University of Twente
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BACHELOR THESIS

Design of a solar home system for an unelectrified household in a rural community in the province of Limpopo, South Africa

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Keywords

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Abstract

In rural sub-Saharan Africa 77.4% of the population does not have access to electricity. Connecting isolated areas to the grid results in losses for the power suppliers in Africa in 80% of the cases. Off-grid electrification solutions such as solar home systems are required to achieve the SDG 7 defined by the UN as universal electrification by 2030. A literature review as well as interviews with students and staff from the UJ-PEETS that have been directly involved with the implementation of solar system in South Africa have been conducted. Based on the obtained information, a model methodology was presented that enabled the simulation and evaluation of solar home system performance.

Traditional generic solar home system sizing methods are often based on a number of nights or days of autonomy. A case-specific sizing approach was designed to optimise the size compared to generic sizing methods that in turn increased household affordability. Possibilities due to large amounts of additional wasted energies were explored and recommendations for future work discussed, which could further improve the positive impact of solar home systems on education, income and overall quality of life.

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List of Abbreviations

BMS Battery management system.

CUE Consumptive use of energy.

DOA Day(s) of autonomy.

DOD (Battery) Depth Of Discharge.

ESMAP Energy Sector Management Assistance Program.

GOGLA Global Off-Grid Lighting Association.

IDCOL Infrastructure Development Company Limited.

INEP Integrated National Electrification Programme.

LLP Loss Of Load Probability.

MPPT Maximum power point tracking.

MTF Multi-tier framework.

NOA Night(s) of autonomy.

PAYG Pay-as-you-go.

PUE Productive use of energy.

PV Photovoltaic.

PVGIS Photovoltaic Geographical Information System.

PWM Pulse-width modulation.

SDG Sustainable Development Goal.

SE4ALL Sustainable Energy for ALL.

SHS Solar home system.

SOC (Battery) State Of Charge.

UJ-PEETS University of Johannesburg's Process, Energy and Environmental Technology Station.

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Chapter 1 - Introduction

This first chapter of the thesis provides background information on the topic of off-grid electrification using solar home systems (SHSs) in section 1.1, outlines the context addressed in this research (section 1.2) and presents an overview of the layout of the document (section 1.3).

1.1 - Background

1.1.1 - Off-grid electrification

Ideally, every household in the world would have access to a reliable and "unlimited" electricity supply. While this might be possible in developed countries where the electricity grid developed over decades, the situation is a different one in the developing world, especially in ares of low population density. Besides the fact that it is generally costly to connect rural households to a centralised grid, people in developing countries use so little electricity that 80% of the power suppliers in Africa lose money every time they connect to a rural customer [1]. This is where off-grid solutions can offer an interesting alternative to supply electricity to communities in a possibly much cheaper way.
The concept of enabling access to electricity to rural households using off-grid solutions like SHSs is not a new one; projects from the World Bank, for example, date back to as early as 1997 [2]. The acceleration of worldwide efforts to minimise the impact of the climate change in the last years has massively increased the production and development of sustainable energy technologies like photovoltaic (PV) systems and storage technologies like lithium-ion batteries, which as a consequence decreased the prices of these technologies while improving performance in terms of efficiency and lifetime. In Germany, for example, prices of PV rooftop-systems dropped by 92% between 1990 and 2018 reflecting global trends [3]. For lithium-ion batteries a global price decrease of almost 85% between 2010 and 2018 can be observed [4]. This development makes it increasingly affordable for households to install privately funded solar systems in developed countries, but also enables communities in developing countries to participate in this advancement.
In 2012, the Global Off-Grid Lighting Association (GOGLA) was established, which represents a variety of companies, institutions and organisations in a network with the common ambition to "build sustainable markets and profitable businesses delivering quality, affordable off-grid electricity products and services to as many customers as possible across the developing world" [5]. 8 years later, in 2020, this network consisted of 180 members with a combined global share of 28% in the off-grid solar market. This market grew to the size of 1.75 billion annually with revenues growing 30% per year since 2017. As can be seen in figure 1.1, the largest share of the potential off-grid market is found in Africa, with approximately 600 million people not having access to electricity [6].

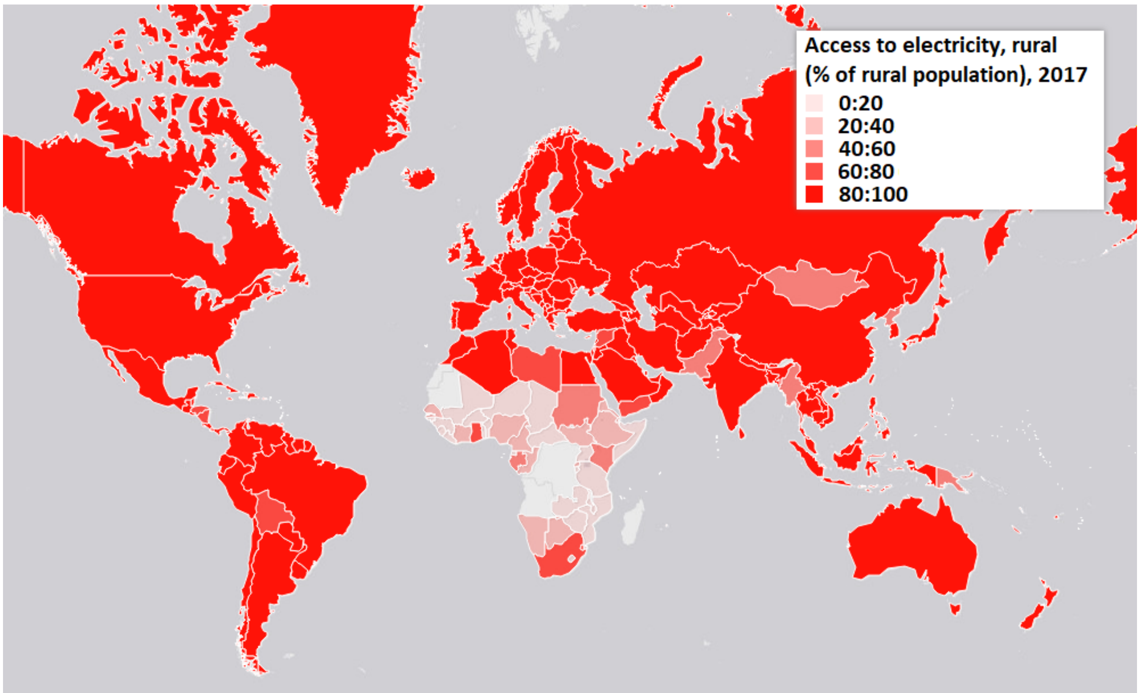


Figure 1.1: *Worldmap showing the rural electrification rates per country in 2017. For countries marked completely white no data was available. Obtained from [7].*

The United Nations addresses this issue in its Sustainable Development Goal 7 (SDG 7), which aims for universal electrification by 2030 (SDG 7.1) amongst other energy-related targets such as a higher share of renewable energy sources (SDG 7.2) and advancements in energy efficiency (SDG 7.3). Currently about 20 million people in Africa gain access to electricity annually, outpacing population growth but still being short of an annual rate of 60 million required to reach SDG 7.1 by 2030 [8].
As a case study, discussed in detail in chapter 4, Gwakwani village in the northernmost province of Limpopo in South Africa was chosen to gain insight into the situation of unelectrified communities in Africa. In 2017, South Africa had a relatively high rural electrification rate at 66.9% compared to the average of 22.6% in sub-Saharan Africa, which is the reason why the country has not been in the focus of research on off-grid electrification in the past [7]. Companies specialised in SHS solutions and related technologies are rather looking for countries with low electrification rates, where a large possible market exists and where government regulations support off-grid energy solutions. In Bangladesh, for example, which is used as a case study in many existing papers on the topic, the electrification rate (percentage of the population having access to electricity) surged from 48.1% in 2014 to 81.3% in 2017 [7]. The number of installed small-scale SHS units reached 4.13 million in January 2019, supplying renewable electricity to 18 million people (12% of the population), which are implemented by 56 partner organisations. This programme in Bangladesh, which "has been acclaimed the largest off-grid renewable energy programme in the world", exemplifies the possibilities a successful SHS story enables [9].
The numbers presented here are already visualising a part of the problem; in the general public "being electrified" is understood as having access to the fully functional grid as it is standard in the developed world. In reality, many households, counted as being electrified, lack any stability in the energy supply and often cannot afford the amount of electricity they would need. For this reason, the initiative Sustainable

Energy for ALL (SE4ALL), launched by the United Nations in 2011, together with the World Bank's Energy Sector Management Assistance Program (ESMAP), developed a multi-tier framework (MTF) allowing to define electricity access in 5 tiers in terms of capacity, duration, reliability, quality, affordability, legality, health and safety [10].

	Tier				
Attribute	1	2	3	4	5
Power	≥ 3 W_p	≥ 50 W_p	≥ 200 W_p	≥ 800 W_p	≥ 2 kW_p
Daily supply capacity	≥ 12 Wh	≥ 200 Wh	≥ 1 kWh	≥ 3.4 kWh	≥ 8.2 kWh
Hours per day	≥ 4	≥ 4	≥ 8	≥ 16	≥ 23
Hours per night	≥ 1	≥ 2	≥ 3	≥ 4	≥ 4
Affordability			Cost of 365 kWh/year < 5% of household income		
Reliability				≤ 14 disruptions per week	≤ 3 disruptions per week, total $\leq$ 2h
Legality				Bill is paid to the utility/prepaid card seller/ authorised representative	
Health & Safety				Absence of past accidents, no perception of high risk in the future	
Quality				Voltage problems do not affect use of desired appliances	

Table 1.1: *Overview of the multi-tier framework developed by SE4ALL and ESMAP to categorise electrification levels. Adapted from [10].*

As can be seen in table 1.1, this categorisation depends on technical specifications of the supply such as available peak power and daily supply capacity, but also requires legal and qualitative standards for the higher tiers. Looking at the requirements in terms of power and daily supply capacity it becomes clear that the tiers are not following a linear structure, meaning the higher tiers are increasingly hard to achieve by simply adding larger panels and batteries to a SHS. Other solutions like grid connection or interconnected SHSs in the form of a micro-grid have to be considered to reach tiers 4 and 5. Another important remark is that tier 3 should not be understood as the average household level, but rather that all 5 tiers are only steps towards the electrification as it is available in developed countries.

1.1.2 - Solar home systems

A solar home system is generally a standalone system consisting of a PV panel for electricity generation, a battery for energy storage and power electronics that are necessary to convert the produced energy into a stable supply and improve efficiency. GOGLA roughly defines SHSs as systems with a maximum power output between 11 and 100 W, while devices up to 10 W are referred to as pico-solar devices. SHSs above 100 W are not considered feasible entry systems for single households [11].

The performance of the system mainly depends on *i)* the size of the PV panel, rated in Wp, which refers to the maximum possible power output and *ii)* the size of the battery, rated in Wh, which determines the amount of energy that can be stored inside the system. While the power electronics are equally important for the functionality of the system, they are of small interest when rating its performance. The technical components of SHSs are discussed in more detail in chapter 2. The SHSs discussed in this document are meant as single-household solutions that are specifically designed to meet the requirements of one household.
Referring back to the MTF seen in table 1.1, it is relatively simple to categorise a SHS into one of the tiers. The power is solely defined by the size of the PV panel, while the daily supply capacity is limited by the size of the battery and the energy generated by the PV panel. The duration of the available energy in terms of hours per day and night are more complex, since they highly depend on the way the user draws energy from the system. The usage pattern of an individual SHS user is referred to as the load profile, which is one of the most important parameters for SHS designers. The load profile depends on the amount of energy the user requires, but also the time of the day at which this energy is needed. Since the only source of energy is the light of the sun, the time plays an especially important role to determine what amount of energy the battery needs to supply while there is no sunlight. For SHSs designers the often unknown load profiles poses a major challenge to appropriately size the system.

1.2 - Context

1.2.1 - Problem definition

This document can by far not cover all aspects that are relevant for a successful implementation of a SHS in a real community, since that requires not only a technical analysis of the system, but also a thorough case-specific socio-economic evaluation. The focus lied on the technical design of the system, using an estimation of a load profile of the potential users as a foundation. In order to develop this estimation, interviews with students and staff from the University of Johannesburg's Process, Energy and Environmental Technology Station (UJ-PEETS) were conducted.
Traditionally, the size of the "optimal" SHS for a user is determined using a rule of thumb such as requiring a fixed amount of days or nights of autonomy (DOA/NOA) for which the system should supply energy. This approach can result in significant oversizing of the system. Often, a much smaller combination of battery and PV panel results in almost the same performance if certain limitations are accepted, but come at a much lower price [12]. In a market that is highly cost-sensitive, an oversized system is extremely inappropriate.

1.2.2 - Approach

To properly design the size of a SHS in terms of battery and PV panel size, this research followed the approach to firstly develop a clear idea of the system requirements in the specific village case and secondly to create a model that provided insight into the effects of different parameters on the performance of the SHS. The results were evaluated to present conclusions and recommendations on the improvements that could be done on SHSs when considering case-specific energy needs during the design process.

1.3 - Thesis outline

This thesis is split into 7 chapters, organised as follows:

- Chapter 1 introduced the background and content of this research.
- Chapter 2 explains the technical components of a SHS.
- Chapter 3 provides a review of existing literature on the topic of off-grid solar home systems which leads to the research question addressed in this document.
- Chapter 4 gives insight into the electricity market in South Africa and specifically into the situation in Gwakwani in the province of Limpopo, which is used as a case study.
- Chapter 5 explains the sizing approach used to create a solution tailored to the needs of the people in Gwakwani and the methodology to design a suitable SHS model.
- Chapter 6 presents and discusses the results achieved with the described approach and provides ideas for future improvements.
- Chapter 7 ends the thesis with conclusions and limitations of the work and provides recommendations for future work.

In the beginning of each chapter a short section on the outline of the chapter can be found. Chapters 2 to 6 are each concluded with a summary in the form of a list containing the key takeaways of the chapter.
Chapters 2 and 5 discuss the technical aspects of the research while chapters 3 and 4 focus on the context around the technical solution.

Chapter 2 - Solar home system components

This chapter presents a brief description of the components of a basic SHS and their physical behaviour, emphasising the differences between ideal components and realistic models in terms of efficiency and lifetime. Section 2.1 starts the chapter with a system block diagram of a SHS. The following sections each discuss one of the subsystems shown in the block diagram, which are all summarised in section 2.5.

2.1 - System overview

Figure 2.1 shows a system block diagram of the most important parts of a SHS. Each blue marked subsystem is discussed in a separate section.

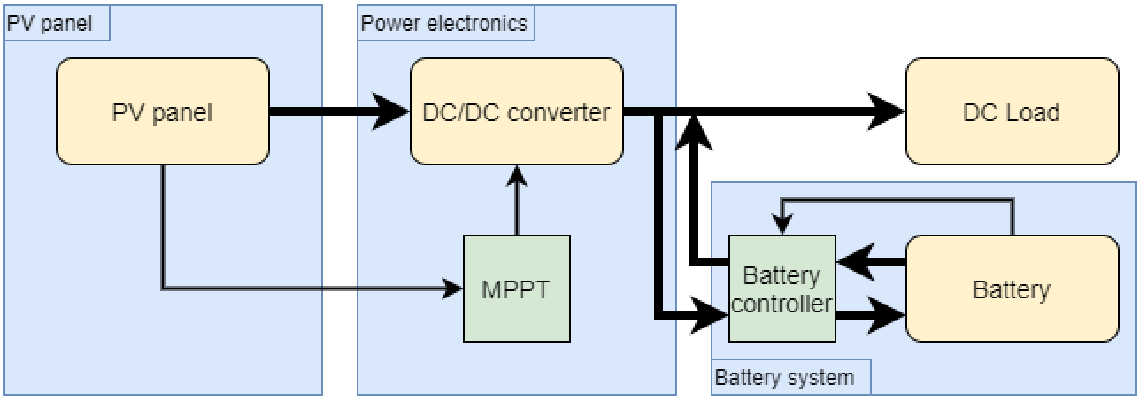


Figure 2.1: *Block diagram of a basic SHS. The thin arrows represent data exchange, while the thick arrows represent power transfer. The green boxes represent digital control components.*

The PV panel converts sunlight into direct current, which flows into a DC/DC converter. The green maximum power point tracking (MPPT) block represents a controller that regulates the DC/DC converter in such a way that the maximum power can be received from the panel. Depending on battery and load levels, the output power of the DC/DC converter either flows into the battery or directly powers a connected load. The battery serves as the energy storage of the system, which is required to provide energy when the sun is not shining. To monitor the battery state of charge, a battery controller is required that prevents over-charging and -discharging the battery. If energy is produced while no load is connected and the battery full, this energy is dumped. The SHSs discussed in this document are not connected to the grid and therefore do not include any DC/AC converter.
Section 2.2 provides more detailed information on PV panels, section 2.3 details the

working principle of the DC/DC converter and the MPPT and section 2.4 provides an overview over the batteries used in a SHS.

2.2 - PV panel

2.2.1 - Operating principle

The power-producing component of a SHS is the PV panel, which is using the photovoltaic effect inside semiconductor p-n junctions to convert sunlight into electric power. A PV panel is an assembly of individual PV cells connected in series and/or parallel to increase output voltage and/or current. The amount of current generated by each PV cell is depending on several factors such as radiation incident angles or cell temperature, but generally the more light the panel receives the more current is generated. This makes PV technology extremely attractive for the off-grid market in sub-Saharan Africa, since solar radiation levels throughout the African continent are amongst the highest in the world, which is discussed in chapter 4. Another positive aspect of PV panels compared to other renewable energy sources is the lack of mechanical parts, which reduces the amount of required maintenance and allows for a long lifetime of usually more than 20 years.
PV panels are rated in their nominal output power Wp, which is the power they produce under standard test conditions defined as 1000 kW/m^2 irradiance and 25°C cell temperature [13]. Irradiance is the solar power per unit area falling on the surface of the PV panel and is the sum of the direct radiation from the sun, diffused radiation, which is radiation that has been scattered by the atmosphere, and reflected radiation, which is radiation reflected from objects or the ground. When installing a PV panel, the angle with respect to the horizontal plane (called slope) as well as the east/west orientation (called azimuth) need to be optimised to receive most of the available irradiance at a specific location over seasonal periods. The actual output power of the PV panel is then dependent on its efficiency, which describes the portion of energy from sunlight that is converted into electrical energy. This efficiency depends on the material and manufacturing method used to produce the individual PV cells as well as the interconnection of the cells and the surface material of the panel; for commercially available crystalline silicon PV panels it lies around 17% [14].

2.2.2 - Electrical modelling

For this research, the single-diode model is used to represent the PV panel, which is a widely used electrical equivalent circuit of a PV panel, shown in figure 2.2 [15]. The PV cell is a current source that produces current proportional to the received light, while the other components model non-ideal behaviour of the PV panel, such as *i)* a small leakage current caused by minority carriers in the semiconductor layers, represented by the diode, *ii)* impurities in the material, especially at the edges of the semiconductor material, that cause an alternative finite-ohmic way for the generated current to flow, represented by the shunt resistance R_{SH} (ideal: R_{SH} = infinite) and *iii)* a series resistance R_S, caused by the resistance of the semiconductor material and imperfect metal contacts (ideal: $R_S = 0$) [16].

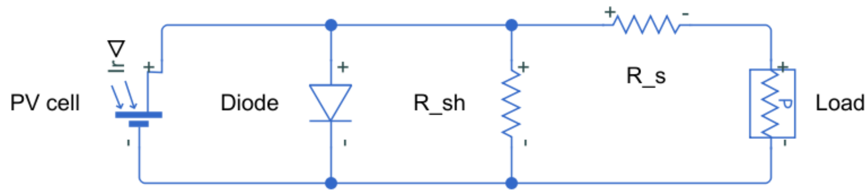
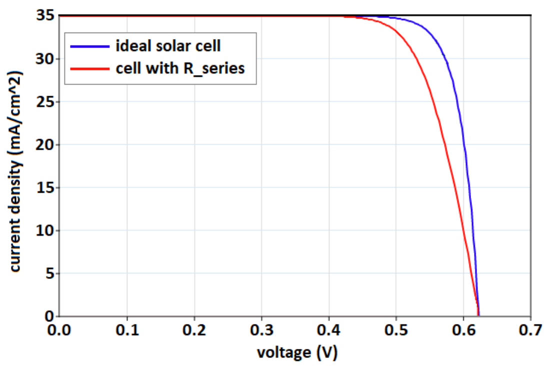


Figure 2.2: *The single-diode model consists of a current source representing the PV cell, a diode and 2 resistors which are used to represent realistic behaviour of a non-ideal PV panel.*

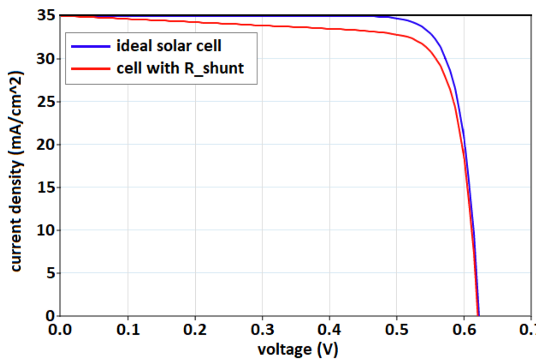
Using this equivalent circuit to model the cell allows to describe its performance and efficiency in a more realistic way than simply using a current source. The current that is available at the output of the PV panel I_L is given by equation 2.1.

$$I_L = I_D - I_{SH} - I_0 \cdot e^{\frac{qV}{nkT}} \tag{2.1}$$

With I_D being the current generated by the PV cell, I_{SH} being the current through the shunt resistor and the rightmost term describing the leakage current through the diode. Within this rightmost term, I_0 is the saturation current of the diode, q the elementary charge, k the Boltzmann constant, n the ideality factor of the diode, V the voltage across the cell terminal and T the cell temperature. Of these terms, only V and T are parameters depending on external conditions [16].
The values of the series and shunt resistance have an influence on the available output power as seen in figure 2.3.



(a)



(b)

Figure 2.3: *Effect of parasitic resistances on the output current of a PV cell (red curves) compared to an ideal cell (blue curves); (a) shows the effect of a series resistance and (b) shows the effect of a shunt resistance. Adapted from [16].*

The higher the series resistance, the lower the output voltage of the panel and the lower the shunt resistance, the lower the output current of the panel. Only for extreme values do the series resistance affect the output current and the shunt resistance the output voltage. The effect of changes in output voltage and cell temperature on the generated current is shown in the context of MPPT in figure 2.5 in section 2.3.2.

2.2.3 - External factors

This single-diode model describes the losses that occur even inside a newly fabricated PV cell due to parasitic components. In addition to these losses, degradation has an influence on the PV cell's performance over longer periods of time. To determine longterm performance of a SHS, it is important to create a model that takes degradation effects on the components into account. As summarised by Ndiaye et. al, these degradation effects are mainly caused by corrosion, discoloration, delamination and breakage or cracking cells [17]. For crystalline silicon cells, these effects cause a yearly degradation of around 0.6% in output power [18]. The placement of PV panels outside under any weather condition causes not only longterm damage on the panel, but also results in general deviations from laboratory conditions. Temperature and humidity changes accumulate small damages on the panel over time, while dust, (partial) shade on the panel, soiling or passing clouds limit the immediately available solar power. Ideal conditions for PV panels are high solar irradiance and cold temperatures; per 1°C increase in temperature, the generated solar power is estimated to decrease by between 0.38 and 0.45% [19].

2.3 - Power electronics

2.3.1 - DC/DC converter

The PV panel, which behaves like a current source, neither supplies a fixed voltage nor a fixed current. This fluctuating output needs to be suited to the battery or load, which can be done using a DC/DC converter. This converter can be either of Boost or Buck typology, a combination of both, or one of many other circuit typologies, depending on the voltage levels of the PV panel, the battery and the load to be driven. Figure 2.4 shows the circuit schematic of a basic Buck converter.

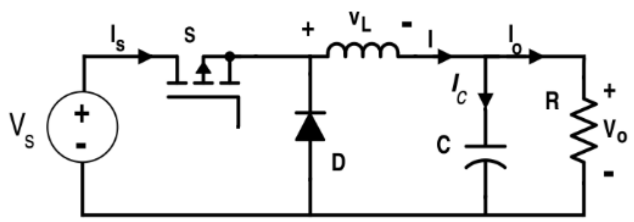


Figure 2.4: *Basic circuit of a Buck converter. Obtained from [20].*

The transistor is used as a switch that connects or disconnects the power supply, which is the PV panel in the case of a SHS. Whenever the transistor is conducting, current flows from the source into the inductor; after the transistor opens the gate, the diode sustains the current flow through the inductor, which discharges into the capacitor and the load. Depending on the duty signal of the pulse-width modulation (PWM) signal applied to the transistor gate, the output voltage can be any level below or equal to the input voltage. A Boost converter follows a very similar principle, but allows for an increase in output voltage instead of a decrease as created in the Buck converter. More advanced circuits exist that replace the diode by a second transistor to reduce power losses, but they follow the same DC/DC conversion principle.
In terms of efficiency, modern DC/DC converters usually range around 95% [21, 22].

Losses occur due to parasitic resistances in the circuitry of the DC/DC converter and a finite channel resistance of the switching transistor, especially during transitions between the transistor's states [23, 24].

2.3.2 - Maximum power point tracking

Another important task of the DC/DC converter is to ensure the panel is operating at its maximum power point, which can be done via different MPPT techniques. As shown in figure 2.5, the net output power of a PV panel depends on its output voltage and current, which in turn depend on the load impedance.

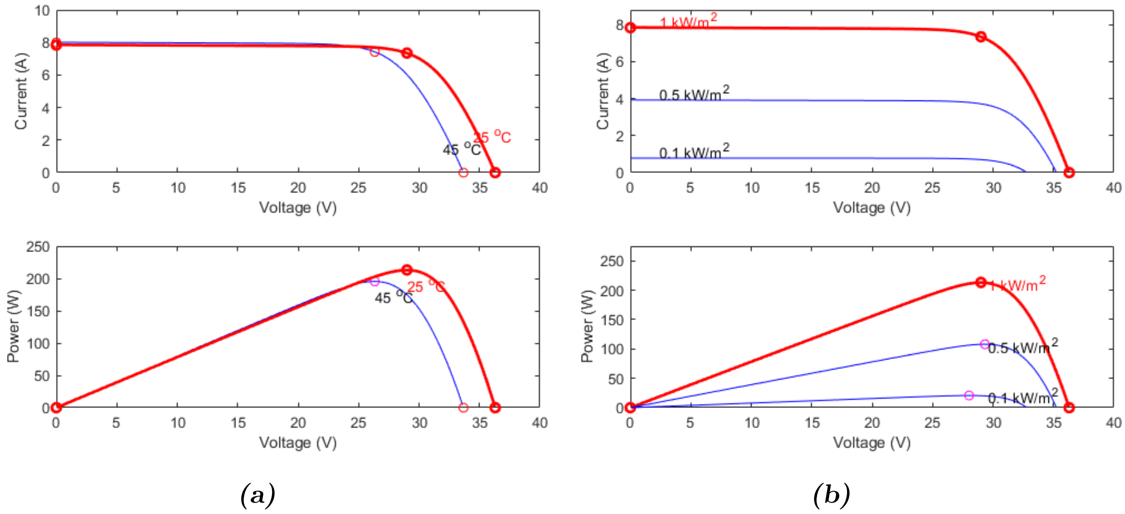


Figure 2.5: *Representative IV characteristics of a PV panel with rated W_p = 213 W, (a) at constant irradiance of 1kW/m^2 and different temperatures and (b) at constant 25°C and different irradiance levels. The red circles mark the peaks corresponding to the maximum power point. Created in Simulink using the Specialised Power Systems of the Simscape Electrical library.*

The internal transistor of the DC/DC converter is driven by a PWM signal. The duty cycle of this PWM signal is proportional to the input impedance seen by the PV panel, thus it can be used to set the input impedance to a desired level. While there exist many different established algorithms to effectively find the maximum power point of a PV panel (e.g. Perturb & Observe, Incremental Conductance or Constant Voltage), they all follow the same idea of adjusting the duty cycle of the PWM signal that controls the transistor gate inside the DC/DC converter until maximum power is transferred. The Constant Voltage method simply keeps the input voltage of the converter on a fixed ratio of the open circuit voltage of the panel, which is the least dynamic method, that fails to effectively adjust to changes in temperature or irradiance levels. A more dynamic algorithm is described by the Perturb & Observe method, which is a basic control algorithm that increases or decreases the duty cycle in small steps, based on if the previous step resulted in a increased or decreased power transfer [25]. This algorithm can result in oscillation around the maximum power point, thus more advanced algorithms exist. These algorithms are not discussed in detail, since the operation principle remains the same.

2.4 - Battery system

2.4.1 - Battery control

The battery system consists of the battery itself and the battery controller (or battery management system, BMS), which ensures the battery only operates in its safe range by monitoring temperature, charge and discharge levels. The controller is needed to extend the lifetime of the battery by avoiding deep discharge levels and operation in high temperatures. In lithium-ion batteries, the BMS has to not only monitor the complete battery pack, but also individual cells to ensure cell balancing and fulfil a range of operation requirements [26]. For this research, the only important aspect of the BMS is the limitation of charge and discharge levels, which limits the overall energy available from the battery.

2.4.2 - Battery

Different battery chemistries are available on the market, but in most high-quality SHSs lithium based batteries are used [6]. An ideal battery has a constant nominal output voltage, can charge and discharge to its maximum and minimum levels and introduces no losses during charging and discharging. A real battery has a series resistance, which introduces losses during charge cycles in the form of heat and has a maximum capacity that depends on many factors such as temperature, depth of discharge (DOD) and discharge currents. It is also affected by longterm degradation, the severity of which depends on the conditions under which the battery is operated. The main factor influencing lifetime is the cycle depth, as can be seen in figure 2.6, which shows the number of possible cycles versus DOD until the end of life of the battery is reached (defined as the maximum capacity reaching 80% of the rated capacity) [27].

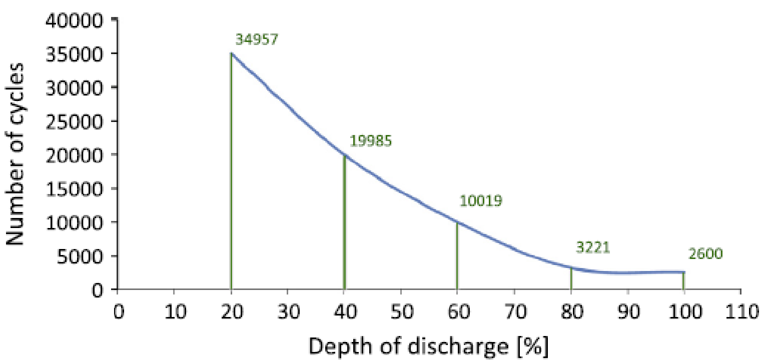


Figure 2.6: *Number of possible cycles until the end of life of a lithium-ion battery is reached against the depth of discharge of the cycles. Obtained from [27].*

The maximum and minimum state of charge (SOC) levels of the battery are limited to extend its lifetime, but also to increase overall efficiency, since it is dependent on the SOC of the battery and drops near its maximum and minimum levels [19]. During proper operation of a lithium-ion battery, round-trip efficiencies of up to 99% can be achieved [28]. Since temperature and discharge currents are mainly depending on location and usage, these parameters can barely be changed to optimise the performance of the battery. The capacity of the battery, on the other hand, can be chosen such that lower DOD is reached during each cycle, extending the battery's lifetime. This creates an interesting trade-off between a larger battery, that comes with higher upfront costs but might make up for it due to a longer lifetime, or a smaller battery, that comes with smaller upfront costs but might need replacement earlier. This can be expressed as the price of a battery per total Wh stored in it over its lifetime [$€/(Wh \cdot \#cycles)$], which is a useful definition to compare the total energy stored in the battery over its lifetime to the upfront cost.

2.5 - Summary

The key takeaways of this chapter, which are relevant to create a realistic SHS model, are summarised as follows:

- PV panel:
  - Losses occur due to impurities in the manufacturing process and finite-ohmic series and shunt resistances, which reduce output voltage and current of a PV cell.
  - Degradation over time decreases the maximum available output power by an estimated 0.6% annually.
  - Cell temperature plays an important role for the performance of a PV cell, per 1°C increase in temperature the power output is reduced by between 0.38 and 0.45%.
- Power electronics:
  - A DC/DC converter induces power losses of around 5% in the system.
  - MPPT should be used to allow for maximum power generation.
- Battery system:
  - The battery is limited to certain maximum and minimum charge levels to extend lifetime and efficiency.
  - Degradation over time lowers the maximum capacity of the battery and increases losses during charge cycles.
  - Choosing the right battery capacity creates a trade-off between upfront cost and lifetime by expressing the cost in [$€/(Wh \cdot \#cycles)$], allowing for optimisation in this aspect.

Chapter 3 - Literature review

This chapter provides an overview of existing literature on the topic of SHS and evaluates different viewpoints on the material. The chapter first summarises positive and negative aspects of SHSs reported in literature in section 3.1, using data from research papers and technical reports. This is followed by a short introduction to the appliances used together with SHSs (section 3.2). Section 3.3 explains the problem of optimal system sizing in more detail. Section 3.4 gives a short overview over financing models used by companies active in the off-grid sector. The chapter is summarised in section 3.5 and concluded with the statement of the main research objective section 3.6.
As mentioned in chapter 1, researchers have not been focusing on South Africa as a case for off-grid electrification, but nonetheless results obtained in other African countries and in South Asia remain interesting for the case of north-eastern South Africa for multiple reasons; *i)* the underlying long-term goal of universal electrification and economic development is the same for all SHS projects, *ii)* basic electricity needs of people are for large parts the same, independent of the location, except for some climate-dependent appliances, *iii)* while the income can vary from region to region, most studies focus on generally poor people relying on subsistence farming and *iv)* countries most interesting for SHS projects require a tropical or subtropical climate with a high number of daily sun hours.

3.1 - Experiences with solar home systems

The problems that are observed in existing literature regarding SHSs are partly of technical nature and partly depending on the circumstances under which they are implemented. A study conducted by Azimoh et. al in South Africa, partly in Limpopo, in which a total of 88 households using SHSs were interviewed, reports that more than 56% of users were dissatisfied with the performance of the systems [29]. Reasons were declines in performance after a few months, too little power output to use appliances and frequent system breakdowns. Other problems of non-technical nature were reported such as frequent theft of solar systems or non-optimal usage due to unawareness by the users. A different study conducted by the same authors showed SHSs placed in the shade in front of the door of the users instead of the sunny rooftop to avoid theft of the device [30]. This reveals that, in order to satisfy SHS users, not only must the system be appropriately sized to avoid frustration with breakdowns and unmet power demands, the users must also be educated about the proper use of the system. If users are not aware of the functionality of the system and the possible performance they can expect, dissatisfaction can destroy trust in the systems.
Regarding the economic impact of SHSs, in the same study only 23% of interviewed users believed that SHSs had a positive impact on the economic development and around 80% were not aware of any new business that started as a result of the

introduction of SHSs [29]. The main positive effect that was reported was the light in the evening which allows children to spend more time on school work and perform better at school, which in the long term will lead to higher education levels in the region. This agrees with a study conducted in Bangladesh in 2019 where the main benefits of SHSs are listed as comfort in household chores, security at night due to solar lights, longer study hours for children and access to information via TV or phones [31]. Next to the direct impacts of SHSs on the individual households, a spillover effect can be observed that allows residents without access to electricity to indirectly benefit from neighbours with for example lights or a TV [32]. This effect also has an important social impact on the communities and can uplift the social status of a family [33].
While the mentioned effects are clearly positive, it remains unclear how SHSs can enable longterm economic development. Diallo and Moussa created an overview of how this could be achieved, which can be seen in figure 3.1.

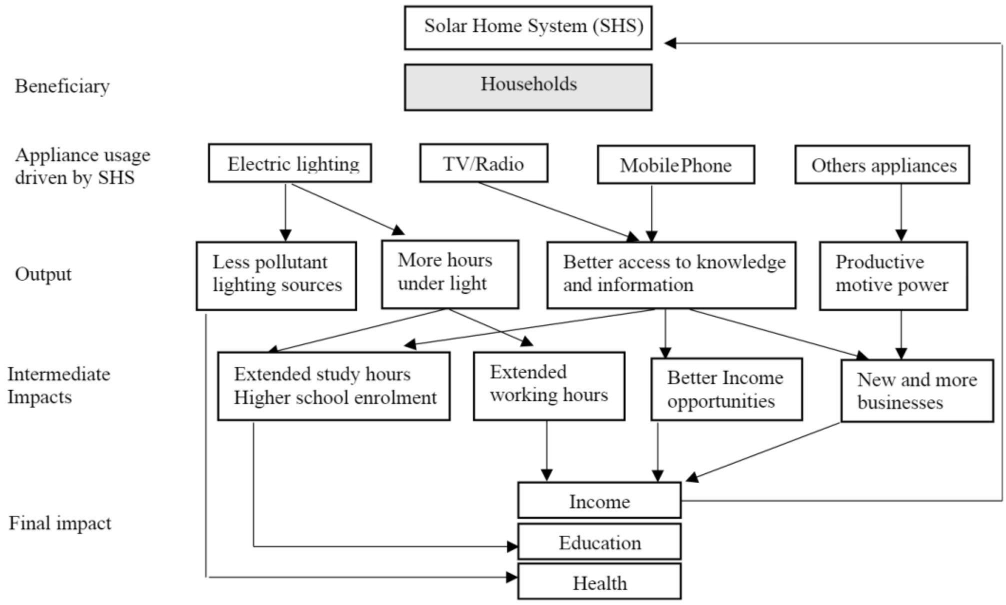


Figure 3.1: *How SHSs can improve users' quality of life. Obtained from [32].*

The overview shows that in theory there is a clear idea how SHSs can improve local economies, but looking closely one can observe that the main drivers of income generation are better access to knowledge and the usage of income generating appliances. The improved access to information and knowledge is one of the most observed direct impacts of SHSs that can, on its own, already have a profound impact on the income opportunities of households. Having energy to regularly charge phones and listen to radio or watch TV gives a household access to knowledge from outside the local community. A farmer could, for example, improve the yield of a crop by learning how to optimally treat the plants, or could grow more profitable crops. The possibility to use income generating appliances, for example a water pump for a farmer, that could allow a family to transition from subsistence to income generating farming, remains a more complex problem, since the required power is often too much for a single SHS to handle. But next to power-consuming motive appliances, even lights and the electricity itself can create income for a household. In a report published by GOGLA in 2019, over 1400 SHS users were interviewed in eastern

Africa, with a focus on the economic benefits of the system. The report stated that per 100 SHSs sold, 21 full time equivalent jobs were created and 34% of customers were more economically active [34]. The created job opportunities were partly based on the ability to work more hours and partly on the creation of new businesses directly linked to the installation of the SHSs. The newly created businesses were often phone charging stations, shops and stalls, bars and restaurants or hair cutters. With a phone charging station, customers could directly sell the generated electricity and thus pay off their SHS. This might be a great option for an individual household, but since the market for solar charging stations is quickly saturated, even more so through the widespread distribution of SHSs, it is not a business that lifts whole communities out of poverty. Shops and restaurants can benefit from solar lights through extended working hours in the evening or through the sale of cold food and drinks. The breakeven point of the economic activity, when the SHS is paid off through the additional income generated through its usage, is usually reached within a few months [35]. In addition to the job opportunities for users of SHSs, the sales and distribution of these solar systems can stimulate the local industry.

Next to the benefits of SHSs on education and income, the third most often named positive effect of SHSs in literature is on the health of its users. Replacing air polluting candles or kerosene lamps used for lighting with clean LEDs can drastically improve indoor air quality, which was listed as one for the major causes of deaths in low-income countries by the World Health Organisation in 2009, accounting for 1.3 million deaths annually [36]. In a survey conducted by GOGLA, 89% of SHS users report an improved health since purchasing the system [34].

3.2 - Off-grid DC appliances

The way electricity is consumed can be broadly divided into two options; consumptive or productive use of electricity (CUE/PUE). CUE describes the consumption of electricity for leisure purposes, such as watching TV or powering a fan, while PUE describes the usage of electricity to support income generating activities. CUE might not directly contribute to the income generation of a household, but can improve overall quality of life and indirectly benefit communities, e.g. by watching TV shows that discuss societal issues or provide additional education [37]. Appliances required for CUE also tend to consume less energy than those for PUE, which makes them more attractive for the off-grid market [35]. Devices that could allow for PUE, such as water pumps, rice hullers, sewing machines or drills, consuming several tens or hundreds of watts, show where the technical limitations of SHSs pose a problem. Narayan captured these limitations, which he refers to as “the paradox of SHS-based electrification”, as can be seen in figure 3.2 [12]. The paradox refers to the fact that some appliances are extremely cheap (e.g. water kettles, rice cookers) but need huge amounts of power, while other appliances like computers require much less power but are expensive themselves.

This requirement of having cheap but efficient appliances led to the development of the so-called super efficient DC appliances. These appliances are directly running on a DC input, compared to the standard 50 Hz AC appliances that have been traditionally used, which eliminates the need of loss-inducing DC/AC converters. A widespread example of DC appliances are LED lights, which are more than twice as efficient as traditional lights [38]. Due to the growing SHS market, the market for

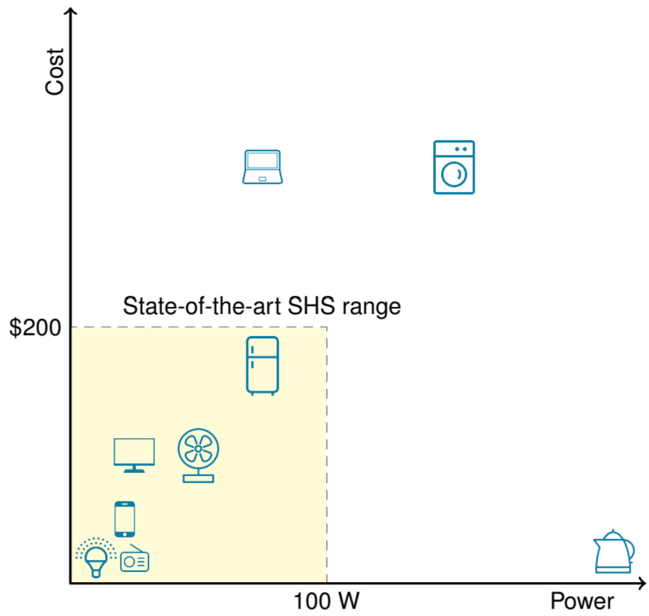


Figure 3.2: *Conceptual graph visualising the limitations of SHSs. The numbers are purely indicative. Obtained from [12].*

DC appliances is also expanding and offers a range of devices from DC radios and TVs to fridges, microwaves or rice hullers [35]. These efficient devices have also found their application in camping and outdoor equipment, where some originate from. As was shown by Den Heeten, when using off-grid DC appliances instead of traditional AC ones, the power consumption can be lowered by around 30-40%, depending on the number and type of appliances in use [39].[1] While these DC appliances can be more expensive than traditional AC ones, a much smaller SHS can potentially power the same appliances and thus reduce overall costs of the SHS of up to 50% [40].

3.3 - System sizing

The combination of requirements to design a system that can produce and store as much power as possible to drive a high number of appliances for a long time while suiting the extremely limited budget of potential customers clearly shows that the size of the SHS has to be carefully chosen. The most expensive part of a SHS is usually the battery, which often accounts for around 50% of total system costs while its lifetime is significantly lower than that of the other components of a SHS [40]. In recent years, most system manufacturers switched to $LiFePo_4$ as chemistry for the built-in batteries in SHSs due to its advantages over alternative chemistries like lead-acid in terms of total lifetime, depth of discharge, round-trip efficiency, energy density and an expected further price decline in the future. In Bangladesh, the Technical Standards Committee of the Infrastructure Development Company Limited (IDCOL) has set a hardware standard for SHSs to allow for a minimum of 2 DOA [41]. While Bangladesh is a country affected by heavy seasonal rainfalls, where there might be a consecutive number of days without sunshine, this is less applicable

[1] An overview of the expected power consumption of some common DC appliances is shown in section 4.3 (table 4.1).

in South Africa and thus a less generic sizing method is needed to optimally meet user demand. As Narayan has shown, an approach based on individual load profiles combined with regional climate data can result in a much better suited size for the overall system [12]. While load profile data of SHS customers provides great insight into the required energy per day, these load profiles are not often known. Predicting the energy usage of newly electrified customers poses a major challenge for SHSs designers since the available appliances and energy requirements can be extremely different from customer to customer. Additionally, once electrified, SHS users might add appliances which can quickly create the need for a larger system, thus the initial system should not be sized too small to enable consumer's growth.

Regarding the battery, the sizing becomes even more complex when taking into account the effect of the DOD on battery lifetime. The cycle life of $LiFePo_4$ batteries is highly dependent on the depth of each charge cycle, where deeper cycles generally lower the total cycle life, thus an oversized battery will increase upfront costs but through a longer lifetime might reduce costs in the longterm [42]. Next to the battery, the PV panel needs to be properly sized. Due to price declines in recent years, PV has become a relatively cheap technology with a long lifetime (usually around 20-25 years) and thus accounts for a smaller part of the overall costs compared to the battery. This cost distribution favours, to a certain extent, a combination of a relatively larger panel and smaller battery over a smaller panel with a larger battery, which explains why a strict demand of 2 DOA for the system is not an appropriate requirement.

The performance of a SHS is usually measured in the loss of load probability (LLP) and the amount of generated excess ("dumped") energy. The LLP describes the percentage of time in which no load can be driven due to too low supply from the PV panel and the battery. For the electricity grid in Germany, for example, a standard of maximum 0.06% for the LLP was defined in a project commissioned by the Federal Ministry of Economics and Energy, while it virtually reaches a value of 0%, i.e. electricity is available at any given time [43]. Reaching such a performance with a solar panel as the only energy source would only be possible with a tremendously oversized system and is not feasible for single household solutions.

The excess energy is the sum of the additional power generated by the PV panel while the battery is fully charged and the load satisfied. Ideally, both the LLP and the dumped energy are kept as small as possible, but due to the inconstant nature of the energy exchange in the system this is only possible to a certain extent. When accepting certain values for the LLP and the dumped energy, different design options emerge that can allow significant changes to the overall size of the SHS [12].

3.4 - Financing

Since the customers of SHSs in rural Africa are often unemployed or only earning a small income, it is not feasible for companies to sell their systems for a direct payment. Instead, leasing models have been developed and adopted, with many companies offering pay-as-you-go (PAYG) financing models. Customers have to pay a relatively small deposit in the beginning and then pay off the system via frequent (mostly monthly) payments. The key here is that the customers' ownership of the system is built up over time, at the beginning the customer pays for the electricity drawn from the panel until a certain amount is reached which equals the total cost

of the system. From this point on, it belongs solely to the customer and the only additional costs are created from maintenance or replacement of parts. The leasing period typically has a length between 18 and 30 months, which allows even extremely poor people to afford their own SHS. The downside of these leasing methods are the additional costs due to the required electronics and financing services [44].
Allowing people to develop a sense of ownership has been proven very important in a successful adaption of SHSs, since people tend to care less of about a system that has been donated to them. This can mean that, if the incentive to install a SHS in a household comes from an external party rather than the residents using the systems, maintenance and usage of the system is more likely to be done in a non-optimal way. At the same time, if residents afford the system themselves, chances are higher that they will ensure proper management of it.

3.5 - Summary

Summarising the previous sections, one can draw a number of conclusions that lead to requirements for a successful implementation of SHSs in low-income households:

- Users of SHSs have to be educated about the technology and the limitations of their system to avoid dissatisfaction.
- An appropriately sized system is important to meet the sensitive cost and performance requirements on SHSs.
- Financing schemes have to be tailored to the possibilities of low-income households.
- User ownership plays a key role in the long term success of SHSs.
- SHSs have a profound impact on education, income and health of their users and improve quality of life overall, while building a foundation for further economic development.

The practical issues are much more complex than the list that is presented here, thus it merely serves as a summary of the topics discussed in the previous sections and should not be understood as a framework for an implementation of SHSs. The focus of this paper lies on the system sizing aspect, while the socio-economic aspects are treated as system constraints.

3.6 - Research objective

The main research objective of this document is formulated as:

How can a SHS be appropriately sized to meet the specific (energy) needs of a rural low-income household?

In order to find an answer to this question, it can be split up into several sub-questions;

- *R1: What are the specific energy needs of a rural low-income household?*
- *R2: What are the performance requirements on the SHS?*

Gwakwani village is used as a case study, since it exemplifies the case of an isolated village with little to no job opportunities for its residents and the results obtained are not meant to be solely applicable in this specific village, but also in a broader sense in cases with a similar initial objective.

Chapter 4 - Case study

This chapter aims to give an overview of the situation in unelectrified communities in South Africa. Section 4.1 provides a brief description of the state of the South African energy system. The regional climate of Gwakwani is summarised in section 4.2, together with general information regarding the village obtained through interviews. The chapter continues with an overview of the approach used to create a load profile in section 4.3 and concludes with a summary of the content in section 4.4.
The content of this chapter, except for the conducted interviews, was researched based on information that is publicly available. This information is highly limited and often lacks clear facts, e.g. regarding possible government funding or exact electricity prices. The chapter serves as a base to answer research question *R1* focusing on the specific energy needs of a rural low-income household and will be used in this research to investigate which energy needs are realistic and achievable.

4.1 - Electricity in South Africa

The relatively high electrification rate in South Africa has been a reason for off-grid companies to not favour the country, but a closer look reveals that there is a much higher need for off-grid electrification than it might seem at first. The state-owned power monopoly Eskom has been struggling to meet customer demand in the country since 2007 with frequent, partly scheduled, local blackouts that threw the country into an energy crisis. Eskom refers to these blackouts as "Loadshedding", which means cutting off the supply to certain areas for 2-4 hours as a fair distribution strategy to avoid nationwide blackouts. The company itself advises people to buy solar powered lights and security devices to be prepared for unforeseen power outages and asks people to shut off their appliances during peak times [45].
The current target set by the South African government under the Integrated National Electrification Programme (INEP) is to reach universal electrification ($\geq$ 97% of households) by 2025 with 7% of households (300000 households, or approximately 1.5 million people) planned to receive electricity through off-grid technologies [46]. These two factors, the unreliable grid and the inclusion of SHSs in the INEP, proves the legitimate role that SHSs play in the electrification of rural areas in South Africa. The Dutch Ministry of Foreign Affairs published a report on the energy situation in South Africa in July 2018, which states that the South African government would provide subsidies of 19500 RAND[1] per rural electricity connection, including off-grid solutions [46]. The same report states that connections are subsidised by 80%, or up to 100% for indigent citizens, with the customer being charged only a onetime fee of max. 89 RAND and small monthly payments afterwards, to cover running costs and maintenance. According to the South African government, the "free basic electricity" service allows every poor household to consume up to 50 kWh per month

[1]Based on exchange rates on the 24.06.2020, 1000 RAND $\approx$ 50 EUR.

free of charge if connected to the grid, or access to a 50 Wp SHS if connected to the official non-grid system, through the national electrification programme. Next to the consumption, a monthly maintenance subsidy of 48 RAND is available for SHS users [47]. It remains unclear how this free basic electricity is applied in reality, since many South Africans living in poverty still remain without access to electricity or are not able to pay for it. A general problem in sub-Saharan Africa is the high level of corruption and the misusage of public funds, which can lead to capital, that was intended to support poor people, simply disappear. On the Corruption Perception Index, South Africa reached a score of 43 in 2018, slightly better than most other African countries, but far behind the scores reached by countries in Europe [48]. The numbers show that grid-connected customers are clearly favoured, since 50 kWh/month is a relatively large amount compared to access to a 50 Wp panel, which will only produce a fraction of this energy (around 7-8 kWh/month for a PV electricity potential of 5 Wh/Wp/day). The plan does also not mention any battery with the PV panel, which imposes additional limitations on the system. To develop a more concrete idea of the situation in South Africa, section 4.2 provides insight into the community of Gwakwani.

4.2 - Gwakwani village

Figure 4.1: *Impression of Gwakwani village through a picture showing a typical house in Gwakwani. Obtained from [49].*

Gwakwani is a small village located in the very north-east of South Africa close to the border with Zimbabwe on a height of around 400m. The region is an attractive candidate for the use of off-grid solar energy, considering it has a PV electricity potential of around 4-5 kWh/kWp/day (see figure 4.2). For comparison, only the very south of Spain reaches similar numbers in Europe. The climate in Gwakwani is generally warm, with dry winters and wet summers. The small size and isolated location of Gwakwani make it unfavourable for an expensive grid connection, but even more interesting for an off-grid energy system. To obtain information about the village and the local situation, interviews were conducted with students and a project manager from the UJ-PEETS, who have all been involved with existing projects in Gwakwani or bringing energy to rural communities in South Africa in a broader context for several years. The gained information was used to predict the energy needs of the residents of the village, which in turn serves as a base to optimally size the SHS. This section is based on information collected during these interviews.

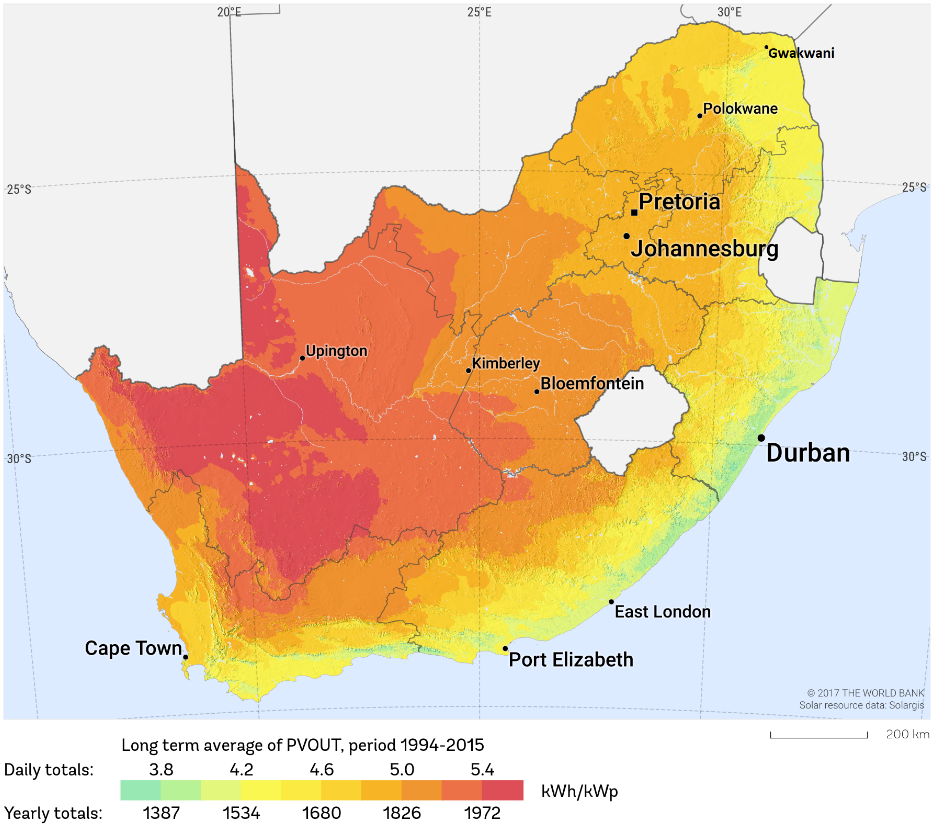


Figure 4.2: *Map of South Africa showing the PV electricity potential and the location of the village Gwakwani in the very north-east of the country. Adapted from [50].*

The residents of Gwakwani, a village of approximately 40 households, are generally poor with few people having jobs in nearby towns and most people living off monthly government grants of around 3000 RAND per household. With an average of 5 residents per household, this leaves about 1 €/day/person, putting them in the category of extreme poverty following the definition of the World Bank [51]. Most households carry out subsistence farming on small gardens where they grow basic vegetables and hold some animals like chickens or donkeys. Since 2015, a collaboration between the University of Johannesburg and the technology firm Schneider Electric has installed several solar systems in the village, such as a water irrigation system with a 750 W PV panel, 12 V panels on rooftops, which provide light inside the houses and on streets, phone charging possibilities, one TV running educational channels for children and even a bakery running on 15 kW of solar power, shown in figure 4.3.

Figure 4.3: *Picture showing the solar bakery in Gwakwani. Obtained from [52].*

The impacts of these systems can be observed from a reduction in malaria cases, which often occurred when fetching water from the nearby river, to the generation of new jobs in the bakery which sells bread to people from the surrounding villages. The lights additionally provide the opportunity for children, who have to walk up to 18 km to the nearest school and thus arrive home after sunset, to work on their homework in the evenings. Furthermore, the installed TV helps to educate the youngest children, who consequently even grasped some basic English. Despite the mentioned effects of the solar systems, the residents also stated that the projects gave them the feeling of being more included in society. The students from UJ-PEETS additionally mentioned that people in Gwakwani rely on open fire for cooking and it would be a great relief if they were able to use electricity to cook and a fridge to store groceries. A problem that became visible during the implementation of these system was the missing incentive of people to use the solar systems as they were intended. The water pump supplied enough water for a small vegetable patch, but the villagers did not use this opportunity to move beyond subsistence farming.
The interviews revealed the fact that since late 2019 Gwakwani has a connection to the national electricity grid, but the only households that can afford the electricity from the grid are the ones employed in the solar bakery. Despite the access of grid electricity, all the installed systems continue to run on solar power. The bakery, for example, would not make any profit if they would pay for the electricity from the grid and can only sustain if it continues using the energy generated by their PV system.
Next to the presented information, the interviews gave a much broader insight into the life in a village like Gwakwani and the challenges that the implementation of SHSs face. At the same time, the amount of information that could be used to create a load profile remained limited and external resources had to be used to

develop a comprehensive usage pattern of newly electrified households. Ideally, an anthropological design approach would have been carried out, including a visit of the village and a direct dialogue with the villagers, but this was not feasible given the resources and time frame of this thesis. The unknown load profile posed a challenge to produce accurate results that could be directly applicable in the village. Instead, general results were generated that created valuable insights and recommendations for SHSs sizing.

4.3 - Load profile estimation

Predicting the usage pattern of new SHS customers is a huge challenge for the off-grid market. It is much more difficult to estimate how a household, that never had access to electricity, will use the electricity once it has access, than predicting how much energy a new house in a developed country will consume. The reason is the highly limited availability of data on first-time SHS users.
In almost all existing literature on the topic, lights and phones are the first appliances that are powered by a SHS. According to the South African Department of Mineral Resources and Energy, a SHS provides basic lighting and access to a small radio and a black-and-white TV [47]. While there might be better possibilities than basic lighting and black-and-white TV due to advancements in LED technology, which leaves this information outdated, the essential appliances used nowadays remain the same. Additionally, in rural South Africa about two thirds of households own a TV and a fan [53]. For these reasons, it can be expected that customers in Gwakwani will sooner or later power lights, phones, a radio, a TV and a fan. Table 4.1 provides an overview over some common appliances and their approximate power consumption based on information from market reports and data from manufacturers [35, 53, 54].

Appliance	LED Lights	Phone charge	Radio	TV 19"	Fan
Power	2 W	3 W	1 W	15 W	10 W
Possible time	00:00 - 04:00 19:00 - 24:00	00:00 - 03:00 23:00 - 24:00	07:00 - 13:00	17:00 - 21:00	12:00 - 15:00
Energy	18 Wh/day	12 Wh/day	6 Wh/day	60 Wh/day	30 Wh/day

Table 4.1: *Overview of the power consumption of a selection of common appliances and their possible time of usage, assuming super-efficient DC appliances. The total consumption of this load profile would be 126 Wh/day. A visualisation of this load profile can be found in figure 5.2 in section 5.2.*

This load profile was an estimation based on observations made in existing literature [12, 31, 39, 55]. SHS users often mentioned that leaving a light on over night provided safety and it was assumed that one phone would be charged over night. Modern smartphones often consume more than 3 W while charging but charge faster, so the overall consumed energy does not change much. The radio and fan was assumed to be turned on during the day, while the TV is more often used in the evening, similar to what is common in the developed world. There exist individual appliances that are more efficient, but it is not reasonable to expect the latest development of appliances to be available in rural South Africa, so the power consumption was slightly rounded up. The table visualises the two dimensions that determine the total energy consumption of a household, one is the power consumption of the individual

appliance and the other the time they are used for. Especially for appliances with a higher power consumption, it makes huge differences if they are used for a short time or for several hours each day and even more if they are used during the day or in the evening, since the energy available at night is directly limited by the battery capacity.
Generally, it is a challenge to determine which appliances are actually available in South Africa and for which price. As was mentioned during the interviews, an important achievement would be to allow for electric cooking and a fridge inside the houses, but these appliances have a very high power consumption. A fridge consumes around 600 Wh/day for a size of 100 l, tremendously raising the daily energy consumption [53]. A kettle on the other hand, consuming around 150 W while in use, has a less severe impact, since it only needs to run for a relatively short time to boil water. Kettles exist that were designed to run on the DC cigarette lighter outlet in vehicles, which consume only around 50-60 Wh to boil about 500 ml of water. For this reason, they might be a feasible option to be used with SHSs, which was investigated during this research. The high power consumption of the kettle would require the battery to allow for relatively high discharge currents, with lithium-ion batteries this would be achievable.

4.4 - Summary

The key insights presented in this chapter can be summarised as follows:

- Electricity in South Africa
  - Power supplier Eskom struggles to meet customer demand in the country and is frequently forced to cut off the power supply to certain areas, referred to as “Loadsheeding”.
  - The South African governments offers a range of subsidies for citizens under the INEP and the “free basic electricity” service, but the actual execution and effectiveness of these promised subsidies remain unclear.
- Gwakwani village
  - Gwakwani exemplifies the situation of an unelectrified poor village in sub-Saharan Africa.
  - Households live off approx. 3000 RAND/month, classifying them as extremely poor.
  - People in the village cannot afford to use grid electricity and rely on subsistence farming and open fire for cooking.
  - In the village solar system have been installed, including street lights, a TV, a water irrigation system and a solar powered bakery in a collaboration between Schneider Electric and the UJ-PEETS.
  - Limited knowledge on the load profile of the villagers forced the research to focus on generally applicable results rather than designing a specific solution for Gwakwani.
- Load profile estimation
  - Common appliances used in combination with SHS are for example LED lights, phones, radios, TVs or fans.

- Being able to cook electrically would be a great relieve for households but the power requirements for the necessary appliances are much higher than for the listed appliances.
- The two dimensions determining load profiles are the power consumption of the appliances and the time for how long and when they are used each day.

Chapter 5 - Solar home system sizing - modelling and software design

To find answers to the research questions stated in section 3.5, a model was created to simulate the performance of a SHS and produce results that were used to gain insight into the effects of different parameters on the SHS. The model consisted of three main parts, namely *i)* a calculation of the generated solar power based on existing satellite data, *ii)* a creation of a realistic load profile of potential users and *iii)* an algorithm to simulate the performance of a chosen SHS. The complete software described within this chapter was written in the App designer in Matlab R2020a.[1]

5.1 - Solar data

The solar data used in this research was obtained from the Photovoltaic Geographical Information System (PVGIS) webtool and the information in this section is based on the information provided by the PVGIS team [13].
The PVGIS webtool offers freely available solar data for most parts of the world. It provides hourly climate data for any location specified in latitude and longitude, but also an estimation of the output power of a PV panel per hour in the form of a csv or json file. To generate this hourly output power of a panel, PVGIS first estimates the solar radiation received at ground level based on satellite data on clouds, aerosols in the atmosphere and the concentrations of water vapour and ozone. This method does not provide perfectly accurate data, but as the comparison with data measured on the ground shows, it usually achieves accuracies within a few percentage points. PVGIS states that one of the main problems introducing estimation errors is snow that is mistaken as clouds, but this should not pose a problem in the climate of Gwakwani. Next to satellite data, PVGIS also takes into account the elevation levels around the specified location to determine the horizon height.
Once the solar radiation on ground level was determined, the next step was to calculate the generated output power of the PV panel. The mounting type, slope and azimuth needed to be set before calculating the hourly data, for which PVGIS offers an optimisation. The calculation of the generated power includes *i)* effects of light being reflected away from the PV panel, which depend on the angle of the incoming radiation, *ii)* effects of changes in the solar spectrum, which depend on

[1] *Remark on notation:* For convenience, vectors in this chapter are marked with an underline, while 1-dimensional variables are marked in *italic* style. The indexing variable m is used for minutes within a day and d for different days, while n is used to indicate the number of iterations of the algorithm running within each day.
The number of minutes in a day is equal to $24h/day \cdot 60min/h = 1440min/day$.
The number of days in 12 years (including 3 leap years) is equal to $9 \cdot 365 + 3 \cdot 366 = 4383$.

the time of the day and meteorological conditions, and *iii)* the module temperature, which is estimated using solar radiation, wind and temperature data. The resulting hourly power generation of a PV panel is therefore an estimation that will have some deviation from the real performance, but the data comes as close to the real performance as possible within the scope of this research. For this reason, the data from PVGIS was used for the analysis of the SHS' performance in Gwakwani. The settings that were used in the webtool to generate the appropriate data are summarised in table 5.1.

Lat.	Lon.	Mounting	Slope	Azimuth	PV tech.	Sys. loss
-22.571	30.804	Fixed	26° (opt.)	-179° (opt.)	Cryst. Si.	0%

Table 5.1: *PVGIS settings used to generated hourly PV output power data for the location of Gwakwani.*

The PV peak power was not specified since the generated data could simply be divided by this number to obtain general output power in W/Wp. The system loss was set to 0% to create ideal data, which could later be changed inside the algorithm to include losses within the SHS. For these settings, the generated PV output power included losses due to the angle of incidence of 2.69%, spectral effects adding 0.81% to the output power and temperature and low irradiance causing losses of 9.71%, adding up to total losses of 11.43% compared to standard test conditions.
Data for the years 2005 until 2016 was available on the webtool, which was downloaded as a csv file that contained a vector of 24 entries per day over 4383 days. Figure 5.1 shows an example day of this data, visualised in a graph.

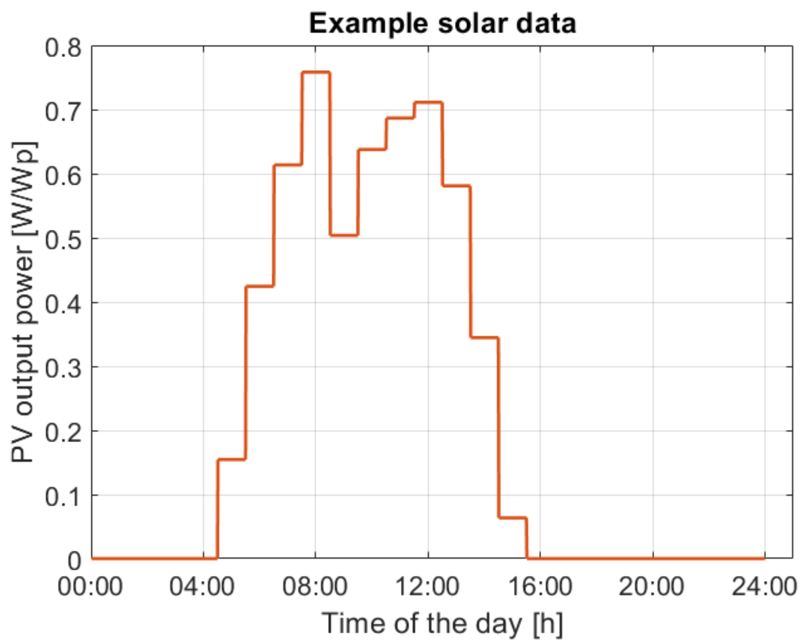


Figure 5.1: *Graph showing the solar data on the 25.04.2014 as an example. The total generated energy on this day was 5.48 Wh/Wp, excluding losses in the SHS.*

The graph was created after upsampling the data into minute resolution and centring the data point for each hour (e.g. the value 0.7583 W/Wp at 08:03 was extended to the time window 07:31 to 08:30). After upsampling, the vector consisted of 1440 entries per day, one for each minute, which was stored in $\underline{E_{sun}} \in \mathbb{R}^{1\times1440}$.

5.2 - Load profile generation

While the solar data was one part of the required inputs for the model, another part was the load profile. An algorithm was created to generate load profiles of potential users. The appliances were described in terms of power consumption, the moment(s) when they were turned on and the duration of each individual usage window. This was done for each day, with a randomised shift in the turn-on-moment and the duration, to create a more realistic usage pattern that includes a non-identical routine of the users each day. To easily represent and further process this data, it was stored in the vector $\underline{E_{load}} \in \mathbb{R}^{1\times1440}$. A minute-resolution was chosen for the load profile, which explains the size of 1440 entries in the vector. Figure 5.2 visualises the possible usage of appliances by a SHS user, based on the load profile from table 4.1.

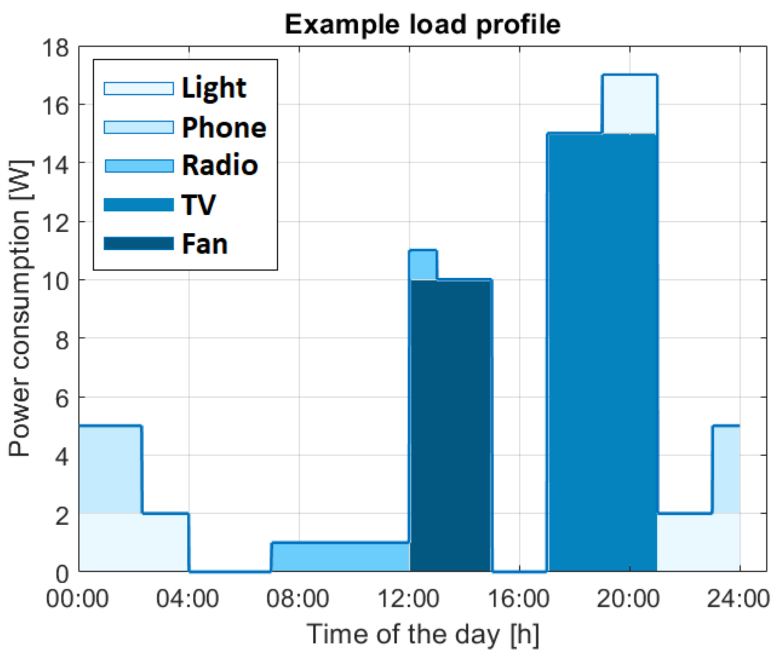


Figure 5.2: *Visualisation of an example load profile of a SHS user powering a light, phone, radio, TV and fan, based on the consumption described in table 4.1. A large share of the total energy is consumed while the sun is not shining, visualising the need for an appropriate energy storage.*

During the day, in the morning hours the radio was used and around midday the fan, while in the afternoon and evening the TV was turned on. It is not meant to represent the most realistic load profile, but simply to visualise the usage pattern and develop a feeling for the absolute numbers. The total consumption on this day would have been 126 Wh.

Comparing this load profile with the solar data shown in figure 5.1, one can see that only the radio and fan could have been directly powered by the PV panel, adding up to 36 Wh (29% of total), while the other 90 Wh (71%) had to be provided by the battery. It does not have a great impact at what time appliances are used, e.g.

if the phone is plugged in to charge at 23:00 or at 22:00, but only if the power has to come from the battery or can directly be used from the panel. For this reason, the normally distributed random number generator in Matlab was used to add a standard deviation of 30min to the moment the appliances were turned on and a standard deviation of 25% to the duration they were used for. This resulted in e.g. the TV sometimes being turned on while there was still some PV power produced and sometimes only after sunset, which represented a more realistic usage pattern.

5.3 - Model generation and performance simulation

After the solar data for each day over 12 years was processed into the right format and the algorithm to create a load profile was finished, they could be used together to allow for a simulation of the performance of a pre-defined PV system (in terms of PV size, battery size, efficiencies and minimum and maximum battery SOC). Essentially, the simulation needed to run through the data day by day, create a randomised load profile for each day, determine the energy exchange in the system and store data such as the generated, dumped and missed energy with their corresponding time instances. This simulation could be split into three parts, *i)* an initiation of the data for each simulation day, *ii)* an algorithm that runs through the data, generating results for each individual day and *iii)* a final part computing the overall results after all the simulation days have been computed. These parts are described in subsections 5.3.1, 5.3.2 and 5.3.3, respectively.
Before the model could be used to simulate the performance of a SHS, inputs were required to specify the parameters of this SHS. These required inputs are presented in table 5.2. Next to these quantities, the load profile had to be specified as described in section 5.2.

Quantity	Description	Unit
P_{peak}	Nominal power of the PV panel	Wp
Q_{min}	Minimum possible battery SOC	Wh
Q_{max}	Maximum possible battery SOC	Wh
η_{trans}	Transmission efficiency	-
η_{conv}	DC/DC converter efficiency	-
η_{batt}	Battery round-trip efficiency	-

Table 5.2: *Overview of the quantities to be specified in the model. In case of no limitations on charge and discharge levels of the battery, Q_{max} would be the battery capacity and Q_{min} equal to 0. If charge limitations were included, they would be the respective maximum and minimum charge levels. The efficiencies were included in section 5.4.*

5.3.1 - Initiation of the data for each simulation day

The algorithm described in this subsection ran once for each day to initiate the solar power data based on the specified quantities, which, together with the defined load profile, create the base data for the simulation. This data had to be computed daily, since the solar data as well as the load profile were different for each simulation day.

For ease of understanding, table 5.3 provides an overview of the most important quantities used to simulate the behaviour of the SHS.

Quantity	Description	Defined in	Unit	Entries
$\underline{E_{sun}}$	Normalised solar energy per min	Section 5.1	Wmin/Wp	1440
$\underline{E_{load}}$	Energy required by the load per min	Section 5.2	Wmin	1440
$\underline{E_{solar}}$	Produced solar energy per min	Equation (5.1)	Wmin	1440
$\underline{E_{exchange}}$	Energy exchange per min	Equation (5.3)	Wh	1440
$\underline{SOC}$	Battery SOC per min	Equation (5.4)	Wh	1440
$\underline{E_{produced}}$	Produced energy per day	Equation (5.2)	Wh	4383
$\underline{E_{missed,T}}$	Missed energy per day	Equation (5.10)	Wh	4383
$\underline{E_{dumped,T}}$	Dumped energy per day	Equation (5.12)	Wh	4383
$\underline{t_{loss,T}}$	Total time of lost load per day	Equation (5.14)	min	4383
R_{dump}	Dumped energy / produced energy	Equation (5.15)	-	1
LLP	Time of lost load / total time	Equation (5.16)	-	1

Table 5.3: *Overview of the most important parameters used to simulate the performance of a SHS.*

As discussed in sections 5.1 and 5.2, the energy generated by the panel and the one consumed by the load were stored in the vectors $\underline{E_{sun}}$ and $\underline{E_{load}}$, respectively. The vector $\underline{E_{load}}$ described the load consumption in Wmin, but $\underline{E_{sun}}$ only included the normalised generated energy in Wmin/Wp. This vector had to be multiplied by the nominal power of the PV panel P_{peak} in Wp to create the vector $\underline{E_{solar}} \in \mathbb{R}^{1\times1440}$, which expressed the generated output energy in Wmin, shown in equation (5.1).

$$\underline{E_{solar}}[m] = \underline{E_{sun}}[m] \cdot P_{peak} \qquad m = 1, \dots, 1440 \tag{5.1}$$

From $\underline{E_{solar}}$ the generated energy on each simulation day d could easily be found, since the solar energy is the only energy source in the system, as shown in equation (5.2). The factor 1/60 was included to convert the units from Wmin to Wh.

$$\underline{E_{produced}}[d] = \frac{1}{60}\sum_{m=1}^{1440} \underline{E_{solar}}[m] \tag{5.2}$$

Subtracting the consumed energy per minute $\underline{E_{load}}$ from the produced energy $\underline{E_{solar}}$ resulted in the vector $\underline{E_{exchange}}$ describing the energy exchange in the system, as seen in equation (5.3).

$$\underline{E_{exchange}}[m] = \frac{1}{60}(\underline{E_{solar}}[m] - \underline{E_{load}}[m]) \qquad m = 1, \dots, 1440 \tag{5.3}$$

When $\underline{E_{load}}$ was greater than $\underline{E_{solar}}$, energy from the battery was needed to drive the load, while at any time instance when $\underline{E_{load}}$ was smaller than $\underline{E_{solar}}$, the battery was charged. Therefore, the battery SOC at a specific minute m could be determined by summing $\underline{E_{exchange}}$ up to that minute to the previous battery SOC (SOC_{prev}), shown in equation (5.4). SOC_{prev} was the initial charge of the battery for the first simulation day and the SOC at the end of the previous day of simulation for all other days.

$$\underline{SOC_0}[m] = SOC_{prev} + \sum_{n=1}^{m} \underline{E_{exchange}}[n] \qquad m = 1, \dots, 1440 \tag{5.4}$$

5.3.2 - Computation of the results of each individual day

The algorithm described in this subsection explains the computation of the results for each individual day and was looped multiple times within each day, with d being the current simulation day.
After the initiation of the data had been done, this data had to be manipulated to create the desired results. The vector $\underline{SOC_0}[m]$ contained the theoretical battery SOC without considering the minimum and maximum capacity of the battery (Q_{min} and Q_{max}). To include these limitations, the entries of the vector had to be adjusted as visualised in figure 5.3. This figure serves as an example to explain the algorithm and should not be understood as actual data created during this research.

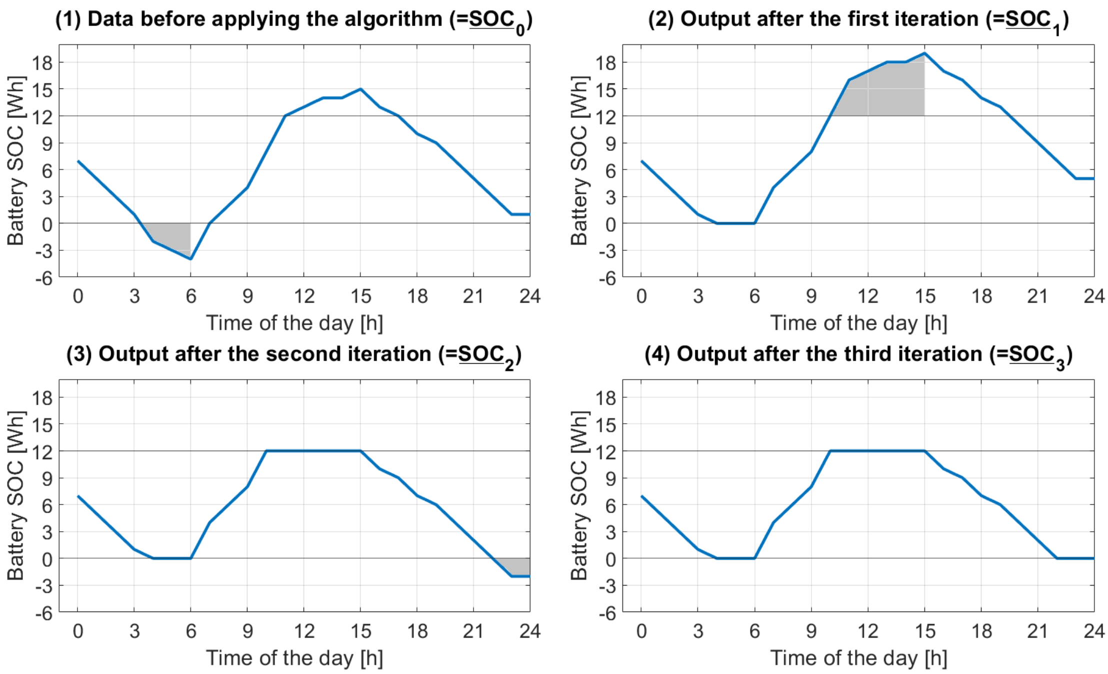


Figure 5.3: *Picture sequence visualising the working principle of the algorithm used to compute $\underline{SOC_n}$, represented by the blue graph. The horizontal black lines represent $Q_{min} = 0$ [Wh] and $Q_{max} = 12$ [Wh], while the grey marked areas represent all the time instances for which the battery was either empty ($SOC \leq 0$) or full ($SOC \geq 12$).*

As can be seen in figure 5.3 (1), from 00:00 to 06:00 the battery was discharging and at 06:00 began to charge. This created a local minimum below the minimum battery capacity $Q_{min} = 0$ Wh, where the battery switched from discharging to charging. It can be seen that the battery had to first charge back to a SOC of 0 Wh, but actually this charging would have started at a SOC of 0 Wh, since a battery cannot charge below its minimum capacity. To include the charging that took place from 06:00 to 07:00, SOC had to be adjusted by setting all entries below 0 and before 06:00 to 0 and adding 4 Wh to all the following entries, creating the graph seen in figure 5.3 (2).
In general, the data had to be adjusted every time a local extremum with time instance $t_{extr,n}$ occurred outside the threshold levels, creating a vector $\underline{SOC_n}$ after each iteration n. n increased with each iteration of the algorithm described in this

subsection.
To do so, the first local extremum outside the possible battery levels was detected and its time instance stored in $t_{extr,n}$, and the next $\underline{SOC_n}$ computed. The extremum could be a local minimum or maximum, with $t_{min,n}$ and $t_{max,n}$ being defined as the first time instance of a local minimum below Q_{min} and the first time instance of a local maximum above Q_{max}, respectively. $t_{extr,n}$ was defined as shown in equation (5.5).

$$t_{extr,n} = \begin{cases} min(t_{min,n}, t_{max,n}) & \text{if } t_{min,n} \neq \emptyset \wedge t_{max,n} \neq \emptyset, \\ t_{min,n} & \text{if } t_{min,n} \neq \emptyset \wedge t_{max,n} = \emptyset, \\ t_{max,n} & \text{if } t_{min,n} = \emptyset \wedge t_{max,n} \neq \emptyset, \\ 1440 & \text{if } t_{min,n} = \emptyset \wedge t_{max,n} = \emptyset. \end{cases} \tag{5.5}$$

Based on the value of $\underline{SOC_{n-1}}[t_{extr,n}]$, so the theoretical SOC at the time instance $t_{extr,n}$ before creating the new $\underline{SOC_n}$, parameters such as the dumped and missed energy could be calculated. Using this definition of $t_{extr,n}$, $\underline{SOC_n}$ could be calculated for three cases:
i) If $t_{extr,n} = t_{min,n}$ then

$$\underline{SOC_n}[m] = \begin{cases} max(\underline{SOC_{n-1}}[m], Q_{min}) & \text{for } m = 1, \dots, t_{extr,n}, \\ \sum_{n=t_{extr,n}}^{m} \underline{E_{exchange}}[n] + Q_{min} & \text{for } m = t_{extr,n}+1, \dots, 1440. \end{cases} \tag{5.6}$$

ii) If $t_{extr,n} = t_{max,n}$ then

$$\underline{SOC_n}[m] = \begin{cases} min(\underline{SOC_{n-1}}[m], Q_{max}) & \text{for } m = 1, \dots, t_{extr,n}, \\ \sum_{n=t_{extr,n}}^{m} \underline{E_{exchange}}[n] + Q_{max} & \text{for } m = t_{extr,n}+1, \dots, 1440. \end{cases} \tag{5.7}$$

iii) If $t_{extr,n} = 1440$ then

$$\underline{SOC_n}[m] = \begin{cases} min(\underline{SOC_{n-1}}[m], Q_{max}) & \text{if } \underline{SOC_{n-1}}[1440] > Q_{max}, \\ max(\underline{SOC_{n-1}}[m], Q_{min}) & \text{if } \underline{SOC_{n-1}}[1440] < Q_{min}, \\ \underline{SOC_{n-1}}[m] & \text{if } Q_{min} \leq \underline{SOC_{n-1}}[1440] \leq Q_{max}. \end{cases} \tag{5.8}$$

Case iii) also terminated the algorithm, since no more peaks outside of the threshold levels could be found.
In case i), an amount of energy was missing to drive the load equal to the value of $\underline{SOC_{n-1}}$ at time instance $t_{min,n}$, as shown in equation (5.9).

$$E_{missed,k}[d] = \underline{SOC_{n-1}}[t_{min,n}] - Q_{min} \tag{5.9}$$

Here, k increased each time $t_{extr,n} = t_{min,n}$ or if $\underline{SOC_{n-1}}[1440] < Q_{min}$ after the last iteration and K being the total number of these iterations. This resulted in a total missed energy $\underline{E_{missed,T}}$ for each day as given in equation (5.10).

$$\underline{E_{missed,T}}[d] = \sum_{k=1}^{K} E_{missed,k} \tag{5.10}$$

For the example in figure 5.3, the missed energy would have been 4 Wh at 06:00 and 2 Wh at 24:00, resulting in a total of 6 Wh for that simulation day.

Following the same procedure, the dumped energy could be computed for each day as shown inequation (5.11).

$$E_{dumped,l}[d] = \underline{SOC_{n-1}}[t_{max,n}] - Q_{max} \tag{5.11}$$

With l increasing each time $t_{extr,n} = t_{max,n}$ or if $\underline{SOC_{n-1}}[1440] > Q_{max}$ after the last iteration and L being the total number of these iterations. This resulted in a total dumped energy $\underline{E_{dumped,T}}$ for each day as given in equation (5.12).

$$\underline{E_{dumped,T}}[d] = \sum_{l=1}^{L} E_{dumped,l} \tag{5.12}$$

For the example in figure 5.3 (2), the dumped energy would have been 7 Wh at 15:00.
In order to calculate the LLP it was also required to know the time instances when the battery was empty, corresponding to the grey marked areas in figure 5.3 (1) and (3). All the time instances when $\underline{SOC_{n-1}}$ was less or equal than Q_{min} before the local minima were considered a loss of load, since in these time instances no energy was available to power a load. These instances were stored in the vector $\underline{t_{loss,k}}$ as defined in equation (5.13).

$$\underline{t_{loss,k}}[m] = \begin{cases} 1 & \text{if } \underline{SOC_{n-1}}[m] \leq Q_{min}, \\ 0 & \text{if } \underline{SOC_{n-1}}[m] > Q_{min}. \end{cases} \tag{5.13}$$

The sum of all entries of the vector $\underline{t_{loss,n}}$ provided the total time of energy where the battery was empty during a day $\underline{t_{loss,T}}$, shown in equation (5.14).

$$\underline{t_{loss,T}}[d] = \sum_{k=1}^{K} \sum_{m=1}^{1440} \underline{t_{loss,k}}[m] \tag{5.14}$$

The four parameters $\underline{E_{produced}}$, $\underline{E_{missed,T}}$, $\underline{E_{dumped,T}}$ and $\underline{t_{loss,T}}$ were then used to evaluate the complete performance of the system over the full simulation time.

5.3.3 - Computation of the final results

Once the simulation was finished, the total results could be calculated based on the results for each individual day, thus the calculations in this section were only done once, at the end of the simulation. The dump ratio R_{dump} was defined as the percentage of the produced energy that was dumped, as shown in equation (5.15).

$$R_{dump} = \frac{\sum_{d=1}^{4383} \underline{E_{dumped,T}}[d]}{\sum_{d=1}^{4383} \underline{E_{produced}}[d]} \tag{5.15}$$

Next to the dump ratio, the LLP was a parameter of interest, which could be computed as shown in equation (5.16), assuming a total simulation time of 4383 days (12 years).

$$LLP = \frac{\sum_{d=1}^{4383} \underline{t_{loss,T}}[d]}{4383 \cdot 1440} \tag{5.16}$$

Other than these two ratios, also the net numbers of the produced, missed and dumped energy were used to determine the performance of the system, which were normalised to kWh/year.

5.4 - Efficiencies

While the solar power data includes several losses, the rest of the system did not yet take into account any losses inside the SHS, as they were described in detail in chapter 2. To include losses in the transmission and in the DC/DC converter, the power could simply be multiplied by the corresponding efficiencies η_{trans} and η_{conv}. An alternative way was to apply this change to the specified nominal power of the PV panel P_{peak} as shown in equation (5.17).

$$P_{peak} = P_{peak} \cdot \eta_{trans} \cdot \eta_{conv} \tag{5.17}$$

This resulted in the same decrease in produced solar energy E_{solar} when the modified P_{peak} is used in equation (5.1).
The round-trip efficiency η_{batt} of the battery described the energy that could be discharged from the battery relative to the amount of energy that was needed to charge it. This was included by multiplying all positive and dividing all negative entries of the vector $E_{exchange}$ with the square-root of η_{batt}, as shown in equation (5.18).

$$\underline{E_{exchange}}[m] = \begin{cases} \underline{E_{exchange}}[m] \cdot \sqrt{\eta_{batt}} & \{m|\underline{E_{exchange}}[m] > 0\}, \\ \underline{E_{exchange}}[m] / \sqrt{\eta_{batt}} & \{m|\underline{E_{exchange}}[m] < 0\}, \qquad m = 1, \ldots, 1440 \\ 0 & \text{otherwise.} \end{cases} \tag{5.18}$$

This resulted in a reduced amount of energy being charged and an increased amount of energy discharged, such that that overall round-trip efficiency was equal to η_{batt}.

5.5 - Assumptions & limitations

Before the creation of the model was started, certain assumptions were done to decide on the relevant parameters that needed to be included in the model and those that could be left out:

- Load profiles, which were a key component of the model, could only be created based on estimations, with very limited information on the actual usage of households.
- The load profiles were assumed to remain unchanged over 12 years, which was unrealistic as users would most likely add more appliances after some time.
- No ageing effects were included in the model, because the performance of the system after multiple years was not the most interesting for the research objective. Instead, the normalised annual performance provided a more useful insight that could be used to compare the results for different system sizes.
- Efficiencies and lifetime of components that were depending on voltage and current levels were not modelled, since the model was only based on power and energy flows.
- External effects on the components, such as partial shading of the panel or temperature effects on the battery, were not included.

These assumptions limited the accuracy of the model to simulate the real performance of the SHS, but it served as a sufficient tool to gain insight into effects of the different SHS parameters. The overall results might therefore be slightly overoptimistic compared to the performance in reality and should be appropriately analysed.

5.6 - Summary

The model generated in Matlab was presented in this chapter and described in detail, which is summarised as follows:

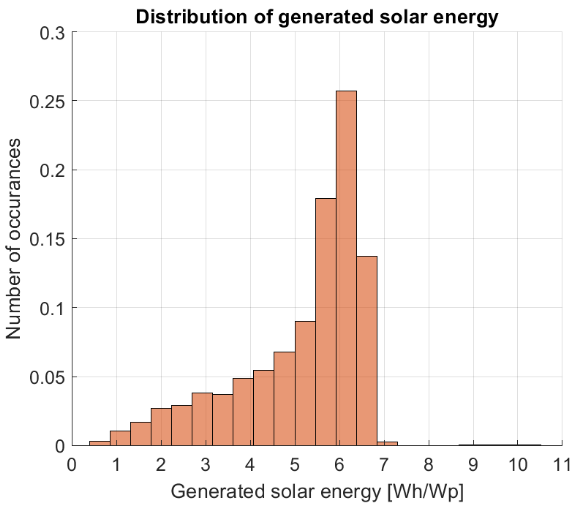
- Solar data
  - Location-specific solar data of Gwakwani was obtained from PVGIS and manipulated to the right format.
  - This data provided the specific power output of a PV panel in Wh/Wp, estimated based on satellite data.
  - Losses occurring due to lights being reflected away from the panel, changes in the solar spectrum and the module temperature were included in the data.
- Load profile generation
  - Load profiles were generated based on specified appliances in terms of power consumption and time of usage.
  - A randomisation was added to the time of usage of the appliances to simulate a more realistic user behaviour.
- Model generation and performance simulation
  - A model was created based on the solar data and the generated load profiles that simulated the performance of the SHS over 12 years.
  - The input to the model were the nominal power of the PV panel in Wp and the possible maximum and minimum battery capacity Q_{max} and Q_{min} in Wh.
  - The performance was measured in terms of the percentage of energy produced by the PV panel but dumped due to a full battery and a satisfied load (dump ratio) and the amount of time during which no load could be driven (LLP).
- Efficiencies
  - To improve the reliability of the results produced in the model, the transmission, converter and battery round-trip efficiency were included in the model.

Chapter 6 - Results and discussion

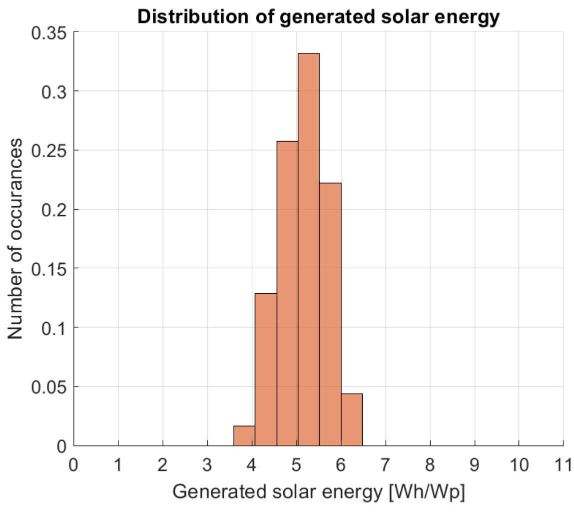
In this chapter, the results created with the Matlab app (given the name “the Electrificator”) are presented and discussed. Screenshots of the Electrificator can be found in the Appendix. Section 6.1 provides an overview over daily solar energy data that was obtained for Gwakwani. It is followed by a comparison between the Electrificator and the commercial simulation software PVsyst in section 6.2, which is used to validate the results of the app. Sections 6.3 and 6.4 show how the insight gained from the simulation in the Electrificator can be used to better understand the performance of SHSs and to use them in a more effective way, to in turn reduce the overall size required to drive loads. To conclude the chapter, section 6.5 presents an overview of the possibilities to make SHSs more feasible, summarised in section 6.5.

6.1 - General location-specific results

In this section, general information about the solar data in Gwakwani is presented. Figure 6.1a shows the distribution of the daily generated solar energy in Gwakwani, excluding any losses except for those included in the PVGIS data, for the full dataset of the years 2005 - 2016. Figure 6.1b shows the distribution of an averaged year, which was created by averaging each individual day based on the same dataset of 12 years.



(a)



(b)

Figure 6.1: *Normalised histograms showing the probability of the daily generated solar energy; (a) shows the full 12 years and (b) an average year, based on the same set of data. The numbers are excluding any losses except for those included in the PVGIS data. One can clearly see the filtering effect of creating averaged data.*

The minimum and maximum values were much closer to the mean value in the averaged distribution. This was visualised for the reason that programmes often use

averaged years for simulation, but as the figure shows, this has a filtering effect that removes all the days with relatively low energy output, which would result in an overestimation of the performance in the simulation in terms of LLP. The results of a SHS simulation for both cases were compared in section 6.2.
Figure 6.2 shows the average daily generated solar energy per month.

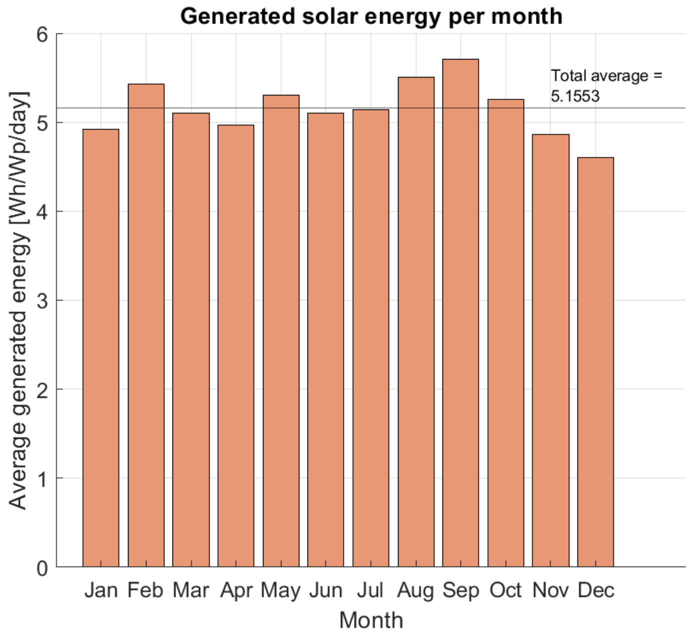


Figure 6.2: *Bar chart displaying the average solar energy production in Wh/Wp/day in Gwakwani per month, excluding any losses except for those included in the PVGIS data. Due to the optimised orientation of the PV panel, the production is almost constant throughout the year.*

The influence of seasons is highly dependent on the orientation of the PV panel in terms of slope and azimuth, but PVGIS optimised the angles such that the production was almost constant throughout the year. The dry winters and wet summers might contribute to this distribution of the available solar energy, which made seasonal effects basically negligible for the location of Gwakwani. This is highly beneficial for the SHS design process as the system will deliver a constant performance throughout the year.

6.2 - Comparison with PVsyst

The load profile as it was shown in figure 5.2 was used to compare the results produced by the app with the commercially available software PVsyst. PVsyst is a tool that allows for a detailed simulation of grid-connected, but also off-grid PV systems, including many more parameters than what was possible with the Electrificator. Similar to what has been done in Matlab, PVsyst estimates the generated solar power based on the location-specific irradiance, includes losses in the system and determines the performance of the system in terms of dump ratio, LLP and other factors. It was used to validate the model created in Matlab by creating the same load profile in both programs, generating a PV and battery size based on the suggestions given by PVsyst and adjusting the losses in the Electrificator to the ones used in PVsyst.

Instead of running the simulation through multiple years as was done in the app, PVsyst generates a realistic series of 365 days based on longterm monthly averages. Another difference between PVsyst and the Electrificator is the way loss of load is defined; while in the app only the time was counted when the battery was empty (i.e. SOC=0), PVsyst counted all the time when the battery was turned off as a result of reaching the minimum SOC. This minimum SOC is by default set to 10% in the programme, but only at 35% SOC does the charge controller allow discharging again, which means all the time needed to charge the battery to 35% is included in the LLP in PVsyst. Table 6.1 summarises the settings used in the app, based on the numbers given by PVsyst.

PV size	Battery size	min. SOC	max. SOC	η_{trans}	η_{conv}	η_{batt}
50 Wp	156 Wh	10%	96%	94.4%	97.25%	92.7%

Table 6.1: *Table showing the settings used in Matlab to compare the app to PVsyst.*

In the MTF shown in table 1.1, this SHS would be just big enough to be categorised as tier 2. Using these settings, the simulation in the app was computed once over the full dataset of 12 years and once using the averaged year to compare the results to the ones produced in PVsyst, which can be seen in table 6.2.

Quantity	PVsyst	Electrificator (12 years)	Difference to PVsyst	Electrificator (av. year)	Difference to PVsyst
Energy produced (after losses) in kWh/year	84.4	86.4	+2.4%	86.4	+2.4%
Energy missed in kWh/year	0.78	0.77	-1.3%	0.02	-97.4%
Energy dumped in kWh/year	36.2	37.5	+3.6%	36.7	-1.4%
Dump ratio	42.2%	43.4%	+2.8%	42.5%	+0.7%
LLP	2.4%	1.7%	-29.2%	0.09%	-96.3%

Table 6.2: *Table comparing the performance of the app with the commercial simulation software PVsyst.Electrificator (12 years) used the full dataset of 12 years, while Electrificator (av. year) used the averaged year. For a definition of the quantities see table 5.3. As expected, the averaged year resulted in a much better performance in terms of missed energy and LLP compared to PVsyst and the full dataset. The relatively high difference in LLP between PVsyst and the app could be explained by the slightly different definition of the term.*

As table 6.2 shows, the numbers produced in the Electrificator were very close to the performance results from PVsyst. Produced and dumped energy were both slightly higher and the missed energy slightly lower in the app than what was estimated in PVsyst, but this might have been caused by the different solar dataset. Considering the simplicity of the app compared to the many parameters that are considered in PVsyst, it was not expected to produce the exact same results. The largest difference could be observed in the LLP, which was most likely caused by the different definition of the term in PVsyst, covering a longer time span each time the battery runs empty and thus a higher LLP. As expected, the averaged year performed much better in terms of missed energy and LLP, which also showed that the climate data generated in PVsyst follows a more advanced and realistic way of generating the data. Overall, the comparison between PVsyst and the app showed that the results from the app were not far off and provided a good validation.

6.3 - System size and loss of load probability

In this section, it is analysed how different thresholds for the LLP influence system sizing when considering individual load profiles (section 6.3.1), which was then compared to the traditional days/nights of autonomy (DOA/NOA) sizing approach in section 6.3.2.

6.3.1 - Load profile based sizing

Figure 6.3 shows different possible combinations of PV and battery size that achieved LLPs below the threshold levels 2%, 5% and 10% for the same load profile and efficiency settings that have been used in the previous sections (see table 4.1 and table 6.1). Only the minimum and maximum battery SOC have been set to 0% and 100% respectively, to display the required useful capacity of the battery.

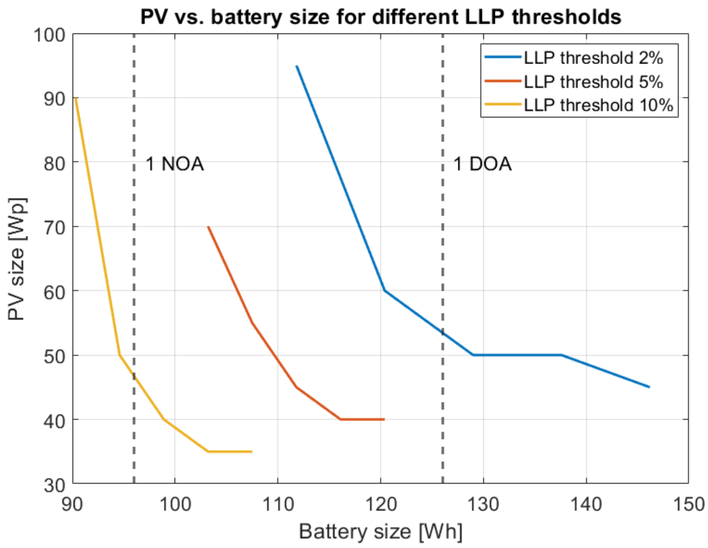


Figure 6.3: *Graphs showing different combinations of PV and battery that achieve results below a certain LLP threshold level, for 2%, 5% and 10% LLP, compared to the battery size that would be used in the generic approaches of 1 NOA and 1 DOA. The generic sizing approaches were not far off from the load profile based approach and were therefore analysed further.*

For both, PV and battery size, a minimum value could be found, below which the specified LLP could not be maintained anymore; e.g. to remain below 10% LLP, a minimum useful battery capacity of 90 Wh was needed and a minimum PV panel of 35 Wp. Maximum sizes could also be found, beyond which no improvement could be observed anymore in terms of decreasing the size of the other component; e.g. increasing the battery size beyond 103 Wh did not allow for any further reduction in

PV size while remaining below a LLP of 10%.
Increasing the accepted LLP from 2% to 5% or 10% decreased the minimum battery size by approximately 8% or 20%, respectively, and the minimum PV size by approximately 11% or 23%, respectively. No ideal solution for PV and battery size could be found based on this graph only, since all solutions satisfied the same LLP requirement. Other factors to consider are the battery lifetime, the cost and the dump ratio. The battery lifetime decreases with increased DOD, meaning if a certain useful capacity is required, it might result in lower longterm costs if a higher battery is chosen with relatively high limitations on minimum and maximum SOC. Regarding the dump ratio, the smaller the battery, the larger the required PV panel, resulting in a higher dump ratio. A larger battery requires a smaller PV panel, resulting in a lower dump ratio but a higher overall cost, since the battery makes up a larger share of the overall system costs.
The graphs visualise that the demand of a performance below a specified LLP restrict the design options in terms of PV and battery size, but also visualise how small both components could be chosen, if not a generic sizing method is used, but one that fits the individual requirements. The daily consumption used in this example was 126 Wh, which means a battery sustaining 2 DOA would require a capacity of 252 Wh. Comparing this number with the graphs, one can see that batteries of even half the size were sufficient to deliver power to the customer in 98% of the time. The approach of 1 DOA or 1 NOA would have resulted in a relatively well performing fit for this specific case. For this reason, these generic sizing methods were compared with the load profile based approach for different ratios between dayload and nightload, to visualise limitations of the generic approaches.

6.3.2 - Comparison with traditional sizing methods

Table 6.3 shows the results in terms of minimum PV panel/battery size of different sizing approaches to sustain a performance below 5% LLP.

Dayload	Nightload	1 NOA LLP $\leq$ 5%	1 DOA LLP $\leq$ 5%	Load profile based LLP $\leq$ 5%
0 Wh	100 Wh	21 Wp/100 Wh	21 Wp/100 Wh	21 Wp/100 Wh
25 Wh	75 Wh	48 Wp/75 Wh	22 Wp/100 Wh	26 Wp/80 Wh
50 Wh	50 Wh	133 Wp/50 Wh	22 Wp/100 Wh	40 Wp/55 Wh
75 Wh	25 Wh	-	22 Wp/100 Wh	45 Wp/35 Wh
100 Wh	0 Wh	-	21 Wp/100 Wh	35 Wp/25 Wh

Table 6.3: *Table showing the results of different sizing methods expressed as PV panel size/battery size. Since the approaches of 1 NOA and 1 DOA fix the size of the battery, the minimum PV panel size was found that sustained a LLP below 5%. This was compared to the load profile based sizing approach, where an alternative combination of battery and PV panel was found that fulfilled the same LLP requirement. Compared to 1 NOA, a slightly larger battery always resulted in a much smaller PV panel. The 1 DOA approach always resulted in an oversized battery. Only the case of a pure nightload did not leave much room for an improved system, since in such a case the performance almost only depends on the battery size.*

The dayload was defined as an evenly distributed load from 04:00 to 16:00 and the

nightload an evenly distributed load from 16:00 to 04:00, since these times represented the average times when the PV panel started and stopped to produce energy for the specified orientation and location. All efficiencies were set to the ideal case.
As can be seen in table 6.3, the traditional sizing methods 1 NOA and 1 DOA, with the exception of the case of a pure nightload, do not result in an optimal system size. Compared to the approach of 1 NOA, an increase in battery size of around 10% could always reduce the PV panel size significantly by up to almost 70%. The 1 NOA approach resulted in a generally too large battery. Using a more adaptable sizing approach offered possibilities to vary both battery and PV panel size to generate an overall smaller system that would come at a smaller cost. Both DOA and NOA based sizing fails to consider the individual load profiles of potential users and thus do not result in an ideal system size.
The downside of a system with a smaller battery is the high amount of excess energy that is dumped. Section 6.4 analyses how this trade-off between battery size and dump ratio could be used beneficially.

6.4 - Exploring additional capacities

A high dump ratio for a SHS means that a high percentage of energy produced by the panel is dumped on days with many sun hours, because the system has been sized to also produce enough energy on days with less sun. It was investigated if the system could maintain the same LLP but achieve a lower dump ratio if the users were aware of the fact that more energy is available on extremely sunny days. To simulate this user behaviour, an additional load was included only on those days that provided solar energy above a certain threshold.
The results shown in table 6.2 included dumped energy of 37.5 kWh/year or on average around 100 Wh/day. It was investigated on which percentage of days an additional load could be powered without increasing the LLP. This was done for loads of 50, 75 and 100 Wh on 2 different time points each, once directly at sunrise (04:10 - 05:10) and once when the solar production was strongest (09:50 - 10:50). The base load profile and all other settings were kept as in the previous sections (see table 4.1 and table 6.1). The results can be seen in table 6.4.

Load size in Wh	Time of usage	Max. percentage of days	Dump ratio	Energy dumped in kWh/year
-	-	-	43.4%	37.5
50	04:10 - 05:10	15%	41.1%	35.5
50	09:50 - 10:50	75%	28.1%	24.2
75	04:10 - 05:10	7%	41.9%	36.2
75	09:50 - 10:50	60%	25.6%	21.2
100	04:10 - 05:10	3%	42.7%	36.9
100	09:50 - 10:50	45%	24.4%	21.1

Table 6.4: *Table showing the maximum percentage of days where possible additional loads could be connected to a SHS without increasing the LLP, in an approach to reduce the dump ratio. The first row represents the results without any additional load. The results show that, if users were educated about the functionality of a SHS, additional loads could be driven on sunny days.*

The table shows that users could power an additional 50 Wh load on 75% of days, a 75 Wh load on 60% of days or a 100 Wh load on 45% of days. This is a significant amount, considering that the consumption without the additional load was on average 126 Wh for this load profile. The dumped energy could be lowered by more than 40% this way. Furthermore, it can be seen that the best time for the additional load to be connected was the late morning, when the sun was strong enough to power the load but leaving enough sun hours afterwards to charge the battery. The additional energy that would be necessary to boil water or cook in general would be too large to be supplied by a SHS of the given size and only much bigger systems could allow for complete electric cooking. Higher loads and different times were tested but did not add any insight to the results.
Thinking beyond the options emerging for one household, an interconnection of multiple SHSs in a community in the form of a microgrid would create high amounts of additional energy available during each day. Households without an own SHS could be connected to this grid and benefit from the access to electricity, while the power supplying households could create additional income by selling their excess energy. The interconnected SHSs could also be used to power community loads such as a water pump that supplies water for a village, similar to what has been implemented in Gwakwani. Water pumps exist that are capable of supplying 12000 l/day with a power consumption of 75 W, meant for smallholder plots of one acre [35]. Such a pump could be driven on more than half the days even with the 50 Wp PV panel used to generate the results in table 6.4, but could also be connected to several smaller SHSs.
The water could be used to grow vegetables that would allow households to move beyond subsistence farming, or to have a consistent water supply in the village. As was seen in the case of Gwakwani, while the technical solution exists and can be feasible, people need to be aware of the possibilities created through the implementation of the technology and have the incentive to use their SHS as a tool to improve their quality of life.

6.5 - Affordability of SHSs

Using the insights gained in the last sections, it was possible to develop an idea how to use SHSs more effectively and thus make them more affordable and useful for their users. Figure 6.4 summarises the different effects on a household's capability to afford a suitable SHS. The general limitation on SHSs is not the technology, but rather the financial situation of the households. Government subsidies would help to lift these limitations and could enable households to afford SHSs that could power more than only the most basic appliances like lights and phones. Additionally, if users understood that on sunny days more energy was available and on cloudy days less, the otherwise dumped energy could be used to power additional appliances on days with many sun hours or could be shared within a community. Lastly, the overall LLP could be increased to power more appliances or increase affordability, but the reduced reliability of the system could lead to customer frustration.
These different aspects summarise the overall challenge of SHSs, while advancements in technology improve possibilities of individual SHSs in terms of possible appliance usage and reliability of the systems, authorities need to be involved in the process to support households to take part in the electrification process.

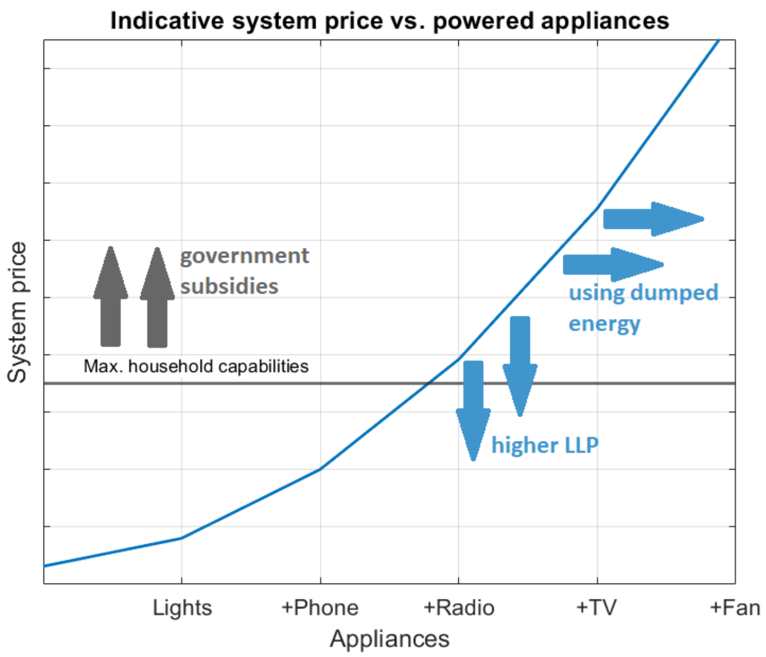


Figure 6.4: *Indicative graph visualising how households could be enabled to use SHSs more effectively. Government subsidies would allow households to afford larger SHSs, while customers that are aware of the functionality of the systems could use the energy more effectively.*

6.6 - Summary

Chapter 6 is summarised in this section, including the key results of this research. The data from PVGIS showed that for the location of Gwakwani and the orientation of the PV panel, the produced solar energy is nearly constant throughout the year. Based on this data, the proposed model was validated using the commercial software PVsyst, which produced very similar results.
The key results that were produced during this research can be summarised as follows:

- Using a dedicated sizing method such as a certain threshold level for the LLP reduces the overall system size of a SHS significantly compared to traditional generic sizing methods, by finding a balance between PV panel and battery size.
- The combination of a relatively larger PV panel and a relatively smaller battery reduces the overall cost of the system while maintaining the same performance in terms of LLP, but increases the dump ratio.
- The dumped energy could be used to power additional loads of significant size on more than half the days if users understood at which times additional energy was available, potentially reducing the dump ratio and increasing the possibilities created with SHSs.

Chapter 7 - Conclusion

This chapter contains contributions (section 7.2), conclusions (section 7.3) and recommendations for future work (section 7.4) regarding the topic of off-grid electrification using SHSs. It starts with a summary of the content discussed within this thesis in section 7.1.

7.1 - Content

The main research objective of this thesis was stated as:

How can a SHS be appropriately sized to meet the specific (energy) needs of a rural low-income household?

The different components of SHSs were discussed and analysed to identify losses in the system in order to create a realistic model of a SHS. Using information obtained during a literature review and a case study conducted with the support of staff from UJ-PEETS, different scenarios were simulated in the model to gain insight into the performance of SHSs. The highly limited information about the load profiles of future SHS users were the main challenge and required estimations based on existing studies on the topic.

7.2 - Contributions

The main contributions of this thesis are:

- A general overview of the topic of off-grid electrification using SHSs including insight into the main challenges facing an implementation of SHSs.
- An analysis of the technical components of SHSs including effects on performance and ageing.
- A simple modelling methodology that provides insights into off-grid electrification and can potentially enhance the accuracy of SHS models.

7.3 - Conclusions

Based on the results created within the scope of this thesis, the main conclusions are summarised as follows:

- SHS sizing should be done under careful consideration of the case-specific energy requirements and climate properties, which drastically reduces the overall system size and in turn increase affordability for households compared to generic sizing methods.

- A combination of a relatively smaller battery and a relatively larger PV panel should be favoured since it reduces overall costs and the excess energy produced as a consequence of the limited storage capacities offer a range of possibilities if the SHSs are interconnected in microgrids.
- If households accept to not be able to power appliances for a certain amount of time, overall system sizes and costs can be significantly reduced.
- Designing the right technical solution is one part of a successful SHS implementation, but the education of consumers about the functionality of the system as well as awareness on the possibilities of the technology are equally important.

7.4 - Recommendations and future work

While SHSs create the opportunity for households to access electricity and improve their overall quality of life, the systems come with clear limitations on the available energy. Therefore, SHSs on their own will not achieve the goal of universal electrification. A list of recommendations is presented to continue the work done in this thesis and to potentially further increase the positive impact of SHSs.

- The model presented in this thesis could be extended to investigate the possibilities of SHSs on their own but also interconnected in a micro grid.
- While different sizing methods can significantly increase affordability of SHSs for poor households, regulating authorities have to be included in this process and support the implementation of bottom-up off-grid solutions to achieve electrification goals.
- Most potential for an improvement in the usage of SHSs lies in the large amount of excess energy that is dumped if users mainly power appliances at night and it should be investigated further how this energy could be used in a beneficial way.

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Appendix

Screenshots of the Electrificator

A range of screenshots of the Electrificator were included in the Appendix to show how the app actually looked like.

Load profile and solar power before the simulation

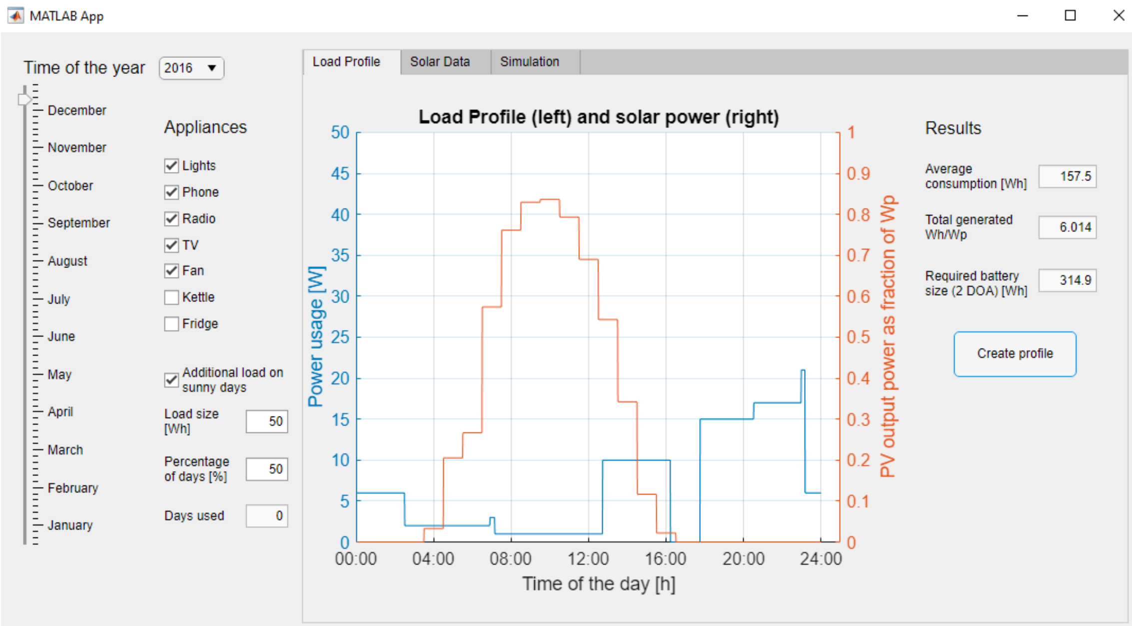

Figure 7.1: *Screenshot showing a load profile and the normalised generated solar power of an arbitrary day. The appliances can be selected on the left with the option to add an additional load on sunny days as was discussed in section 6.4. The year and month on the left can be used to look at different days in terms of the solar power output*

The screen shown in figure 7.1 was mainly used for visualisation and debugging purposes, especially in the beginning of the project, to verify the correct interpretation of the solar data and the generation of the load profiles.

Solar Data histogram

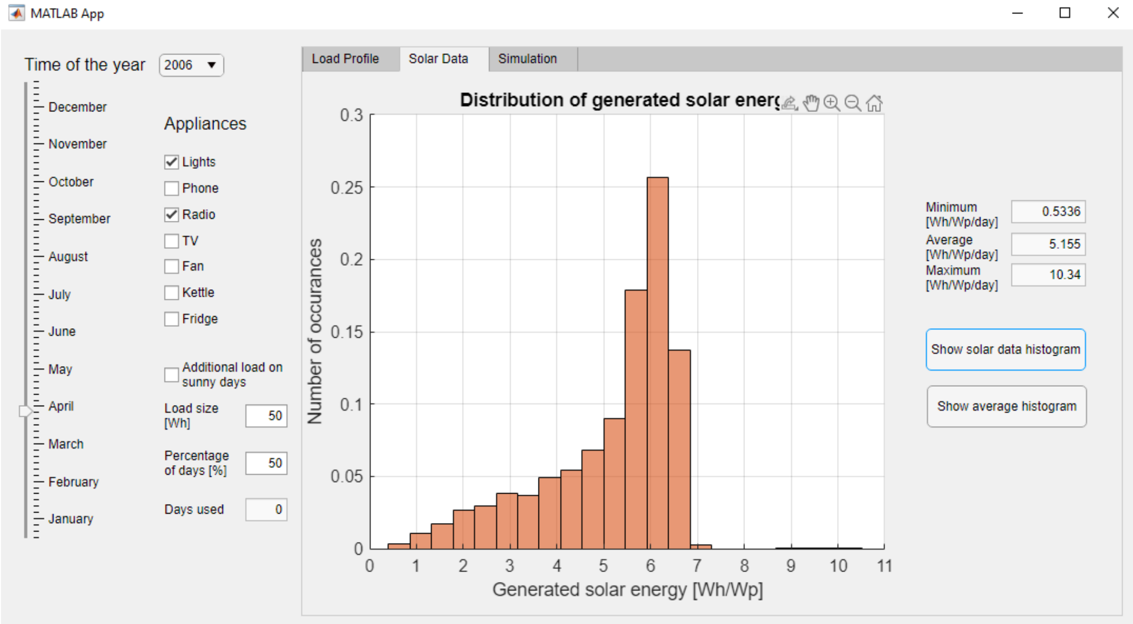

Figure 7.2: *Screenshot showing the solar data from PVGIS for the location of Gwakwani.*

The solar data tab was used to visualise the solar data from PVGIS, for debugging purposes but also to create insight about the data.

Efficiency settings

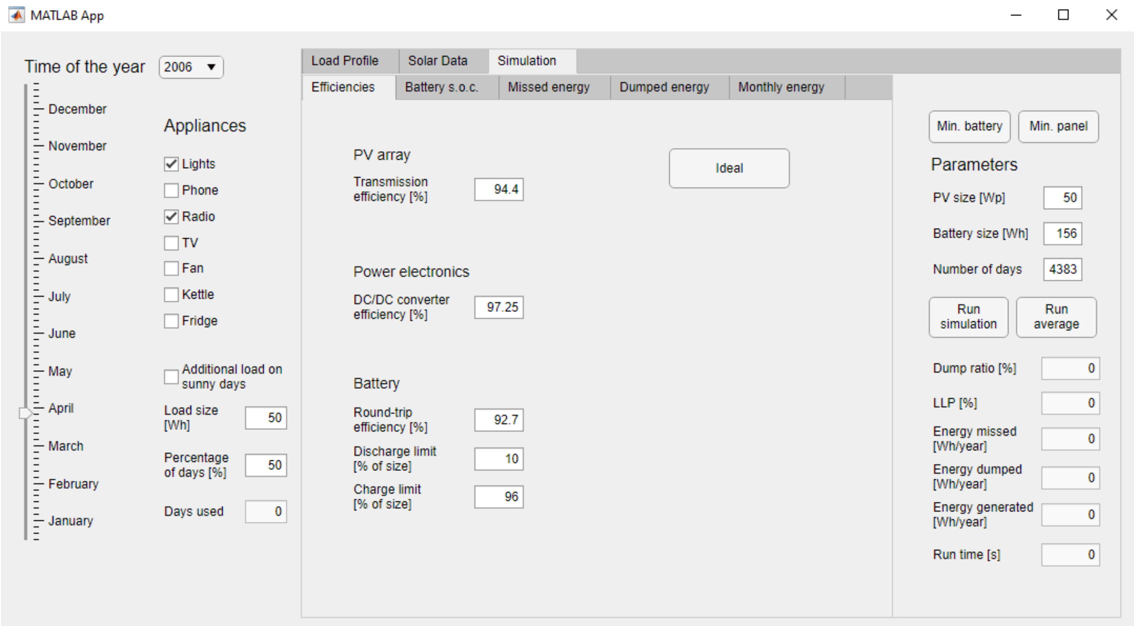

Figure 7.3: *Screenshot showing the tab to set the efficiencies in the app. The numbers shown are the ones used to compare the app to PVsyst. The ideal button set all efficiencies to 100% and removed the discharge and charge limits on the battery.*

The screenshot shows the tab that was used to set the efficiency settings prior to a simulation. While the transmission and converter efficiencies were multiplied together in the code, they could be set separately to have a better overview over the parameter.

Simulation results showing the battery SOC

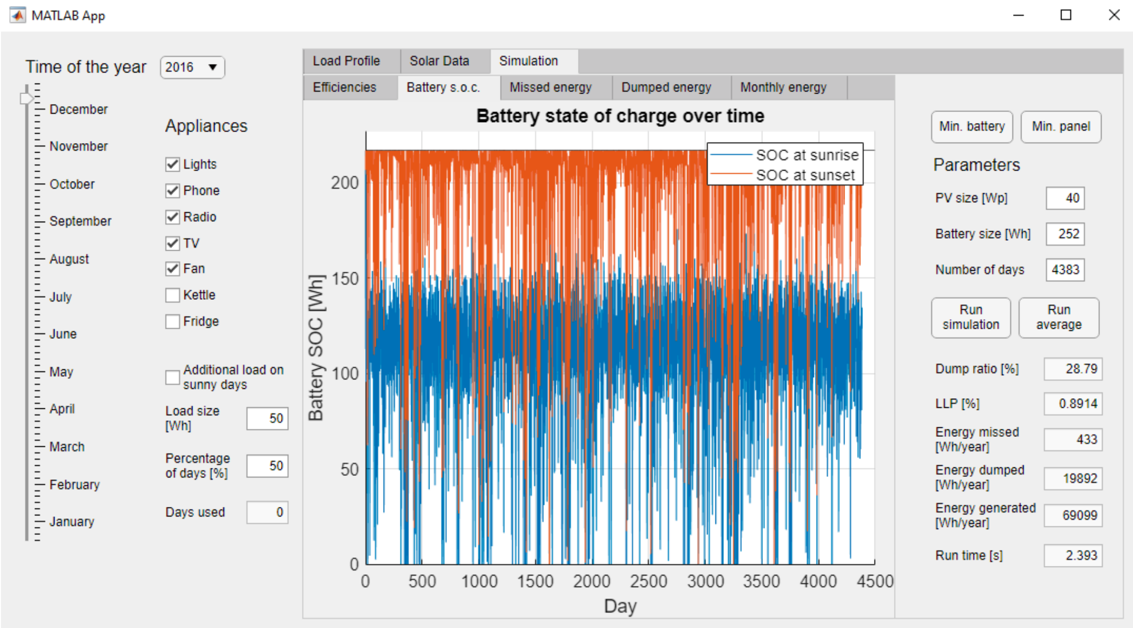

Figure 7.4: *Screenshot of the results of a simulation for a SHS specified in terms of PV and battery size on the right and appliances on the left. Results can be seen on the lower right part of the picture. The graph represents the battery SOC at sunrise and sunset. While it looks messy if the full 12 years are simulated, it shows the average levels to which the battery discharges and charges.*

The tab shown in figure 7.4 shows how the results were visualised in the Electrificator. The graph might seem messy, but in this case it shows that the battery in most days only discharged to a level around 120 Wh, while it has a 252 Wh capacity, so it could have been sized much smaller.
The results in the lower right part of the screenshot show the computed performance in terms of dump ratio, LLP, missed energy, dumped energy and generated energy per year. The run time was also displayed since during the development of the algorithm it was taken into account, to not create an inefficient code.
The "Run simulation" button ran the simulation through the specified number of days, which was usually the full set of 12 years but could also be set to any other number. The "Run average" button used an average year as described in section 6.1. The two buttons on top "Min. battery" and "Min. panel" were used to quickly find the smallest size of battery or panel for a certain LLP, based on a simple algorithm that not always delivered the most accurate results but provided a fast indication of the range of the PV panel and battery that were applicable for the given load profile.

Simulation results showing the dumped energy

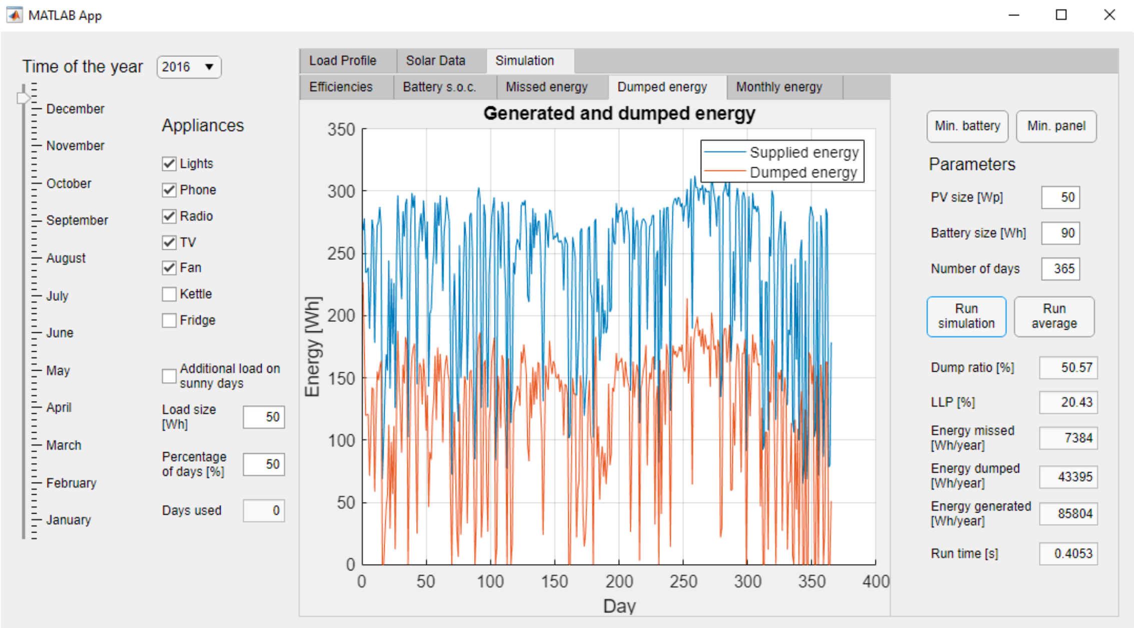

***Figure 7.5:** Screenshot showing 365 days of simulation. The graph shows the supplied and dumped energy. The relatively high dump ratio of 50% and LLP of 20% show that the PV panel and battery size were not sized well.*

The generated and dumped energy was a graph that showed how much energy was wasted, in this case the dump ratio was relatively high.