt safer after dark. Before it was entirely dark outside and they had to bring candles whenever leaving the house if they needed lights. One or two outside lights were included in the SHS and lit up the area. Now they could go outside and see if there were unwanted people or animals around their homes. Some families left the lights on for the whole night because their children were afraid of the dark. With the SHS they felt safer and more comfortable inside the house. In addition it helped children to visit friends and families in the neighbourhood after dark.

5.1.3 Economy

According to the interviews a fee of ZAR30 was indeed manageable. This amount covered lights, phone charging, radio and some times TV for the SHS users. For most people this amount was less than what they used for lighting and phone charging before (Figure 5-1). As depicted in Figure 5-1, only seven household were able to state their previous spending. However, everyone agreed the cost had decreased with the SHS. The seven households had an average monthly reduction of 137 Rand in lighting and phone charging cost.

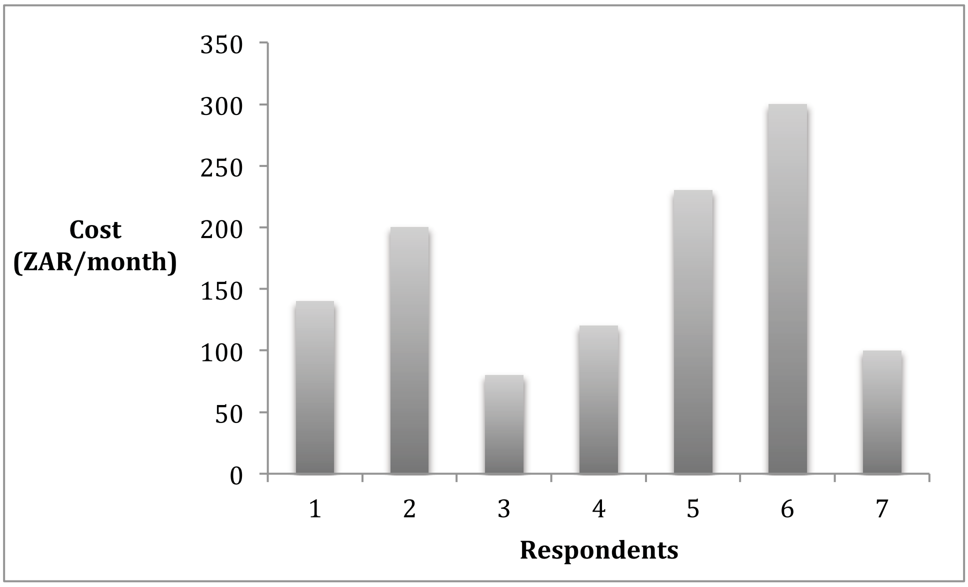

Figure 5-1: The monthly cost for light and phone charging before the SHS for seven households

This economic change were noticed from the end users, and two comments were as following:

"Yes yes. I am saving the money monthly to build my house"

"Yes! I wasn´t saving before, but now I am saving because of the solar. So now I have the chance to save money"

The money saved on energy expenses were used in different ways. People who struggled economically used it for food and daily life expenses, while others who had the opportunity saved the monthly difference.

Some people had ideas about how an increase in electricity could help them create an income in the future. About 70 % of the interviewees agreed the one thing they were missing from the Solar Home System was the possibility to run a fridge. A fridge would allow them to preserve food and save them multiple trips to the market. Four of the twelve people interviewed would use the fridge as a business opportunity. They could buy extra food and sell it in the village. Examples of business ideas were to purchase and store chicken feet and heads for resale or to store fresh fish and sell fish and chips. How much income they would be able to generate from these businesses were unclear.

5.1.4 Maintenance, problems, help, training

The monthly fee covered repairs & maintenance on the SHS. Few people experienced problems with the modules. If any issues occurred, they received help within 48 hours, and normally the same day. For the very rural villages they were promised help within 72 hours, which according to the interviewees seemed to be the case.

The users had received proper training in how to maintain the system and how to use it. The training gave them knowledge on how to clean the module, facing the module towards the sun and how much effect and energy they could use without harming the system. Some respondents described their daily energy use as follows:

"For some hours we watch TV, but not more because if we watch more TV it is going to take to much sun from the battery. So we only switch it on during the night and during the day sometimes when the sun is very light that is when we can use it during the day and night."

"Today I still have enough energy only if I don´t watch the TV"

There were several similar answers. This showed that even thou they did not understand how the system worked, they understood the basics like the sun charges the battery, the battery is not everlasting, and on days with a clear sky they can use more energy during daytime. The modules were placed on the grown and connected to a movable frame. This made them able to turn the module towards the sun, which it seemed like they did. The modules angle was adjusted at brackets at 15°, so the users were unable to adjust this.

One issue turned up for about 30 % of the interviews. People had not received enough information about module cleaning. One family had used the SHS for two years, and never brushed or cleaned the module shown in Figure 5-2. They were unaware this affected the systems efficiency.

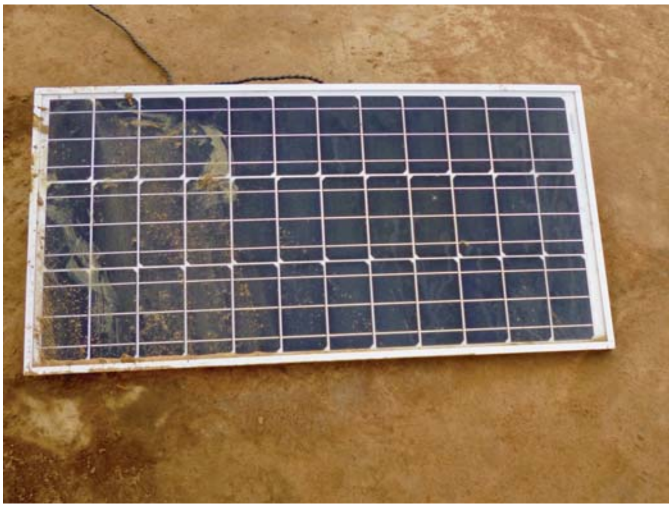

Figure 5-2: An unwashed PV module from the fieldwork

5.1.5 Theft

Most households kept the module indoor during the night and took it out during the day due to the fear of theft. The solar module and the batteries had higher value than most other belongings people in the area had. Therefore they were exposed to thefts. People handle the issue in different ways, and one person's evaluation of the problem and actions against theft went like this:

"They are wandering around during the day knowing that there it is a solar sitting in the sun one day and then they´ll come and see your movements, and then break in. If anyone see it they don´t care. So it´s a challenge. But not for me, because I have a dog. I even hide the panels in a way for people not to see it. I keep it in the bushes"

Theft was a huge problem, especially in the programs early days. Modules were taken from the roof during the night and people would break inside to steal the battery. One story about an unlucky old man went like this:

"*There was this old man staying down there, ehm, he past on not long ago. They stole his panel, and I had to give him mine. Because he needed it more than me. So yes, I went and I bought these small lamps, because I just needed to give him lights. And apparently they even stole that panel from him. So they stole it again. And my mother in law she gave me, in other words she didn't use it, she didn't know how to use it, and they had the electricity, they got it before us. So she gave me that panel, and I gave it to the old man"*

Because of all the thefts Solar Vision changed the standard to placing the modules on the ground and move them indoor at night. This has decreased the frequency of theft in the province, and the percentage of stolen panels in 2017 was assumed to be about 5 % (Solar Vision, 2017)

5.1.6 Grid versus SHS

People connected to the grid who previous had the SHS preferred the SHS. For example, one respondent said:

"…*When I had solar my neighbour had electricity, the only one on that side who could afford to pay for the electricity private. But his system could go of, and I would have lights in my house. So it was better for me. I liked to live like that. And it was nice. They were given problems, and they were paying a lot*"

Energy security was an important reason for why the SHS was preferred. South Africa struggles with black outs from the grid, and this is expected to increase in the future. Further, the spending on electricity increased when they changed from SHS to grid electricity. From the interviews, people spend between ZAR 50 and ZAR 300 monthly on grid electricity. They used more applications and increased the quality of life. Even so, they were focused on the fact that they paid more than ZAR 30 a month. If they were given the opportunity to choose, people wanted a hybrid solution with solar PV and grid electricity. Some wanted solar as backup and others grid electricity as backup. None of the people who had changed from solar to grid electricity had yet invested in a fridge because it was too expensive.

5.2 Daily load profile

From the interviews, a daily use of 357.2 Wh and an average load of 14.9 W and peak load of 72.8 W. The daily average load profile is shown in Figure 5-3. This is lower than what IEA consider the initial threshold level of electricity consumption at 685 Wh daily (Africa Energy Outlook, 2014). The result was also lower than the average use of 484 Wh/day for rural Africa found by (Prinsloo, 2016).

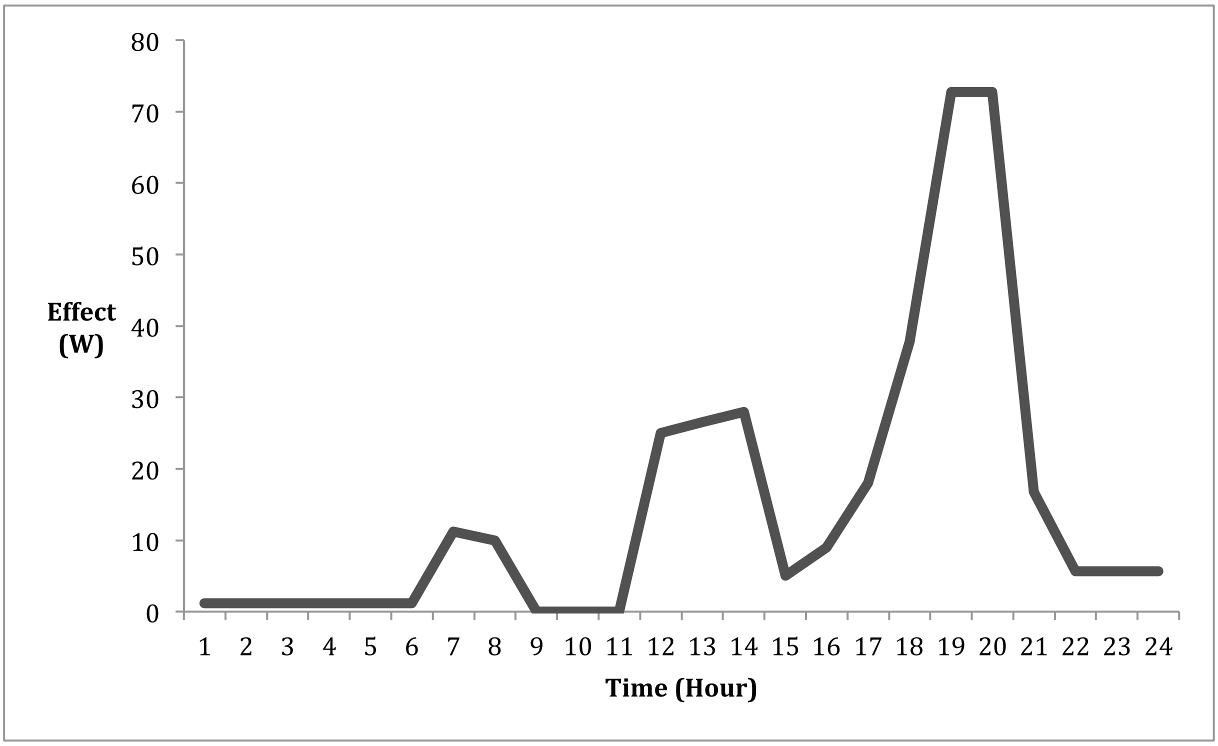

Figure 5-3: Average daily load profile for one household using the SHS

5.3 Solar radiation and optimal tilt angle

The optimal angle for PV modules in the area was found to be 23.8° as opposed to 15° in which they were installed at. Figure 5-4 shows the total irradiation on the inclined surfaces for the two angles and a horizontal surface. If a module was installed at the optimal angle, it could result in an average daily increase in irradiation of 69 $Wh/m^2/day$.

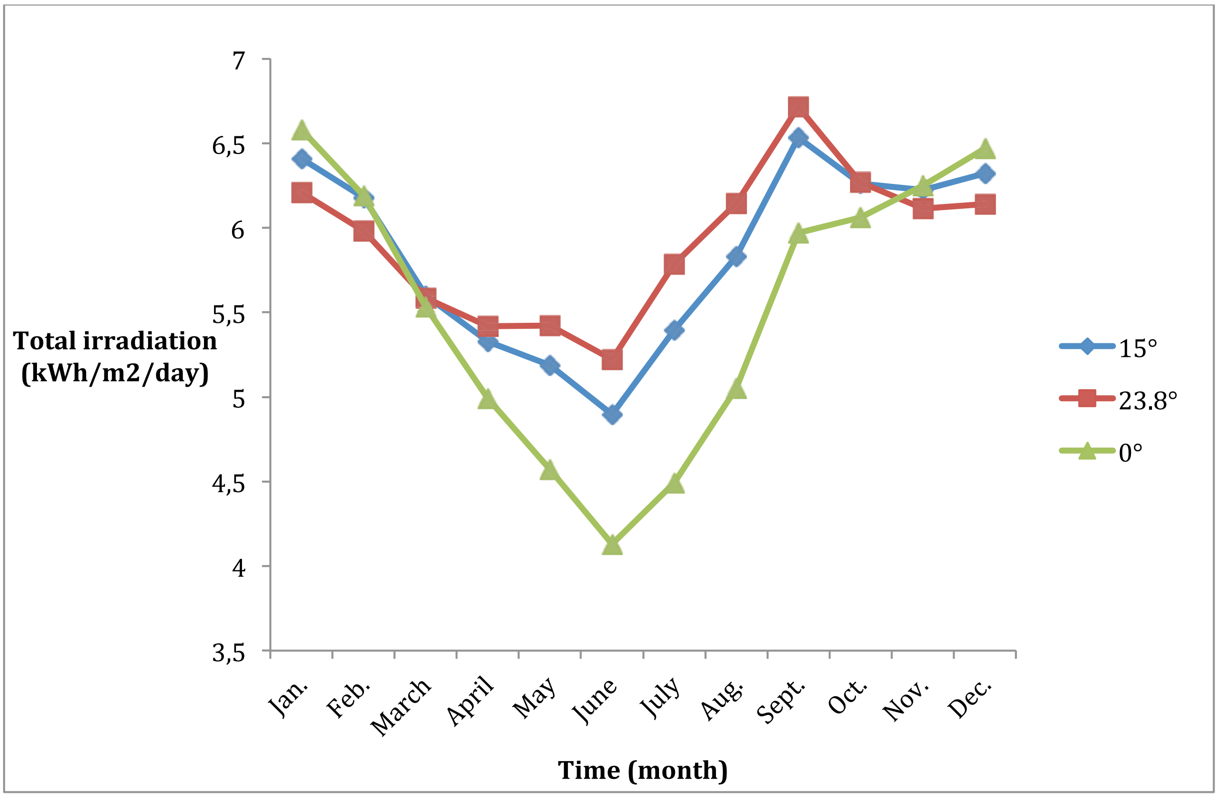

Figure 5-4: Total daily irradiation ($kWh/m^2/day$) at horizontal, 15 ° tilted and 23.8° degree tilted surface in Polokwane (Atmospheric Science Data Center)

5.4 Systems and production

5.4.1 Solar Home System

The results on the Solar Home System are presented in this section. The derating factors found are presented in Table 5-1.

Table 5-1: Derating factors for the SHS

Derating factor	Value
f_{temp}	0.95
$f_{non\text{-}temperature}$	0.82
Overall derating factor	0.78

An optimal battery for the system was found to be 118 Ah, therefore the used 102 Ah battery included in the SHS was considered to be a good match. The charge controller used was also found to be a good mach.

Production and use

Figure 5-5 illustrates the daily monthly difference in production on the 15° declined module and usage for each moth over a year. The daily production differs from 0,356 to 0,460 Wh because of the temperature derating factors. The daily energy consumption of 0,357 kWh was assumed to be equal through the year. During the South African summer months the production is higher than the consumption, and the highest variation was in September with a difference at 0.1 kWh daily.

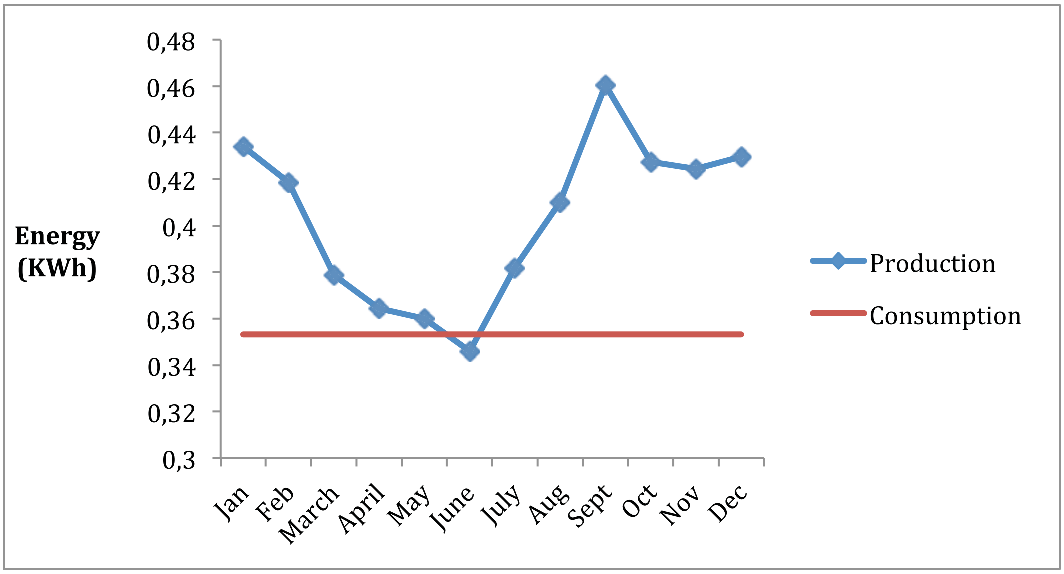

Figure 5-5: Difference between daily energy production (kWh) and daily consumption (kWh) through the year on a 15° tilted 90 W_p module

Load- and capacity factor

The load factor was found to be 20.4 %, meaning the system maximum output is only used for 20.4 % of the time. The capacity factor for the SHS was found to be 18.65 %.

5.4.2 Mini-grid solutions

Daily load profile for mini-grid$_1$ is presented in Figure 5-6 with load peak at 3640 W. Daily load profile for mini-grid$_2$ is presented in Figure 5-7 with a peak load at 15640 W.

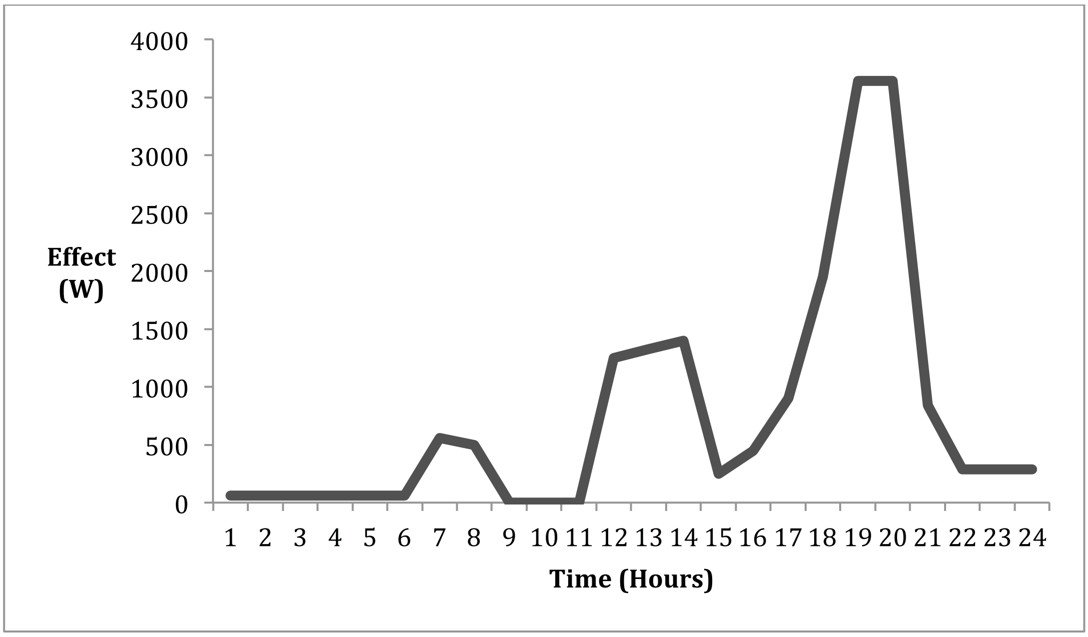

Figure 5-7: Daily load profile for 50 households needed to be met from mini-grid$_1$.

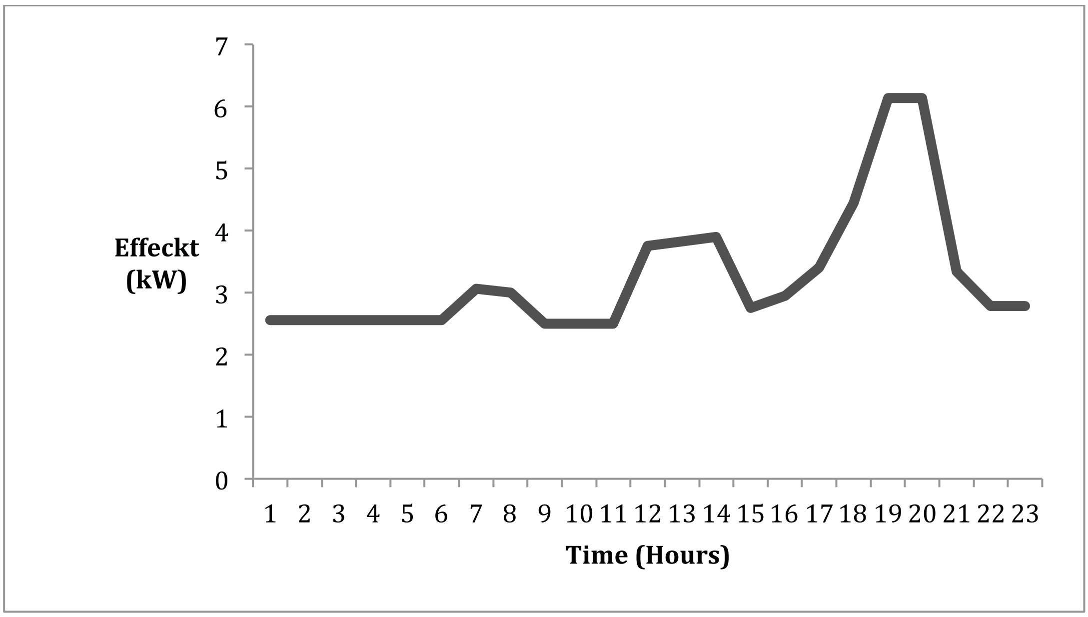

Figure 5-8: Daily load profile from 50 households with fridges needed to be met from mini-grid$_2$.

Derating factors

The derating factors found for the min-grid systems are shown in Table 5-2.

Table 5-2: Derating factors for the mini-grid systems

Derating factor	Value
f_{temp}	0.84
$f_{non\text{-}temp}$	0.95
Overall derating factor	0.80

Dimension of the systems

The size and numbers of modules and batteries needed to cover the demand from mini-grid$_1$ and mini-grid$_2$ is presented in Table 5-3.

Table 5-3: Overview over the needed amount of modules and batteries to deliver the energy demand for the two mini-grid systems

	Mini-grid$_1$	Mini-grid$_2$
Nr. of 315 W_p modules	13	51
Installed capacity (kW)	4.095	16.07
Nr. of 95 Ah batteries	56	228
Batteries in parallel	14	57
Batteries in string	4	4

Production, capacity factor and load factor for the system

Figure 5-8 shows the daily production for each month for the two mini-grid systems. This results in an annual production from mini-grid$_1$ at 7.07 MWh and 27.76 MWh from mini-grid$_2$. The systems average daily production and capacity- and load factor of are presented in Table 5-4.

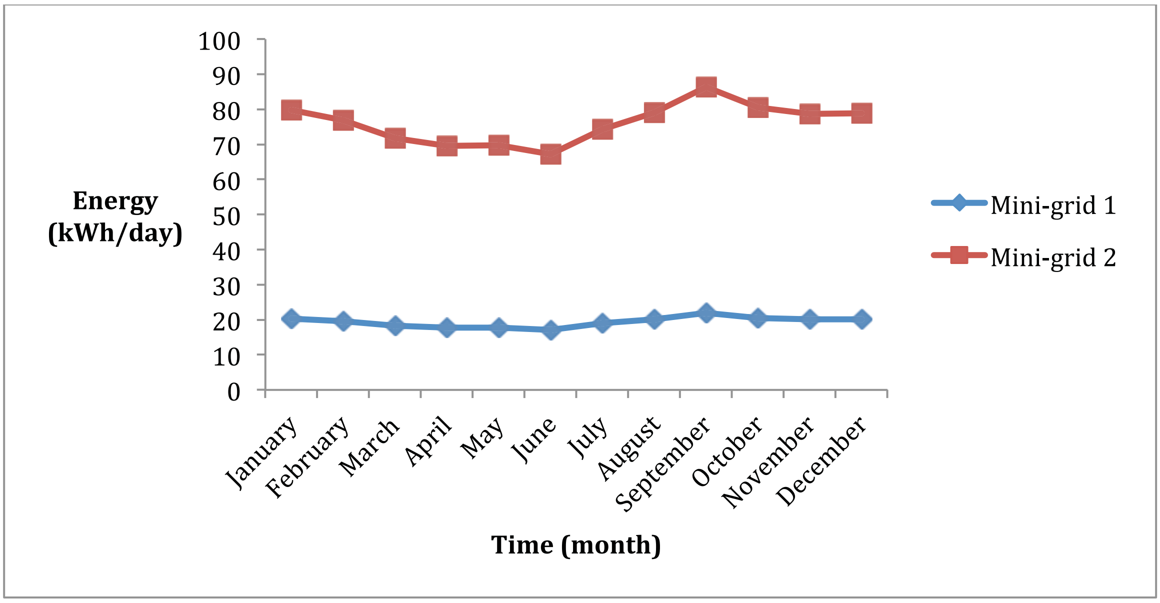

Figure 5-9: Daily expected energy production per month for mini-grid$_1$ and mini-grid$_2$

Table 5-4: Total production, daily supply to each household, capacity factor and load factor for the two mini-grid systems

	Mini-grid$_1$	**Mini-grid$_2$**
Possible daily production (kWh) (average)	19.49	76.5
Daily energy supply each house (kWh) (average)	0.39	1.53
Capacity factor (%)	19.8	19.8
Load factor (%)	20.1	81.5

5.5 Economic results

5.5.1 Investment cost and payback period

Figure 5-9 depicts the total cost per household for the three options through a 25 years period. Mini-grid$_1$ and the SHS provide the same energy amount to each household, but mini-grid$_1$ provides it for a lower total cost. The total investment cost for 50 SHS was 486 650 Rand. The total investment cost for mini-grid$_1$ was 234 265 Rand and the total investment cost for mini-grid$_2$ was 952 380 Rand.

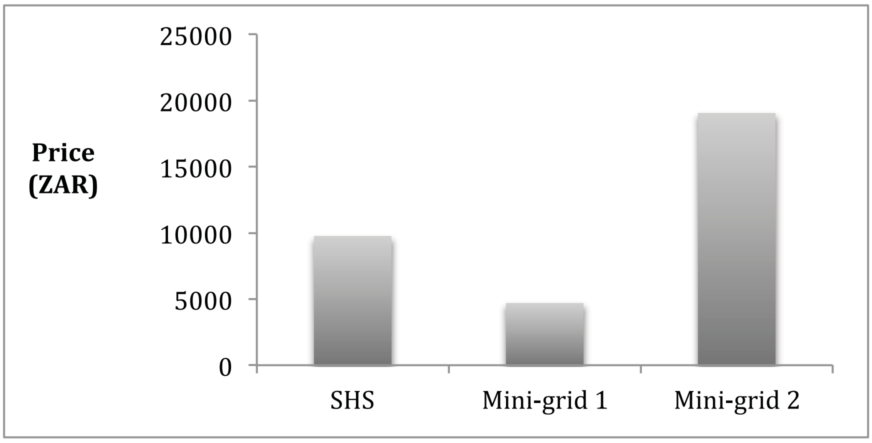

Figure 5-10: Total cost for 25 years divided on each household for the different systems

Figure 5-10 shows the payback period for the three solutions. The Solar Home System had a 44 years payback period, almost twice the project´s life expectancy of 25 years. Both mini-grid systems had expected payback time at 15 years.

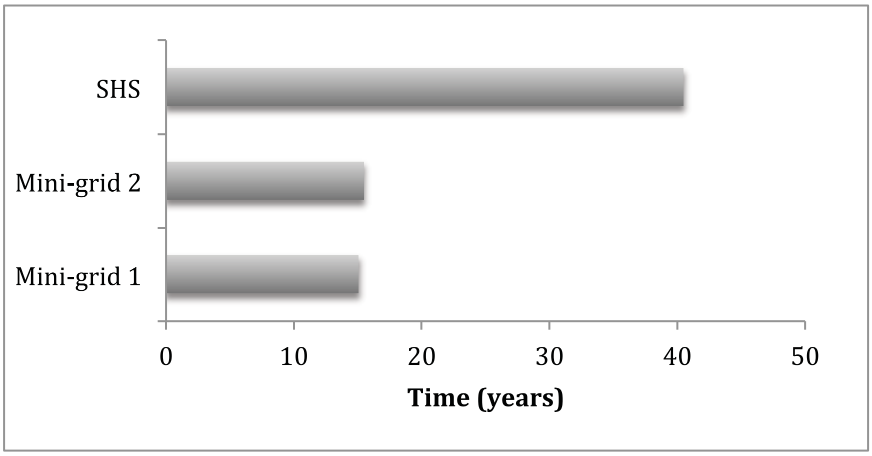

Figure 5-11: Payback period for the three systems

5.5.2 Levelized cost of energy

Figure 5-11 presents the LCOE for the different systems. As shown in the figure, the LCOE for the SHS is approximately twice as high as for both the mini-grid solutions. The LCOE for energy used from the SHS is included to demonstrate the increased LCOE when there is higher production than use.

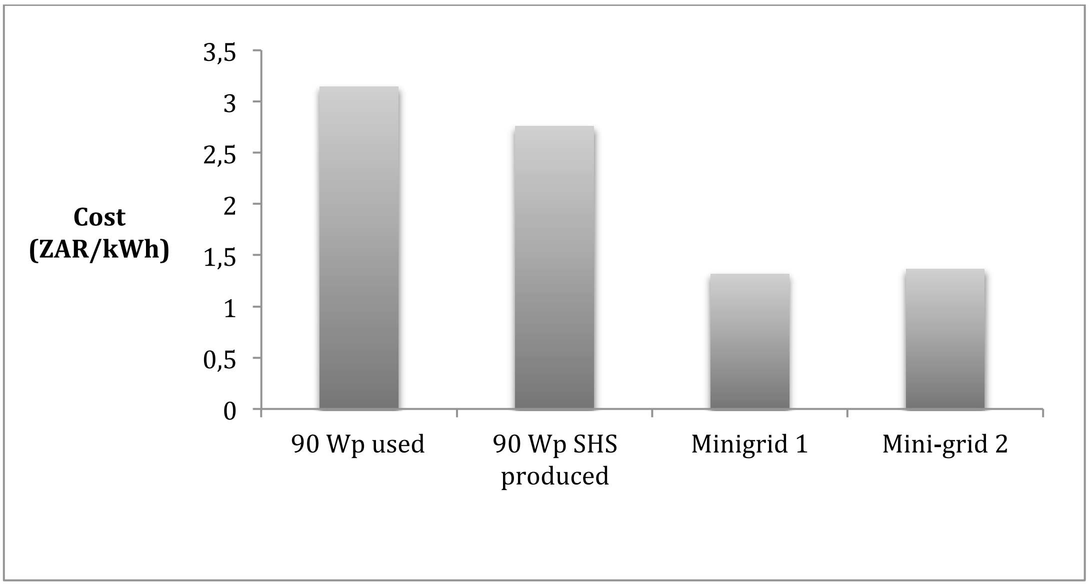

Figure 5-12: Levelized cost of energy for the three systems included LCOE for the consumption from the SHS

5.6 Future trends

Figure 5-12 shows the price prognoses toward 2025. The grid price was only calculated until 2022 due to lack of data. Notice the battery price in ZAR/kWh and the grid price and PV cost are in cent per kWh. The rural tariff for residential consumers were set to 124 c/kWh for 2017 (Eskom, 2017). Based on these trends, the electricity price in 2022 is expected to become 200 c/KWh, which is approximately 35 % higher than the LCOE for the mini-grid solutions.

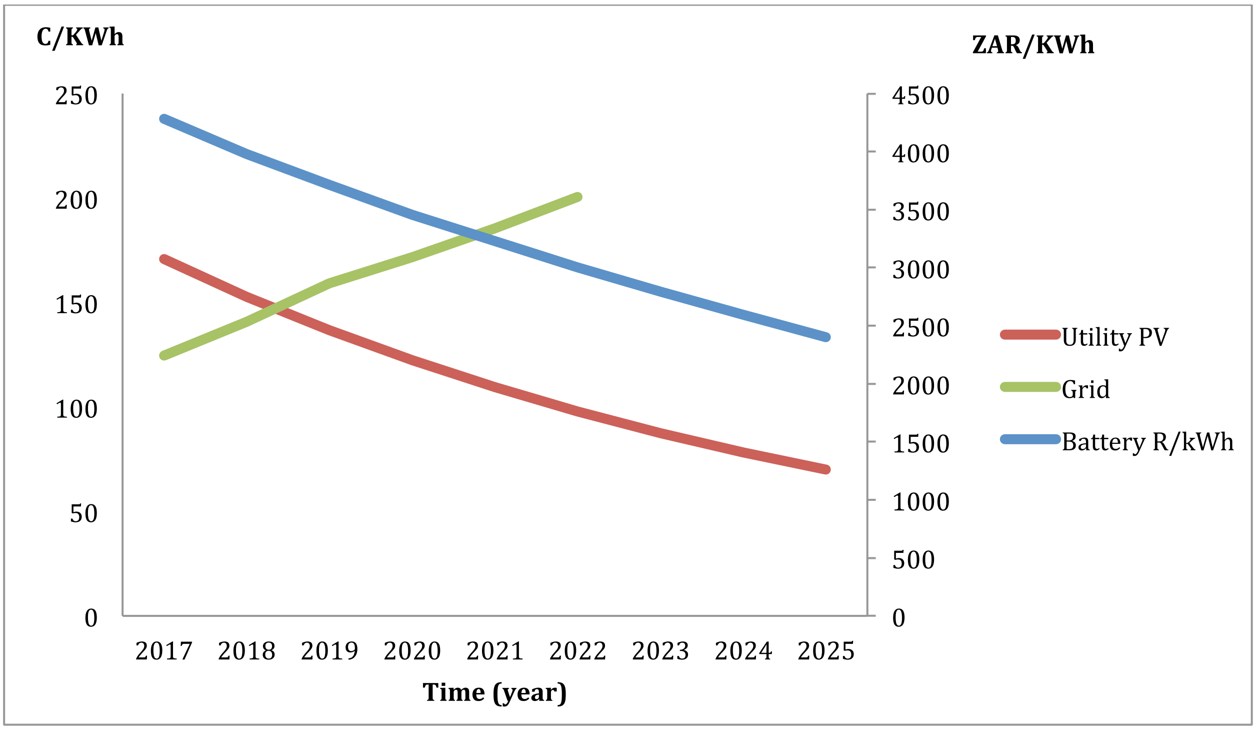

Figure 5-13: Price development prognoses for utility PV, battery price and grid electricity for South Africa

6 Discussion

This chapter presents discussion and analysis of the results (as presented in Chapter 5) of this study in light of the thesis´s objectives and previous studies. In addition, discussion on whether the proposed mini-grid systems have the potential to be better than the present SHS systems is presented. Furthermore, evaluation of the methods used in this research and discussion of shortcomings and possible error sources are presented.

6.1 End-user´s view compared to previous studies

6.1.1 User satisfaction

The end-users in the Limpopo province were pleased with the Solar Home System according to this research. The electric lights quality, increased possibilities to study after dark and the improved safety increased people's life quality. This is similar to findings on SHS in Zambia and Bangladesh (Gustavsson, 2004; Komatsu, 2013). The users appreciated the system and unlike findings from (Wamukonya, 2007; Azimoh, 2015), end-users in this present study aimed at keeping their systems safe. Wamukonya (2007) argued that the systems were often not appreciated because they were given out as donations, and the end-users were lacking understanding about the systems value. The interviewees in this study on the other hand, paid application fee and monthly fee through a leasing agreement. This could explain why the systems were more appreciated even though they did not pay the investment cost. Azimoh et al. (2015) investigated end-users satisfactions both in Solar Vision and NuRas concession areas. The results showed a fluctuating satisfaction degree between the villages, and people were more pleased in the Limpopo province. However, more people in this study were not satisfied than satisfied.

The result from this research showed that people who former had SHS and were now connected to the grid preferred the SHS was interesting. These results were, however, based on only three interviews, so a broader research on the area is necessary to confirm, and to this date, there did not seem to have been done previous research on the area.

6.1.2 Economic impact and economic development

Monthly spending on lighting and phone charging for the users were reduced when the SHSs were installed. This result complies with Azimoh et al. (2015) for the Solar Vision area. A study from Zambia (Ellegård, 2004) found that people there were paying more for the fee for service arrangement compared to what they paid for other light sources like candles and paraffin. However, the electric lights had higher quality with the SHS, and therefore, people were willing to pay the price. The SHSs in the Limpopo province were not working as a contributor to economic development, which is similar to what (Azimoh, 2015) found. This was mainly due to low energy output from the system. The business idea of using fridges to store and sell food came up during several interviews, and is an example of how it is possible to create an income with an increase in electricity. This is, however, an expensive investment and it is uncertain if people in these areas can afford it.

6.1.3 Fee for service arrangement

The fee for service arrangement seemed to be working in the Limpopo province. Previous studies have argued that this arrangement did not work due to several reasons. For example, in the NuRa concession area there were problems receiving the subsidies from the government (Azimoh, 2015), people complained about having to pay when the system was down and the capacity and possibilities with the SHS were to small (Lemaire, 2011). However, this did not seem to be the case in the Limpopo province. Solar Vision had no problems receiving subsidies from the government and each municipality paid their part of the monthly fee. The end-users received help within a short time when there were problems with the system, and no respondents had complaints on the arrangement.

6.1.4 End-user education

Results from (Azimoh, 2014) showed that lack of user education was a problem resulting in reduced output from the system. The findings in this study gave a different result. From the interviews carried out it seemed like the users had received proper training. People had an understanding of how much they could use the system, how the amount of clouds affected whether they could watch TV and use extra electricity, how to turn the module toward the sun etc. The only thing that seemed to be lacking was the importance of cleaning or brushing the module on a regular basis. Even if someone were unaware, most people would do it anyway because they were bringing them inside at night, and then it was natural to brush them.

6.1.5 Thefts

The fear of theft impacted the production from the solar modules. People handled the situation in different ways; some would only keep it outside when they could watch over the module while others hid it outside. Keeping it on the ground made it easier for the module to be exposed to shading and dust. However, due to the end-user education, people usually placed the module facing the sun. The preventing action with keeping the modules on the ground decreased the number of stolen modules, so it boiled down to what risk the users were willing to take to get as high production as possible.

6.2 Comparison of the three systems

Comparison and discussion of load factor, capacity factor and the economic results from the study are presented in this section.

6.2.1 Load- and capacity factor of the systems

Capacity factor

The capacity factor was low for all three systems, however, the capacity factor for both mini-grid systems was slightly higher (19.8 %) than the SHS (18.6 %). This was due to the assumption of a higher overall derating factor for the mini-grid systems. The temperature-derating factors were the same, while the non-temperature derating factors differed with 0.022. The derating factors were similar to other studies (Marion, 2014; Thevenard, 2013). The capacity factors found in this research were comparable to other studies on solar home systems and mini-grids. (Mundada, 2016; ESMAP, 2007) found C_f from mini-grids ranging from 13-18 % for installations in the US and India. The low capacity factors are a consequence of the derating factors and sun hours duration. However, a capacity factor close to 100 % will always be unrealistic for solar power considering lack of sun radiation during night and periods with partial sunlight.

Load factor

The load factor was low for the SHS and mini-grid$_1$ due to low usage during daytime and high electricity consumption during the evenings. This is not unusual for PV off-grid systems, and similar results have been found by other studies (Adaramola, 2017; Thomas, 2012)
The low load factor was increased for mini-grid$_2$ by 40 %. This is a result of the fridges being connected at all times, and the effect withdrawn from them are high compared to the rest of the consumption. To increase the load factor, the load peak must be brought down by evening out the consumption through day and night.

6.2.2 Economic results

Looking at the economic results, a mini-grid solution seemed like the obvious solution. The investment cost, payback period and levelized cost of energy are lowest for mini-grid$_1$. Mini-grid$_2$ on the other hand, delivers about four times as much energy, and has the potential to contribute to economic development with almost the same LCOE and payback period. It is however, a much higher investment.

Mini-grid$_2$ can be scaled down and become cheaper. This could be done if the village creates a system where the households are split into sections, and each section connect the fridges in for example 8 hours bulks. This way, peak load can be reduced by approximately 8000 W. As a result, the systems capacity could be reduced by almost 2/3 and fewer batteries would be needed. This would result in a cheaper system. This is a possible solution if the fridge is well insulated and able to stay cold for several hours after dis-connection (Messenger, 2010). In order to accomplish such a system, appropriate user education need to be in place for the users to understand the importance of such an arrangement. This has, however, not been investigated in this research due to time limitations.

6.3 The mini-grid solutions

There are challenges and advantages with mini-grid systems. First, each household does not have responsibility for their own system. Therefore there would probably be a need to hire people to take care of the solar- and battery park and to monitor it and care for the system. There might also be a need for someone guarding the plant to avoid thefts. These costs are not accounted for in the calculations.

Payment and user control have the potential to become a challenge. Working out a system where people only use what they are supposed to can be challenging. However, there are mini-grid solutions existing around the world with arrangements that can be emulated. For example, in South Africa, Specialized Solar Systems (the SHS components provider in Limpopo province) are using debiting methods for mini-grid solutions in other areas in the country (SpecializedSolarSystems).

The FBE policy states that people should be provided with 50 kWh from the grid for free (Eskom, 2016). Today the end-users with off-grid electrification pay a small amount for less energy. If a mini-grid solution supplying more than 50 kWh monthly to each household, it should be considered to implement a payment system where people who use more pay more. For mini-grid$_2$, being able to provide enough energy to cover 50 fridges, in addition to todays use, the monthly amount produced to each household would be 47,4 kWh. This is less than the FBE, so payment outward the fee should not be an issue. A solution could be to use the same system as today, where the end-user pay a small fee and ESCOs are responsible for operation and maintenance.

Setting up a mini-grid instead of several SHS´s, the mini-grid can later be connected to the grid when it reaches the area. Because the government pay for SHS they could instead pay for the mini-grid and get the advantage of extra energy supply later. With the increasing demand for electricity in the country there will be a need for more supply in the future. Nowadays, when the grid is replacing the SHSs the systems are either used in new places or sold. This has been a suitable solution, but later on when the whole country is getting close to being electrified it is questionable if this solution is the best one. Mini-grids can be considered a more long-lasting investment from the government and it has the possibility to benefit the whole country when connected to the main grid.

However, the main reason Solar Vision has not started providing mini-grids instead of solar home systems could be due to uncertainty in politics. There are no clear instructions from the government on how this would work, and for now the agreement does not involve mini-grids. This can be changed in the future, but it is a political decision.

6.4 Impact for the end-user

Assuming that the monthly fee for the end-user remains the same, the choice of which solution providing them with electricity does not impact their economy. What has an impact on their daily life is the amount of energy it provides. For the investors (the government) it should be a goal to provide as much high quality energy as possible- as cheap as possible. The mini-grid solution providing the same amount of energy for each household as the SHS does today has a LCOE almost three times lower.

For mini-grid$_2$ the investment price is about four times higher, and it provides about four times as much energy. This is a huge increase in energy supply for each household.

Before deciding on such a change, the pros and cons need to be carefully considered. The upsides are increased quality of life for the end-users and increase power supply for the country if it is connected to the main grid. The down side is the expensive investment cost. Proper knowledge on what the users want before scaling up the energy production is important. It is not certain that all users will invest in a fridge themselves, and if this is the case there can be a lot unused energy. Therefore, sizing the system, this needs to be carefully considered.

6.5 Future investment

As shown in Figure 5-10, the future prognoses indicate that the price on solar PV modules and batteries will keep on decreasing rapidly. This will reduce the investment cost for solar power and storage in the future and similar results were found from (Zubi, 2016). The grid price in South Africa, however, is expecting to keep increasing at a rapid rate. In 2022, the price might reach 2 ZAR/kWh. These price prognoses indicate that investing in solar technology in the future can become more profitable.

6.6 Discussion of methods used- challenges

The research was carried out without any previous experience on leading interviews. Each interview gave new experience and the learning curve was steep. The approach was adjusted with experience.

The duration of the interviews was shorter than expected. The interview guide was supposed to include questions for a long conversation, but this turned out to be incorrect. Perhaps there should have been other questions or the questions should have been asked in a different way. Regardless, it is unclear if it would have helped.

Interviews carried out with the translator had some possible concerns. The translator was working for Solar Vision, and that might have impacted the replies. Further, information in the translation might have disappeared or been adjusted. On the other hand, using a translator might have made them feel safer because of the same language, and in several cases, it was the technician who installed their system who was the translator.

Carrying out the calculations there were several assumptions. The data used to make the daily load profile and were only consisting on data from 12 interviews, so these numbers are not certain to be representative for the province. Sizing the mini-grids there was also done many assumptions that might be questionable. For instance, adding the power needed for each fridge and battery capacity was a simplified way of doing it. There has not been accounted for the aggregation effect for such a system, which should be considered. The assumption on BoS and O&M costs for the mini-grid systems were also simplifications and calculating them with right price levels could result in different outcomes.

6.7 Reliability and trustworthiness

Independent of the interviews quality, the method chapter include every decision made through the process. How and where the data was collected, how the transcriptions and analysis where done are thorough described. This has all been done to increase the reliability and trustworthiness of this research.

7 Conclusion and recommendations

The end-user perspective of the Solar Home System programme has to a high degree been neglected in previous research. Therefore, this research focused on peoples experience with the SHS and used information from the interviews to design alternative solutions to provide their additional need of energy and evaluate if these alternatives were better in a techno-economic evaluation.

The results indicate that the SHS have contributed to increased welfare with increased safety as one of the most important causes. Decreased fear of fire around children and the possibility to lighten up outside were the main reasons for the increased safety. Secondly, education became easier due to the possibility to read after dark and increased information received from the radio. The transition to SHS resulted in an average monthly reduction in spending of 137 Rand on candles and phone charging. The energy demand was covered, to a high degree, however, there was an additional wish for enough energy to run a fridge. Due to energy security and reduced spending, people preferred the SHS over being connected to the grid.

The fee for service arrangement in the concession area was highly functioning. People received help within a short period of time and had only a few problems with the systems in general. End-user education had been properly followed up.

The total cost per household was found to be lowest for mini-grid$_1$, approximately 50 % compared to the SHS and 25 % compared to mini-grid$_2$. Furthermore, the LCOE for both mini-grid solutions were about half of the LCOE for the SHS. The payback period for both mini-grid solutions were found to be about 1/3 of the SHSs payback period.

The trend with decreasing price for PV modules and battery technology, and the expected increase of grid electricity in South Africa, indicates the viability for a mini-grid to supply electricity at a lower cost than the grid in the future.

Recommendations for future work

To further investigate the opportunity for mini-grid solutions there is a need for new and more thorough research on the user pattern. When sizing the system, the aggregation effect, which reduces the max peak, should be taken into consideration. There is also a need to consider willingness to pay for more electricity from a mini-grid, and to carefully consider whether the users would invest in extra appliances like fridges.

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Appendix 1

Interview guide:

Introduction questions:

- Number of family members?
- Is anyone in the household working?
- Children: number, age, school?

Energy needs

- Why do you and you family need electricity?
- What energy resources are you using today?
- How long have you had the solar home system?

Daily load profile:

- What are you using the electricity for?
- How many hours do you keep use the lights daily? At what time?
- How many hours do you use the radio a day? When?
- How many hours do you charge the phone? When?
- Other applications and use?

Previous to the SHS:

- What did you use for lighting before?
- How much money did you spend on it?
- Phone charging before? Where? Costs?
- Did you reduce other expenditures it when you got the SHS?

Experience with the SHS

- What do you think about the solar home system?
- Has it been working as you expected when you applied for them?
- Have there been any problems?
- If yes: Did you get help? How long time did it take?
- Amount of energy: is it enough?
- If no: What else would you like? How much more? Devices? Would you in the case that it was possible be willing to pay more?
- Do you have any worries concerning the panels? Theft, fire, ect?

Fee for service

- What do you think about the fee?
- Do you feel like the money you pay is worth it?

Impact on daily life

- How has the SHS impacted you life? What has changed before and after the SHS?
- Has it affected the work in the household?
- Income?
- Studies for children?
- Safety?
- Are you glad you have it? Would you recommend it for others?

Appendix 2

Information on the interviewee's situation

Nr	**Years with the module**	**Size of the module, W_p**	**Persons in household**	**Living conditions**
1	5	75	5	Small house
2	5	75	4	Big house
3	2	90	3	Small, new house
4	2	90	5	Building house
5	1,5	75	4	Shed
6	2,5	75	6	Shed
7	1,5	75	4	Shed
8	3	75	5	Shed
9	3	75	5	House
10	3	75	4	House
11	16	50	2	1 room house
12	8	75	1	2 small houses sharing one module

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