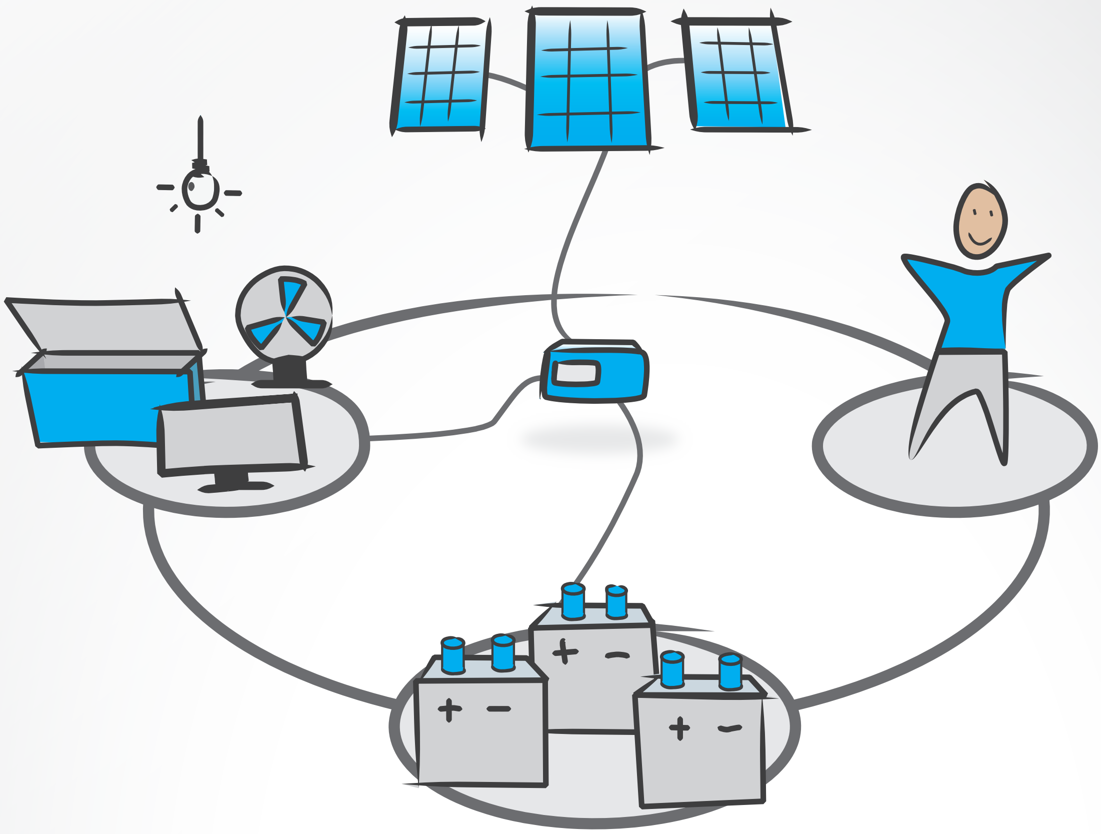

FUTURE SOLAR HOME SYSTEMS: MATCHING ENERGY SUPPLY WITH ENERGY DEMAND

THOMAS DEN HEETEN

MASTER THESIS

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Future solar home systems: matching energy supply with energy demand
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PREFACE

This master thesis describes the final work done for my master's program Integrated Product Design. During this project, I have focussed on future development of Solar Home Systems. The project gave me the opportunity to work on a product with a good cause: bringing electricity to the people in need. I have enjoyed working on this project every single day.

The project is part of a PhD project, which is almost halfway execution. The PhD-candidate will continue with the results of this thesis. I am happy that I could contribute to this project and I am looking forward to the end results.

I would like to thank my coaches for supporting me in the project and pushing me in the right direction. Nishant, thank you for your support and input on technical aspects. Thanks JC for your endless enthusiasm, but also your criticism at times when needed. Sacha, thank you very much for your sharp comments and constructive feedback. Thanks go also to Jelena, one of the initiators of this PhD project.

This project would have been much harder without the help from Kamworks. Special thanks go J. Verschilling, A. Luxwolda and L. Leleu for providing the dataset and hosting me in Kamworks' office in Phnom Penh. Bunheng and Justin, thank you very much for the help during the field research and making it an amazing trip. Thanks also to Bart Deloof, who took me on the incredible trips with Picosol and connected me with a lot of people. Furthermore, I would like to thank all the people that were so kind to tell me all about Cambodia and the SHS market.

Special thanks goes to the TU Delft Global Initiative, who have supported this project with knowledge and promoted the project by spreading the video blogs through their channels. For more information, please visit http://www.delftglobal.tudelft.nl/ The videoblogs can be found on their Youtube channel.

Thanks go also to my friends who have supported me throughout the project. Finally, I would like to thank my family for the unconditional support during my studies.

Thomas den Heeten
Delft, March 2017

EXECUTIVE SUMMARY

1.3 billion people in the world lack access to electricity (International Energy Agency (2013). The largest share of this group is poor and lives in the developing world, and has to deal with unmet basic needs. Having the possibility to use reliable and clean energy is seen as a driver for social development and environmental sustainability. Having access to energy is also often linked to economic growth and has a positive impact on health. (Gradl & Knobloch, 2011) Improving energy access is therefore a hot topic worldwide.

With a Solar Home System (SHS), energy can be generated and used on a household level at places where the electric grid does not reach. The main components of a SHS are a solar panel for the generation of electricity, a battery for energy storage and balance of system (BoS) components, including power electronics, to coordinate the flows of energy. SHS are offered by multiple companies worldwide, and come in various configurations. The smallest SHS are capable of powering for example LED lights, phones and/or a radio, while larger SHS can power for example televisions and fans.

Generally speaking, SHSs are increasing in size. This is due to dropping prices of system components. Where in 2003 a SHS of 20 Wp was economically competitive with kerosene lamps, in 2015 this was already 70-80 Wp. (Chattopadhyay, Bazilian and Peter Lilienthal, 2015) The conventional technologies are likely to dominate the SHS the upcoming years. Proven technologies are favourable as reliability is key for SHSs. This means that most of the SHSs in the future will rely on crystalline silicon panels and lead-acid batteries. In the future, li-ion battery technologies will become competitive as prices are dropping.

Three main challenges of SHSs are the starting point for this project:

1. SHSs come at high upfront costs. This is for many poor households a barrier.
2. SHSs have limited capacity. Current systems do not fulfil all user needs. Households at the BoP have no access to larger SHS that can power appliances that require large amounts of power.
3. Knowledge on current and future demand is limited, not relevant or outdated. Not knowing what the needs of the user are makes it hard to design a system according to the needs.

Matching energy supply and demand is crucial in tackling this challenge, as it will improve user satisfaction and reduce system costs. By sizing a system according to user needs, the user will experience less problems with their system. Furthermore, the user will be able to power more appliances. Secondly, by optimizing the system size according to user needs, the costs of the system can be reduced. Optimizing system size will also result in less maintenance. Solving these challenges will lead to better designed SHS that meet the needs of the user. The project goal of this thesis is therefore:

"Provide design support for future SHS design, that aims to decrease system costs and improve system performance, by focussing on matching energy supply with energy demand."

Chapter 3 presents research on the current energy consumption, and what the relation is between has on system performance. This because there is a lack of knowledge on current energy consumption by SHS users. In this research, a data analysis is done on usage of a 100 Wp, 1200 Wh SHS between 2014-2016, with n=111. The data analysis is verified with household visits. This case study is performed in rural Cambodia.

Although all the households that were part of the research own the same type of system, (100 Wp) there is a wide variety in energy consumption patterns. The mean energy consumption for all users is 310 Wh/day, with σ = 159 Wh. Most energy is consumed at night, when the sun does not shine. This is when the lights are on and when the fan and TV are in use. This is also the time when the peak energy demand occurs. The mean energy demand at the peak of the day is 62 W, with a standard deviation of 27W.

The 100 Wp system is not sufficient for all users. Users in the user group with the highest consumption, experiences an empty battery on 28.2% (!) of the days. User in this user group have a loss of load during 4,03% of the time.

It can be concluded that at the moment, there is a mismatch between energy supply and demand, because a large group of users suffers from loss of load, most energy is consumed at night and electricity needs are unmet.

The spread in energy consumption patterns is something that designers and other engineers should take into account during the design process of a future solar home system, to prevent high loss of loads and deep discharging of batteries.

To better match energy supply and demand in future SHS, it is important to know more about future energy needs. The results of a case study in Cambodia future energy needs are explored in chapter 5. Participants in the field research indicated to be satisfied with their SHS, but would like to use the TV longer and add more appliances, such as a rice cooker, water kettle, iron and a refrigerator. There is user demand for more electricity in rural Cambodia. There are two main reasons why households do not own the appliances they want to own: 1) the household can't afford the appliance; 2) the appliance is not compatible with a solar home system, because it uses too much energy.

Adding more appliances will have impact on the load profile. Some appliances will be used daily and at specific times (water kettle, rice cooker) , while other appliances might only be used every now and then (audio system) or perhaps once a week (iron). Fridges will need to be continuously connected, while water kettles, irons and rice cookers will cause high peaks for a short time in the profiles. In the future, load profiles will therefore have more diversity. Three personas presented in chapter 5 describe this diversity in load profiles and can be used as a guidance for SHS designers.

To accommodate future needs, bigger systems are necessary. Chapter 6 describes how this can be achieved using features as modularity and connectivity. However, solely increasing system size will not be the optimal solution. The full potential of SHSs will be unleashed with an integral approach. Besides optimizing SHSs, future systems should facilitate smart off-grid appliances and DSM features. This will require advanced power electronics. In the next phase of the overarching PhD project, the focus should lay on creating multiple design concepts for the power electronics and evaluating them on key requirements, including price and performance.

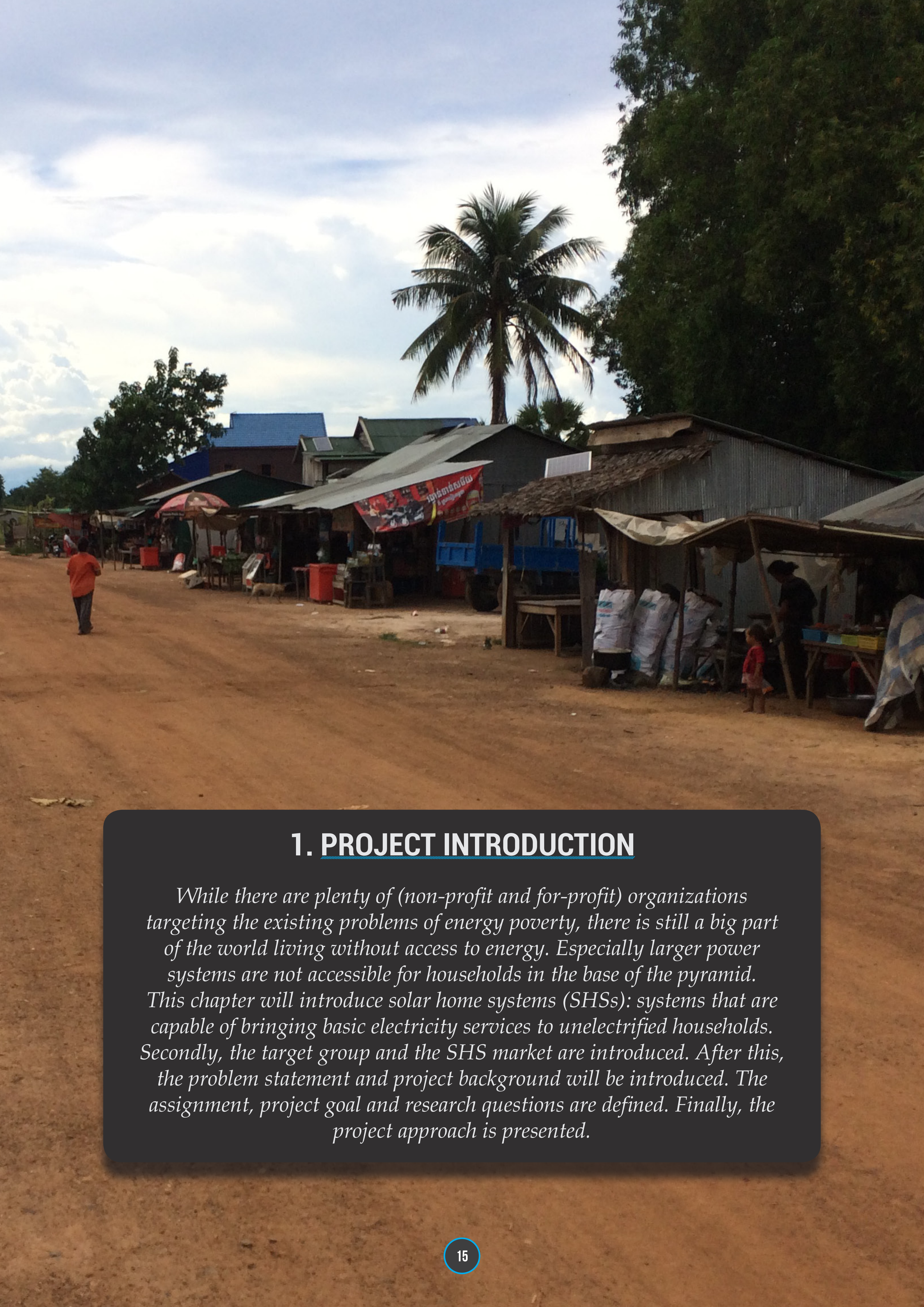
TERMS & ABBREVIATIONS

A	Ampere
AC	Alternating current
Ah	Ampere-hour
BoP	Base of Pyramid
BoS	Balance of System
DC	Direct current
DoD	Depth of discharge
DSM	Demand Side Management
h	Hour
LED	Light emitting diode
I	Current (A)
Khmer	Name for both Cambodian population and language
Li-ion	Lithium-ion
LiFePO4	Lithium iron phosphate
LLP	Loss-of-load probability
lm	lumen
Load profile	The load profile is a graphical expression of the demanded energy over a specific period.
MFI	Micro-finance institute
MPPT	Maximum Power Point Tracker
NiMH	Nickel-metal hydride
NGO	Non-Governmental Organisation
PAYG	Pay-as-you-go
PV	Photovoltaic
REF	Rural Electrification Fund (Cambodia)
SoC	State of charge
SHS	Solar home system
SHSs	Solar home systems
TV	Television
Vb	Battery voltage (V)
Voc	Open circuit voltage (V)
W	Watt
Wh	Watt-hour
Wp	Watt-peak

TABLE OF CONTENT

LIST OF FIGURES

LIST OF TABLES



1. PROJECT INTRODUCTION

While there are plenty of (non-profit and for-profit) organizations targeting the existing problems of energy poverty, there is still a big part of the world living without access to energy. Especially larger power systems are not accessible for households in the base of the pyramid. This chapter will introduce solar home systems (SHSs): systems that are capable of bringing basic electricity services to unelectrified households. Secondly, the target group and the SHS market are introduced. After this, the problem statement and project background will be introduced. The assignment, project goal and research questions are defined. Finally, the project approach is presented.

1.1 INTRODUCTION TO SOLAR HOME SYSTEMS

According to the International Energy Agency (2013), 1.3 billion people in the world lack access to electricity. The largest share of this group is poor and lives in the developing world, and has to deal with unmet basic needs. Having the possibility to use reliable and clean energy is seen as a driver for social development and environmental sustainability. Having access to energy is also often linked to economic growth and has a positive impact on health. (Gradl & Knobloch, 2011) Improving energy access is therefore a hot topic worldwide.

This project focuses on Solar Home Systems (SHSs) for the developing world. With a SHS, energy can be generated and used on a household level at places where the electric grid does not reach.

The main components of a SHS are a solar panel for the generation of electricity, a battery for energy storage and balance of system (BoS) components to coordinate the flows of energy. SHS are offered by multiple companies worldwide, and come in various configurations. The smallest SHSs are capable of powering for example LED lights, phones and/or a radio, while SHSs with more capacity can power for example televisions and fans.

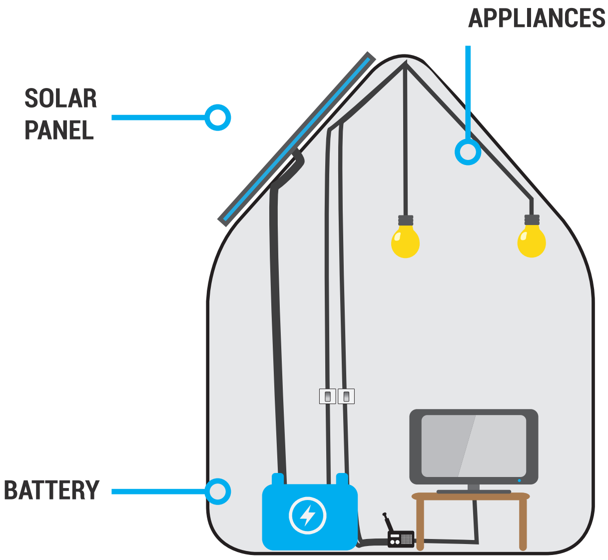


Figure 1: Solar Home System.

1.1.1 TARGET GROUP: THE BASE OF THE PYRAMID

This project focuses on SHSs for the developing world, where the largest share of people without access to energy are situated. This section gives a short introduction in the target group.

Approximately four billion people in the world have to live with less than 3000$ per capita per year, or a mere ~8$ per day. (Hammond, Kramer, Katz, Tran, & Walker, 2007) This big share of the world's population is also known the 'Base of the Pyramid' (BoP). The majority of the BoP lives in South Asia and sub-Saharan Africa, but can also be identified in Latin America and Eastern Europe. (Hammond et al., 2007)

Beside energy poverty, the people at the BoP suffer from other unmet basic needs. One in ten people in the world have no access to safe water and one in three lacks basic sanitation and access to a toilet. Annually 4.3 million people die from health issues caused by poor indoor air quality, as a result of using biomass as wood or animal dung to heat their houses or for cooking. (Harries, Holtorf and Urmee, 2016)

The BoP is not a homogeneous group and not all people suffer from the same problems. For example, one could make segmentation based on income. This already provides a good indication on what the differences can be inbetween households in the BoP. Based on income, the base of the pyramid can be divided into three segments. See Figure 2.

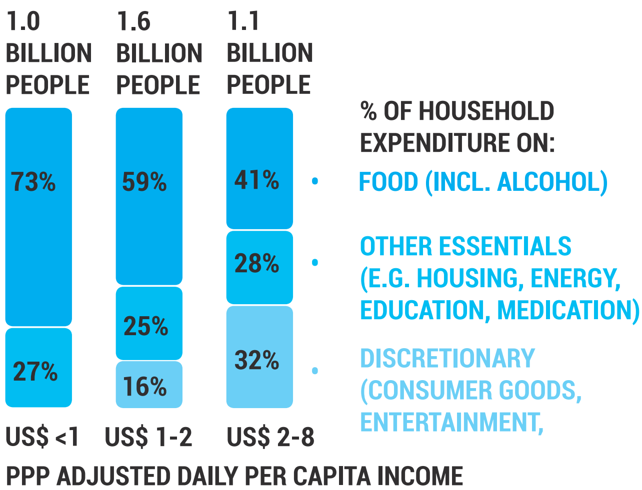


Figure 2: Segmentation of the base of the pyramid based on income. (World Economic Forum, 2009)

The lowest segment spends their income mainly on food and is stuck in the poverty trap. This group has very little opportunities to improve their situation. 27% of their income (<1 $/day/capita) is spend on essentials such as energy.

The middle segment (1-2 $/day/capita) has a bit more to spend and can enjoy some basic discretionary goods such as entertainment and communication.

The third group (2-8$/day/capita) has significantly more means. This last, most affluent group of the Base of the Pyramid is chosen as the target group for this project. This group has some financial means to upgrade their way of living and invest in products such as SHSs.

1.1.2 SHS MARKET

With 1.3 billion people unelectrified and another 1 billion having unreliable grid access, the potential market for SHSs is huge. (Ligthing Global, 2016) The 4 billion people in the base of the pyramid spend (by estimation) 433 billion $ on energy. (Gradl & Knobloch, 2011) Ligthing Global (2016) estimates that 99 million households will rely on off-grid solar as a primary or secondary energy source by the year 2020.

The global market for SHS is growing. The large market potential has attracted new business ventures with some being more successful than others. Successful SHS companies take the various local stakeholders in consideration in the early stages of the project/programme, and involve the local community in installing, operating and managing the systems. (Urmee et al., 2016)

On a product level, successful adoption of SHS is, among others, characterized by the use of appropriate technology and systems that are designed to match users need. (Urmee et al., 2016)

Despite the growth, the SHS market remains a harsh market. Several barriers make the electrification of low-income rural households worldwide difficult. Several studies have summarized these problems. (Global Off-Grid Lighting Association, 2015; Gradl & Knobloch, 2011; Urmee et al., 2016)

One of the biggest hurdles are the financial barriers, a challenge for both companies as well as consumers. The lack of a financial infrastructure makes it difficult for companies to scale-up, and the high up-front costs of a SHS are a reason why households decide not to buy one. (Lighting Global, 2016)

A second reason that slows down the dispersion of SHS, is a lack of awareness and knowledge. Consumers are often not aware of the benefits that SHS can bring. This is due to a lack of education and technical

Figure 3: Promoting SHSs during the Good Solar Initiative campaign at the Krapeu Chas Pagoda, rural Cambodia, by Picosol and Kruosar Solar.

knowledge. Also, consumers often do not know what kind of products are available on the market. (Gradl & Knobloch, 2011)

Another issue is the wide availability of low-quality products. Poor designed products for the base of the pyramid are harmful for the market. As investigated by Global Off-Grid Lighting Association (2015), these low-quality products can damage consumer confidence, increase costs for consumers, increase material waste and pose a threat to the overall opportunities in the market.

Reported by Gradl and Knobloch (2011), market information still remains a challenge. Limited knowledge about the diversity of the market and the changing needs of consumers slow down innovation. Additionally, there is a need for more knowledge on off-grid appliances and their performance. (Global LEAP, 2016)

Applying appropriate technology is crucial in future SHS design. Improving knowledge about the market and customer needs will help in tackling this challenge and is thus required to speed up innovation.

1.2 PROBLEM STATEMENT

Three major issues of SHSs are the starting point for this project:

1. ***SHSs come at high upfront costs.*** This is for many poor households a barrier. (Lighting Global, 2016)
2. ***Current systems do not fulfil user needs.*** Households at the BoP have no access to larger SHS that can power appliances that require large amounts of power.
3. ***Knowledge on current and future demand is limited, not relevant or outdated.*** Not knowing what the needs of the user are makes it hard to design a system according to the needs. (Global LEAP, 2016)

Solving these challenges will lead to better designed SHS that meet the needs of the user.

1.3 PROJECT BACKGROUND

The department of DCE&S at the faculty of EEMCS is performing a PhD-project with the goal to develop a larger PV-based electrification system but at low-cost, that can supply electricity to power basic household appliances such as a fridge, TV and lighting. Their approach is to minimize costs of components by optimizing the sizing of the system to match user needs. The technical challenge of this project is to design a power management system through dedicated power electronics, with the aim to reduce upfront and running costs.

The main objective of the overarching PhD-project is formulated as:

"To analyze core technology aspects and their interdependencies for a modular Solar Home System (SHS) for low income households in developing nations, while taking into account the electricity needs of now and the near future." (Narayan, 2016)

This master thesis will focus on the last part of this objective: *the electricity needs of now and the near future.*

1.3.1 TARGET COUNTRY: CAMBODIA

The primary target countries of the PhD-project are South Africa, India and Cambodia, all countries with large unelectrified populations. (Narayan, 2016) This master thesis project will focus on Cambodia. Over the years, the faculty of Industrial Design Engineering has build a good relationship with Kamworks Ltd., a company active in the Cambodian SHS market. Several student projects have been performed as part of the collaboration between TU Delft and Kamworks. For example, the first SHS of Kamworks was designed as part of a master thesis. (Van Diessen, 2008) This connection is the reason for choosing Cambodia as target country for this thesis and the research performed during this thesis.

1.4 ASSIGNMENT

This master thesis will contribute to the overarching PhD-project. As described in 1.3, the goal is to minimize costs of SHS components by optimizing the sizing of the system to match user needs. Unknown input in the PhD project are the electric user needs. Knowledge on load profiles (energy demand & energy consumption pattern) is limited or outdated. There is a need for up-to-date load profiles and an analysis on how these load profiles can develop in the near future. This project will therefore focus on the usage of

SHS, both now and in the near future.

1.4.1 PROJECT GOAL

The project goal can be formulated as follows:

"Provide ***design support*** *for future SHS design*

with the aim to ***decrease system costs*** *and* ***improve system performance***

by focussing on ***matching energy supply with energy demand****."*

1.4.2 RESEARCH QUESTIONS

The research questions for this thesis are formulated as:

Q1. What system parameters are of importance for SHS sizing?

Q2. What are the current energy needs of SHS users?

Q3. What are the future energy needs of SHS users?

Q4. How can future SHSs serve future energy demand?

NEAR FUTURE: 2021

During this project, a look will be taken at the short-term future. The overarching PhD project is planned to end in 2019. The results of this research should still be relevant at the end of the project. As a point of reference the year 2021 is chosen; 5 years after the research was performed. Making scenarios for longer-term futures will result in less reliable input for the project.

1.5 APPROACH

This section will describe the approach used in this project to answer the research questions and accomplish the project goal.

1.5.1 METHODOLOGY

The project is split up in 3 phases:

- Product analysis phase;
- Research phase;
- Design phase.

During the ***product analysis phase***, research question 1 will be answered. In this phase, the SHS technology will be discussed. This product analysis will be dealt with by literature research. Literature on SHS is widely accessible. Doing this will provide a solid ground for more in-depth analysis in the second phase.

In the ***research phase***, research questions 3 and 4 will be answered in detail. This will be done through a case study on SHS users in rural Cambodia. By focussing on a single area and on one type of system, comparison scan be made between energy consumption patterns. Furthermore, correlation between energy consumption patterns and system performance will be investigated.

Two methods will be used during the research phase: a quantitative data analysis and qualitative field research. The data analysis will be performed on performance logs of SHS in use in rural Cambodia. The results will be verified by household visits at SHS users. The qualitative field research will elicit future demand for appliances and future energy consumption patterns. This will be done through household visits at SHS users. The results will be presented in the format of personas, storyboards and future load profiles.

After the analysis and research phase, a ***design phase*** will discuss what design decisions need to be made so that future SHSs can cater for future electricity needs. During this phase, it is explored how system sizing can be optimized, appliances should be chosen, and how energy consumption patterns can be influenced. Ideas will be generated during brainstorm sessions. The ideas will be developed to a conceptual design, with the goal to be a suitable starting point for further development (incorporated in the overarching PhD project).

The methodology will be further described in the respective chapters.

1.5.2 SUPPORT

The involvement of the DCE&S research group, especially PhD candidate N. Narayan and J. Popovic, is used for information on the technological aspects of this project. The DCE&S research group will use the outcomes of this thesis as input for their design. From Industrial Design Engineering, J.C. Diehl will support the project. His knowledge on working on design projects in developing nations will be beneficial for guidance in the user and the business parts of the project. S. Silvester (also Industrial Design Engineering) will be mentor, who has experience with similar SHS projects, designing for sustainability and PV-based products.

1.5.3 REPORT STRUCTURE

The report will be build up in the following structure:

PHASE I: PRODUCT ANALYSIS

Chapter 2 will present a product analysis on SHS. This has the goal to understand the system and identify technical challenges. This will be done through a literature study.

Chapter 3 goes deeper into the technical details of matching SHS technology with user needs. Goal is to identify the parameters that need to be addressed to match energy supply and energy demand. This will be done through a literature study.

PHASE II: RESEARCH

Chapter 4 presents a study on the current SHS usage. The goal of this chapter is to investigate current energy consumption of SHS-users and figure out what impact this has on system performance. This will be done through a data analysis on actual usage of SHS in rural Cambodia.

Chapter 5 elaborates on the future needs of SHS users. Aim of chapter 5 is to find out what appliances are demanded and what appliances can be expected to be used with SHS in the near future (2021). This will be done by showing the results of field research in rural Cambodia.

PHASE III: DESIGN

Chapter 6 discusses what design choices can be made by SHS designers and companies to decrease costs and optimize system performance.

Chapter 7 will conclude and reflect upon the work and the research performed.

Figure 4 shows a diagram of the report structure.

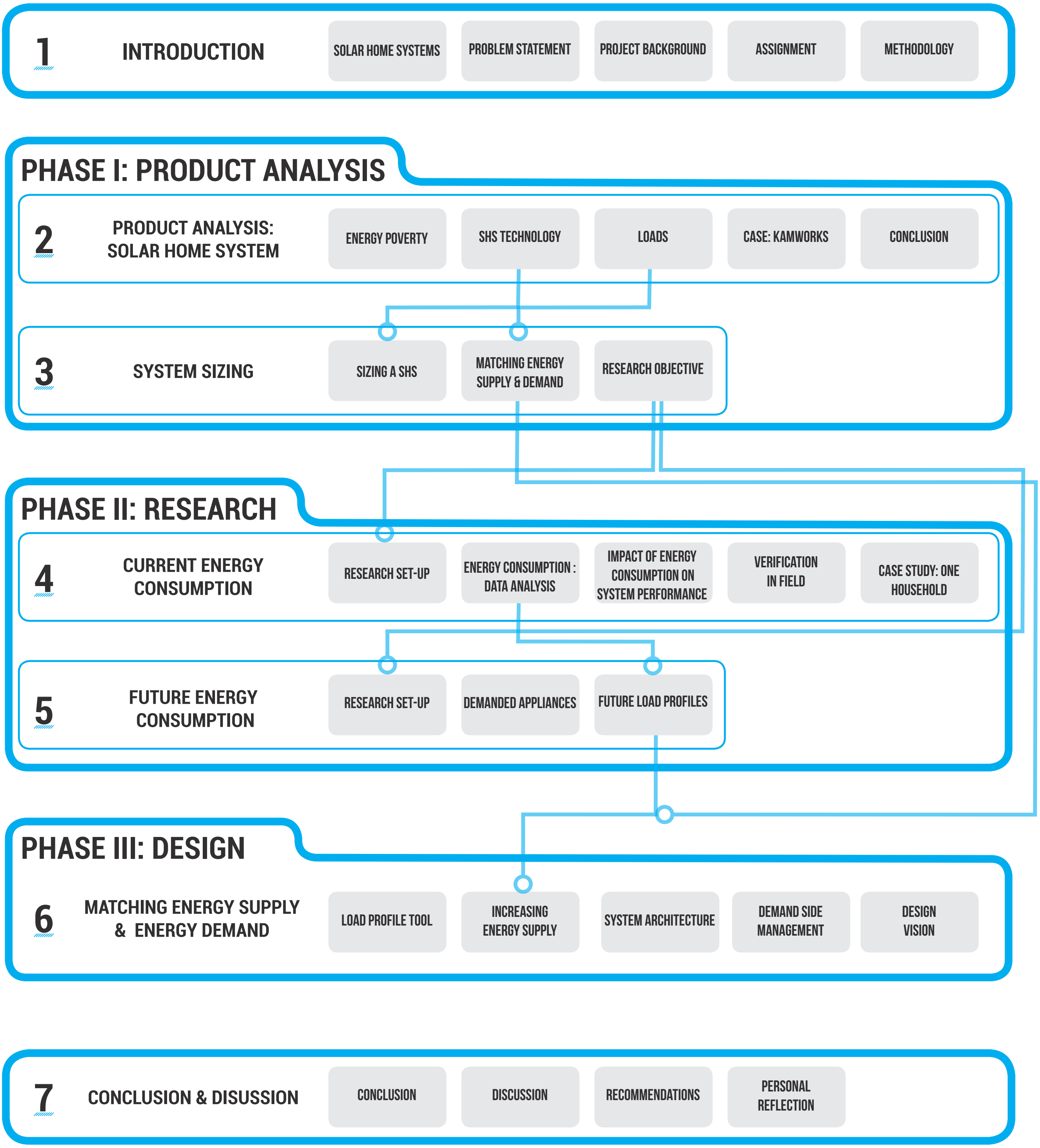


Figure 4: Report structure.

2. PRODUCT ANALYSIS: SOLAR HOME SYSTEMS

1.3 billion people in the world lack access to electricity. (International Energy Agency, 2013) SHSs can serve basic energy needs of the energy poor people in a sustainable manner. This chapter will analyze SHSs, as available on the market today. Secondly, technical challenges of SHSs are identified. A case study on Kamworks, a SHS company operating in Cambodia, puts theory into perspective of reality.

2.1 ENERGY POVERTY

Energy poverty is one of the unmet needs the people at the BoP are struggling with. Unelectrified households and communities rely on other energy sources than the electricity grid. The poor households use kerosene or paraffin to shed light, use car batteries to power television or generate electricity by using diesel generators. (Lighting Global, 2016) Using biomass, kerosene and other fuels leads to health hazards, can cause fires and is bad for the environment. Besides not having access to modern electricity, these BoP households also spend 20-30% of their household budget on outdated and inefficient energy sources. Furthermore, households have to spend a significant amount of time and effort into getting these sources of energy. (Urmee et al., 2016) Having the possibility to use reliable and clean energy is seen as a driver for social development and environmental sustainability. It is linked to economic growth and has a positive impact on health. (Gradl & Knobloch, 2011; Ligthing Global, 2016; Samad, Khandker, Asaduzzaman, & Yunus, 2013)

For example, with longer hours of better illumination by solar powered lighting sources, children can study longer and shops can have longer opening times. (Lighting Global, 2016) Energy thus has a big impact on the life of poor households and providing access to electricity is crucial in solving more problems than energy poverty alone.

While plenty of companies, projects and programmes have tried to solve energy poverty over the past decades (Gradl & Knobloch, 2011), lack of access to electricity remains one of the difficulties 1.3 billion people have to deal with on a daily bases. (International Energy Agency, 2013) Figure 5 shows the size of populations without electricity worldwide. The lowest electrification rates are found in rural areas. In developing countries, the urban electrification rate lies at 90.6% versus 63.2% in rural areas. (The Worldbank, 2012) Table 1 shows the urban, rural and total electrification rate for Cambodia, India & South-Africa.

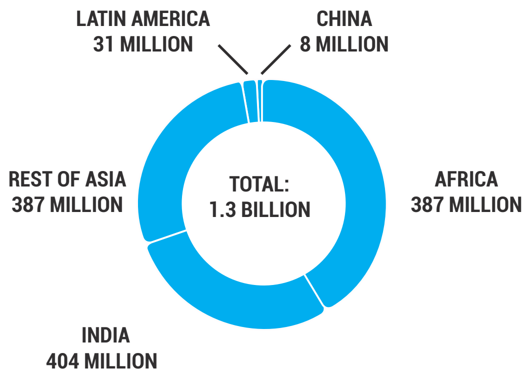


Figure 5: Population without access to electricity. (Gradl & Knobloch, 2011)

Electrification rate	Urban	Rural	Total
Cambodia	91.3%	18.8%	31.1%
India	98.2%	69.7%	78.7%
South-Africa	96.6%	66.9%	85.4%

Table 1: Electrification rates: rural vs. urban environments. (The Worldbank, 2012)

2.1.1 ENERGY POVERTY IN CAMBODIA

As can be seen in Table 1, Cambodia is a country with a low rural electrification rate, even in comparison with other developing countries such as India and South-Africa.

With an electrification rate of only 31% (The Worldbank, 2012) Cambodia is far behind bordering countries Vietnam (99%) and Lao PDR (70%). The rural electrification rate is even lower, with a poor score of 18.8%. With 80% of the population living in these rural areas, it can be estimated that about 8-9 million in rural Cambodia are still lacking proper access to electricity.

The low electrification rate makes Cambodia an interesting country for the research in this thesis.

2.1.2 SERVING ENERGY NEEDS

To serve the energy needs of people at the Base of the Pyramid and prevent the usage of outdated and harmful energy sources, several solutions exist that can improve electricity access. This section makes a comparison between these solutions using the *Multi-tier framework for measuring access to electricity* as developed by Sustainable Energy for All (2013). This framework categorizes access to electricity in 6 tiers. Tier 0 equals no modern energy sources and Tier 5 stands for fully electrified. The Multi-tier framework is a similar of way of framing energy access as the *Electrification ladder*. However, the Multi-Tier Framework focuses on results of energy access, whereas the Electification ladder focuses on the source of energy input. (Tenenbaum, Greacen, Siyambalapitiya, & Knuckles, 2014)

The framework compares the following three drivers for electricity access levels:

- Electricity supply and electricity services;
- Incidence and intensity of access.
- Diversity of supply options;

Table 2 shows an adapted version of the Multi-Tier framework. For sake of simplicity, the following parameters have been left out of the table: affordability, quality and legality.

This section compares the following electricity supply options:

- Pico-solar products;
- SHSs;
- Mini-grid;
- Grid extension.

MULTI-TIER FRAMEWORK FOR MEASURING ACCESS TO ELECTRICITY	TIER 0	TIER 1	TIER 2	TIER 3	TIER 4	TIER 5
		Task lighting, phone charging (or radio)	+ General lighting, television & fan (if needed)	+ any low-power appliances (e.g. food processing, rice cooking)	+ any medium power appliances (e.g fridge, irons, water kettle).	+ any high-power appliances (E.g airconditioners, heaters and electrical cooking.)
ELECTRICITY SUPPLY & INTENSITY						
PEAK AVAILABLE CAPACITY (W)	-	≥4	>50	>200	>2000	>2000
DURATION (HOURS)	-	≥2	≥4	≥8	≥16	≥22
EVENING SUPPLY (HOURS)	-	-	≥2	≥2	≥4	≥4
SUPPLY OPTIONS						
DRY CELL BATTERY	√	√	-	-	-	-
PICO-SOLAR PRODUCTS	√	√	-	-	-	-
RECHARGEABLE BATTERY	√	√	√	-	-	-
SOLAR HOME SYSTEMS	√	√	√	-	-	-
MINI-GRID	√	√	√	√	√	√
GRID	√	√	√	√	√	√

Table 2: Comparing energy solutions using the Multi-tier framework for measuring access to electricity. Adapted from Tenenbaum et al. (2014) and Sustainable Energy for All (2013)

PICO-SOLAR PRODUCTS

Pico-solar products are products and systems that are powered by solar energy, with small solar panels up to 10 Watt-peak [Wp]. (EuroBAT, 2013) Pico-solar products can bring households from Tier 0 up to Tier 1 (see Table 2) , and can act as the first action solving energy poverty. For example, pico-solar lamps can replace kerosene lamps and have a positive impact on health and social life on a household, while costs are low. Pico-solar products are also used to charge small appliances such as mobile phones or radios.

SOLAR HOME SYSTEMS

Solar Home Systems (SHSs) are designed to power a single household. SHSs can serve for basic energy needs. Households can satisfy energy needs up to Tier 2 (see Table 2) with a SHS. Some companies offer SHSs that can power appliances in Tier 3 & 4, but these larger SHSs are not available in all countries and are too expensive for most BoP households. SHSs can also be installed as grid back-up.

SHSs are characterized by high upfront costs and low power capacity, but SHSs are a good solutions when there is no grid available and mini-grids are not an option. Although SHSs cannot power energy heavy appliances, it might be possible to serve growing energy demand in the future. (Duveau, 2015)

MINI-GRIDS

Mini-grids can serve remote villages, by generating electricity in a central source connected to an isolated network distributing electricity to all the attached households. Mini-grids are capable of serving multiple households and delivering energy for productive use. In theory, mini-grids are able to cater for the energy needs up to Tier 3, 4 & 5 (see Table 2).

Mini-grids can be powered by a variety of energy sources, such as wind energy, solar power or fossil fuels. (Gradl & Knobloch, 2011) Just like off-grid systems, mini-grids can be used as grid back-up.

One issue of mini-grids as a concept is that the design has to be adaptable and fit a variety of community sizes, load demands and the availble power resources. (Chattopadhyay, Bazilian, & Lilienthal, 2015)

The fact that mini-grids are communal also has drawbacks. The implementation of mini-grids requires planning and cooperation of the villagers. Overconsumption of one household can lead to power cuts for the whole mini-grid. Hazelton, Bruce, and Macgill (2014) describe some other risks associated with mini-grids. Local entrepreneurs often run the mini-grids and perform maintenance. These operators need to be trained properly to prevent faulty maintenance or operation. Incorrect installation can also lead to performance losses.

ADVANTAGES & DISADVANTAGES	PICO-SOLAR PRODUCTS	SOLAR HOME SYSTEM	MINI-GRID	GRID
ADVANTAGES	• GRID INDEPENDENT • STAND-ALONE • LOW COSTS	• GRID INDEPENDENT • STAND-ALONE • CHEAPER THAN OUTDATED SOURCES	• GRID INDEPENDENT • HIGH CAPACITY • CHEAPER THAN OUTDATED SOURCES	• HIGH CAPACITY • CHEAPER THAN OUTDATED SOURCES
DISADVANTAGES	• ONLY TIER 1, VERY LIMITED CAPACITY	• ONLY TIER 1& 2, LIMITED CAPACITY • HIGH UPFRONT COSTS FOR HOUSEHOLD	• REQUIRES COMMUNAL COOPERATION • HIGH DEVELOPMENT COSTS	• POWER CUTS • VOLTAGE FLUCTUATIONS • HIGH DEVELOPMENT COSTS

Table 3: Advantages and disadvantages of electricity supply options.

GRID EXTENSION

Grid extension seems to be the most obvious option to provide households with electricity, as it can serve high power needs. For households that are closer to the existing grid, it might be the best option. (Gradl & Knobloch, 2011) However, grid extension has one main drawback: for many locations, it is simply not viable to provide grid connection to the rural households. Grid development costs are high and return on investment takes long, especially for dispersed households in rural areas. (Urmee et al., 2016)

Another disadvantage for grid users in developing countries is that the grid is often not well developed. Users suffer from power cuts, and voltage fluctuations can occur. (Sustainable Energy for All, 2013) This may cause damage to appliances. Extending the grid is thus not always the best option to serve energy needs.

2.1.3 WHY SHSs?

The focus of this project will be on SHSs. Grid connection is in many rural areas not realistic, which leaves potential for decentralized systems such as mini-grids and SHSs. SHSs are a fast manner of serving Tier 1 & Tier 2 energy needs for the poor, but dispersion of SHSs is slow due to the high upfront costs and limited energy capacity. The following paragraph (2.2) will analyze the SHS technology. The product analysis has the aim to see what challenge need to be tackled to create SHSs that can provide more power and come at an optimized price. In 2.4, the example of Kamworks is shown. Section 2.5 will show conclusions.

2.2 SOLAR HOME SYSTEMS: THE TECHNOLOGY

This paragraph analyses the technology commonly used in solar home systems. The first section gives an overview of system components. After this, the most frequently used solar panel and battery technologies are discussed. Finally, key technical challenges for solar home system designers are identified.

2.2.1 SOLAR HOME SYSTEM COMPONENTS

A SHS uses a solar panel to generate electricity. This energy can be used to power appliances directly or it can be stored in a battery. Typically, a solar home system consists of:

- Solar panel
- Battery
- Balance of system components (BoS), including:
    - Sockets;
    - Casing;
    - Wires;
    - Switches;
    - Power electronics
        - Charge controller;
        - Maximum Power Point Tracker;

Occasionally, a AC/DC inverter is integrated in the SHS. In this report, an AC/DC inverter is not considered part of a SHS.

Figure 7 presents an overview in block diagram of solar home system components and some common appliances. On the next page, the function of the components are explained. The components are discussed in more detail in the following paragraphs.

Some notes:

1) SHSs can be sold with dedicated appliances. Appliances can therefore also be seen as part of the system. In this project, appliances are not considered part of a solar home system, but will be seen as separate entities.

2) A SHS is a stand-alone system, independent of the grid. However, some SHS have the ability to be attached to the grid. In this manner, the SHS can function as a back-up in case the grid fails.

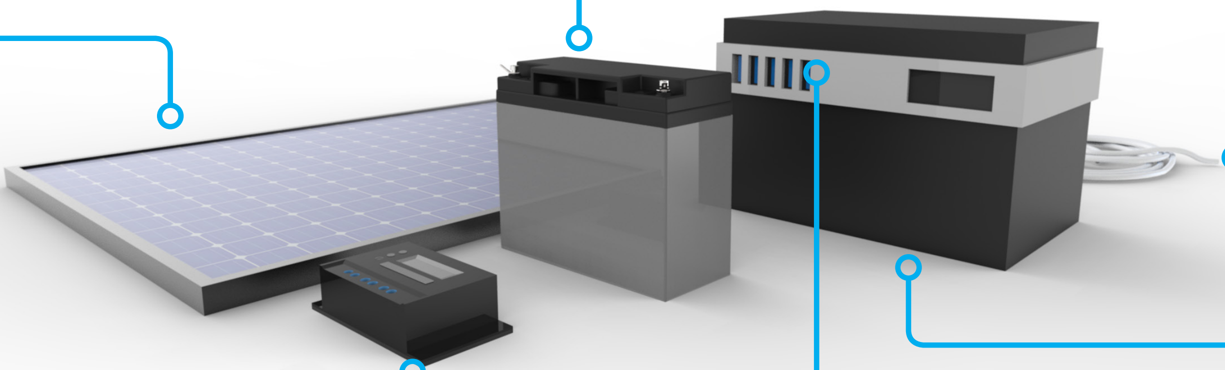
Figure 6: Solar panel (of a SHS) on the roof of a rural Cambodian household.

SOLAR PANEL

- To generate electric energy;

BATTERY

- To store electric energy;
- To supply electric energy;



BALANCE OF SYSTEM COMPONENTS

POWER ELECTRONICS

CHARGE CONTROLLER

- To prevent battery overcharging;
- To prevent battery from deep discharging;
- To control current flow between the battery, solar panel, and the load;
- To provide feedback to user;
- To monitor system performance;
- To optimize the amount of energy generated by solar panel;

OTHER BOS COMPONENTS

SOCKETS

- To connect electric appliances;
- To transfer electricity;

CASING

- To protect components;

CABLES

- To transfer electric energy;
-

SWITCHES

- To enable the user to switch connected lights and appliances on/off.

Figure 7: SHS components.

2.2.2 SOLAR PANELS

A solar home system uses a solar panel to generate electricity. This energy can be used to power appliances directly or it can be stored in a battery. A solar panel (or photovoltaic module/PV module) is constructed by solar cells connected in series. Figure 8 shows a simplified representation of a solar cell.

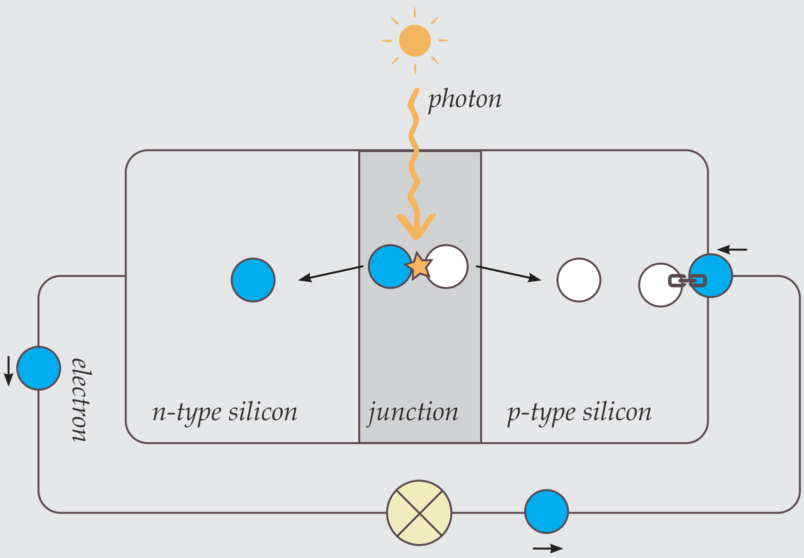
Silicon solar cells generate a voltage of 0.4 - 0.5 volts. This is not enough to charge, for example, a battery. Solar cells are therefore connected in series to increase the voltage level. The solar cells are usually protected by a glass layer on the outside and a metal frame on the edges. Multiple modules together are called a solar array.

The productivity of a solar module is defined in watt peak (Wp). This is peak power that the module is expected to deliver under Standard Test Conditions (STC). Solar panels are available in various configurations. For pico-solar products, solar panels are generally up to 10 Wp. (EuroBAT, 2013) Solar panels for SHSs are generally starting at 10 Wp, ranging to 250 Wp. For reference: a 250 Wp (JA Solar JAM6 60/250-270) panel has the size of 1650 x 991 x 40 mm and weighs 18.2 kg. (JA Solar, 2015)

Figure 9: 250Wp JA Solar panel.

SOLAR CELLS

Solar cells harvest the power of the sun. The majority of the cells on the market are made out of a silicon material. In essence, the material in a solar cell emmits electrons under the influence of photons (radiated by the sun) and creates an electric current. This effect is called the photo-electric effect.



1. A photon strikes the silicicium atom.
2. Electrons are separated with semipermeable membranes.
3. The separated electrons create an electric current.
4. The electrons recombine with holes.

Figure 8: Basic representation of a solar cell. Adapted from Isabella, Jäger, Smets, Swaaij, & Zeman (2016).

2.2.2.1 SOLAR CELL TECHNOLOGY

Solar panels can be made of different cell types. This section describes three common cells: crystalline cells, thin-film cells and third generation cells.

CRYSTALLINE CELLS

Crystalline cells (c-Si) are made of silicon and are made by slicing cylindrical silicon crystals. There are mono- and polycrystalline cell types. The technology is mature and crystalline cells are the most commonly used type of photovoltaic cells. They have high efficiencies and good price levels. Crystalline cells are seen as the first generation cells. (Hankins, 2010)

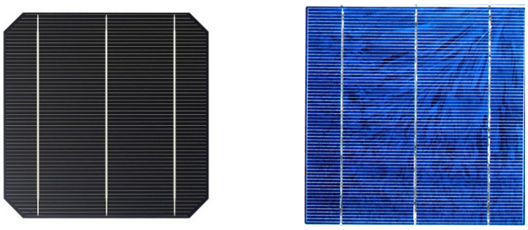


Figure 10: Monocrystalline cell [left] (Sinovoltaics, 2011) and polycrystalline cells [right] (Eco alternative energy, 2013)

THIN-FILM CELLS

Thin film modules are made from non-cystalline material that is placed on e.g. glass or plastic in thin layers. The thin layers allow thin film cells to be flexible and lower in weight. This makes it possible to integrate thin film cells in curved products, for example rooftop elements. The lower weight makes it also possible to place the modules on weaker rooftops. In general, thin film cells have lower efficiencies. Unfortunately, they have not yet become economically viable (Isabella et al., 2016) Thin film cells are known as the second generation photovoltaic cells (Hankins, 2010)

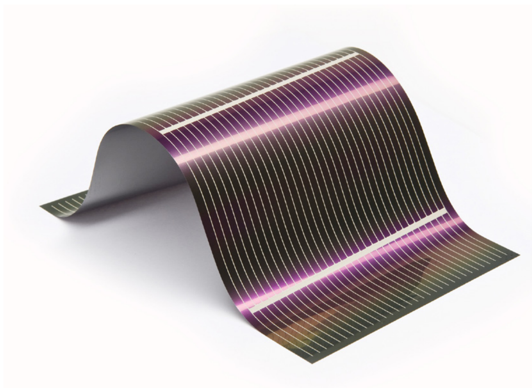


Figure 11: Thin-film solar cells. (Materia, 2016)

THIRD GENERATION CELLS

The name "Third generation cells" refers to several different, emerging technologies, that aim to improve efficiency greatly whilst striving for cost reduction. Several techniques and materials are being developed that are considered as third generation photovoltaics. Note that these technologies are still far out of reach for usage in the base-of-the pyramid environment as prices are still high and technologies are not market-ready yet. (Isabella et al., 2016)

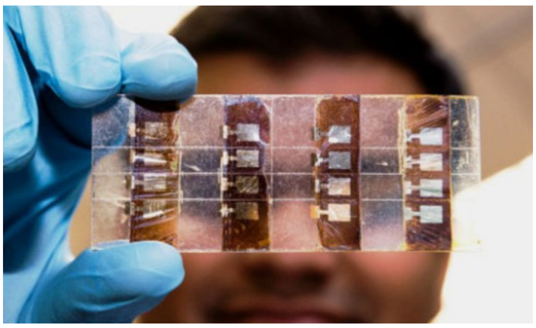


Figure 12: Third generation solar cells: Perovskite cell. (Materia, 2013)

2.2.3 BATTERIES

Rechargeable (solar) batteries are used to store the energy that is generated during the day and not used directly. In this manner, appliances can also work after sunset or during cloudy days when no electricity is generated by the solar panel. Other options than batteries exists (e.g. flywheels, compressed air, pumped water) but are unpractical or economically not feasible for solar home systems. (Hankins, 2010)

When making the choice of battery for a solar home system, an optimum balance should be found of price and performance. Battery characteristics vary per producer and even per battery. There are various characteristics of a battery that have an influence on the battery performance and the battery lifetime. Table 4 presents battery characteristics.

Besides performance characteristics, the following battery characteristics also need to be considered when designing a solar home system:

- Initial costs;
- Total costs of ownership;
- Recycleability;
- Maintenance. Some battery types require frequent maintenance;
- Availability (replacement). Batteries that are locally available are preferred in case of replacement;
- Dimensions and weight.

(Eurobat, 2013; Hankins, 2015; Marioleas, 2016)

BATTERY CHARACTERISTIC	UNIT	DESCRIPTION
STORAGE CAPACITY	Wh	The amount of electrical energy that can be stored in the battery.
ENERGY EFFICIENCY	%	Ratio between the output and input energy of the battery during charging and discharging. (Marioleas, 2016)
BATTERY CYCLING	n	Charging or discharging a battery. The level of (dis) charging is not necessarily fixed. (Narayan, 2016)
CYCLE LIFE	n	The number of cycles a battery has performed until it loses a defined part of its capacity. Typically, end of battery life is defined at 80% of its initial capacity. (Narayan, 2016)
CAPACITY FADING	%	The capacity of the battery decreases after a number of cycles. (Narayan, 2016)
DEPTH OF DISCHARGE (DOD)	%	The percentage of charge that is withdrawn from the battery. 100% DoD equals an empty battery, 0% is a fully charged battery. (Narayan, 2016) The depth of discharge is thus depending on the battery size and the energy consumption.
STATE OF CHARGE (SOC)	%	The percentage of charge that is left in the battery. SoC=100% means that the battery is full.(Narayan, 2016)
C-RATE	C	The rate of charging ora discharging a battery. 1C equals that the battery is fully discharged in 1 hour. For SHS applications, batteries are usually made for C/20 rates. (Narayan, 2016)
TEMPERATURE RANGE		Battery performance is influenced by ambient temperature. Different technologies are differently sensitive. (Marioleas, 2016)
AUTONOMY		The duration the system should function without solar power .
POWER DENSITY	W/m^3	Power per volume.

Table 4: Battery characteristics.

2.2.3.1 BATTERY TYPES

Several types of batteries exist. This section describe the most commonly used battery types.

LEAD-ACID BATTERIES

Lead-acid based batteries are the most commonly used batteries worldwide. It is a proven technology, they are robust, cost-efficient (low costs per kWh), and come in a wide range of sizes and characteristics. (Eurobat, 2013) Drawback of lead based batteries is that the cycle-life is influenced heavily by temperature and DoD. (Marioleas, 2016) Lead based batteries are often used in SHSs.

LITHIUM ION BATTERIES

Lithium-ion battery technologies, such as Li-ion and LiFePo4, have high energy density and high energy efficiency, which is why they are dominating the consumer product market and are the battery of choice for electric vehicle. (Eurobat, 2013) They feature maintenance-free operation and have long lifetimes. Unfortunately, the initial costs are higher than lead-acid batteries. This is why they are less popular for solar home systems.

NICKEL BASED BATTERIES

Nickel based batteries, such as NiMH and NiCD have less issues with deep discharges than Lead-acid batteries. Furthermore, they feature long lifetime and are highly reliable. They are suited for extreme environments. (Eurobat, 2013) Unfortunately, they come at high cost.

BATTERY TYPE	CYCLE LIFETIME (CYCLES)	ADVANTAGES	DISADVANTAGES
Lead-Acid (VRLA)	250-500	Cheap, mature technology.	Low energy and power density. Short lifetime.
NiMH	600-1200	High energy & power density.	High costs.
NiCD	600-2000	High energy & power density.	Toxicity. High costs.
LiFePo4	3000-8500	High efficiency, long lifetime, High energy & power density.	High upfront costs. Not recyclable.
Li-ion	3000-8500	Low sensitivity to deep discharges.	Unsafe for large applications.

Table 5: Comparison of battery types. (Eurobat, 2013; Keane,2014; Marioleas, 2016).

2.2.4 POWER ELECTRONICS

This section will discuss power electronics. In today's SHS, the majority of the systems rely on a charge controller (with or without Maximum Power Point Tracker) for their power electronics. An inverter is optional. However, in the future, power electronics might become more complicated, including features as modularity and interconnectivity (more on these features in chapter 6). This section will briefly discuss a charge controllers, Maximum Power Point Trackers and inverters.

CHARGE CONTROLLERS

A *charge controller* has the task to control the current flow between the solar panel, the battery and the load and prevent damage to the system or appliances. Proper charge controllers are also capable of controlling C-rates. Charge controllers are also used as the point that connects the solar panel, the battery and the load. It can perform system monitoring and provide basic feedback to users, for example by LEDs. Some charge controllers incorporate a Maximum Power Point Tracker. (Hankins, 2010)

Figure 13: Phocos CMLmppt (10 A) solar charge controller. (Phocos, 2015)

MAXIMUM POWER POINT TRACKERS

A *Maximum Power Point Tracker (MPPT)* ensures maximum power output of a solar panel. MPPTs are electronic components dedicated for PV systems.

The voltage at which power is drawn from the module impacts the productivity, and should be matched to the right current for optimal output characteristics. (Hankins, 2010) If a module is directly connected to a load, thus without an MPPT, it will operate at the voltage demanded by the load. By using an MPPT the module can be forced to operate at the maximum power point voltage (V_{mmp}) or current (I_{mmp}). In modern PV systems, the MPPT is often implemented within other system components such as inverters or charge controllers. (Hankins, 2010) A properly designed or chosen MPPT thus ensures maximum performance of solar panels, resulting in a maximum power input by the solar panel.

INVERTERS

Some SHSs are equipped with an inverter, to allow the connection of AC appliances (e.g. televisions). Inverting from DC to AC costs energy which makes an inverter a source of energy losses due to inefficiency. Inverter cables are usually not connected through a charge controller. Therefore, using inverters can cause overusage and drain the batteries below acceptable levels. (Hankins, 2010) This is the reason why some SHS manufacturers do not apply or allow the usage of inverters. (Kamworks, personal communication, 2016)

2.2.5 SYSTEM SIZES

Figure 14 displays a range of SHSs offered by leading SHS companies across the world. Information is retrieved from the respective websites. The largest system offered by the company is indicated.

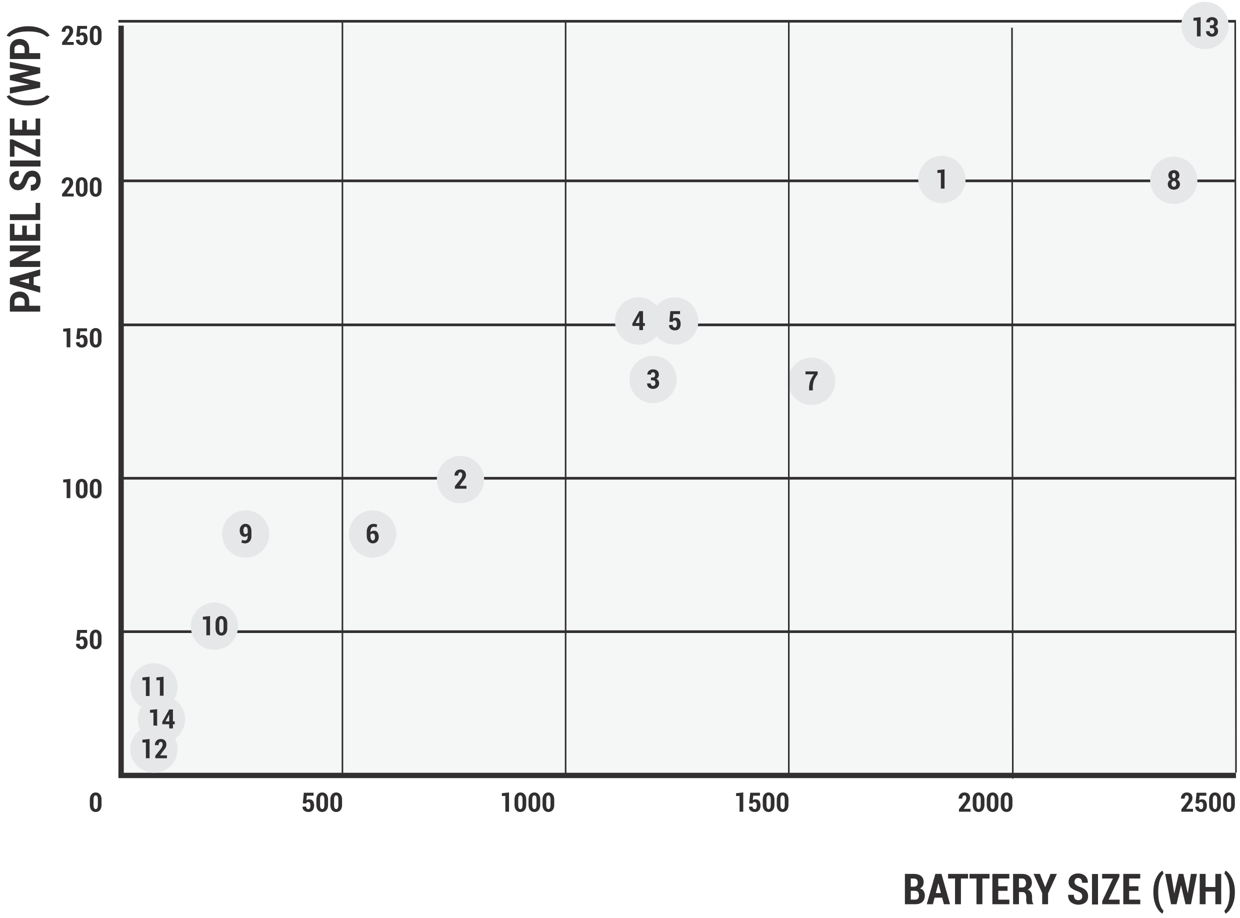


Figure 14: Solar home system sizes. Information is retrieved from the respective websites. The largest system offered (in 2016) by the company is indicated.

CAMBODIA

1. B.N.P.
2. Camsolar
3. Kamworks
4. Lighting Engineering & Solutions Co. Ltd. (LES
5. New Renewable Green Solutions (NRG)
6. Pteah Baitong

ASIA

7. Grameen Shakthi
8. Onergy
9. Rural Spark

SUB-SAHARAN AFRICA

10. BBOXX
11. d.light
12. Fosera
13. Solar Now
14. Solarworks

2.2.6 SYSTEM COSTS

SHSs are a big investment for BoP households. Figure 15 shows an estimation of the total upfront system costs. (Ligthing Global, 2016)

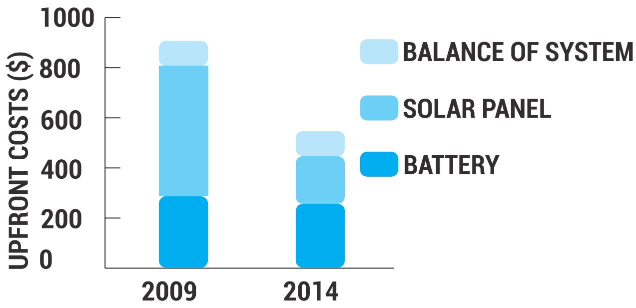


Figure 15: Solar home system cost: 2009 vs 2014. Cost are based on a system suitable for powering standard appliances: a 19" TV, radio and lights. (Lighting Global, 2016).

One can see that prices have dropped, but upfront costs are still high considering the income of the BoP.

The price of batteries dropped slightly, but the main reason are the dropping prices of solar panels. Solar panels used to be the largest cost component of solar home systems. Further pricedrops can be expected. Swanson's law states that costs of silicon PV modules drop by 20% for every doubling of cumulative shipped volume. Where the costs of 1 W were 77$ in 1977, they have dropped to roughly 0.50$/W in 2016. It is expected that costs will go down with 50% every 10 years. (The Economist, 2013; PVinsights.com, 2016)

Battery prices have dropped slightly. Most SHSs have made use of lead-acid batteries so far. (Lighting Global, 2016) Lead-acid batteries are a mature technology and prices have been stable and costs are not expected to change substantially. (Lighting Global, 2016). The growing market for (hybrid) electric cars has stimulated demand for li-ion and LiFePo4 batteries, resulting in dropping prices of these technologies. (McCrone, Usher, Sonntag-O'Brien, Moslener, & Grüning, 2012) Lighting Global (2016) states furthermore that "Battery prices are likely to drop in the coming five years in correlation with electric-vehicle uptake".

Li-ion batteries still come at higher upfront costs than VRLA batteries, but need less replacement as they can perform more cycles. (Marioleas, 2016) This can make li-ion batteries in the long run price competitive, as maintenance costs will drop. As the upfront costs are one of the major barriers for potential SHS users, many SHS companies still opt for lead-acid battery technology.

2.2.7 FUTURE SYSTEMS

Generally speaking, SHSs are increasing in size. This is due to dropping prices of system components. Where in 2003 a SHS of 20 Wp was economically competitive with kerosene lamps, in 2015 this was already 70-80 Wp. (Chattopadhyay et al., 2015)

Mobisol is a SHS company active in Kenya, Rwanda and Tanzania. Thomas Duveau, head of Business Development at Mobisol, states: "*For technical and economic reasons, the grid is unlikely to come to the majority of those 80 percent of rural households that have no access to electricity.*" He sees potential for bigger SHSs. *"When you hear solar home systems next time, think big. They equal real infrastructure, do everything a household needs and are becoming an integral part of every electrification strategy."* Furthermore, he says that a SHS should be able to power all the household needs, including *"LED lights and radio, but also TV, stereo, iron, fan, fridge and small business appliances."* Duveau sees the growing "Middle of the Pyramid", which is the stable and relatively affluent middle class emerging within the BoP in rural settings, as the target group for these bigger SHSs. (Duveau, 2015)

COMPONENTS

For energy storage, it is likely that lead-acid batteries will keep dominating the market of SHSs in the near future. They require low maintenance and come at low upfront costs. However, SHS designers are increasingly making the choice for other technologies. (Lighting Global, 2016) Prices of technologies such as LiFePO4 are decreasing and approaching similar prices as lead-acid batteries. (Global LEAP, 2016) This increases the feasibility of implementation of these battery types within SHSs. When energy density or portability is important, this can be a reason to choose for Lithium-ion or LiFePo4 battery types. (Eurobat, 2013)

Drawback of the lead-acid battery type is its relatively short lifetime. Lithium-Ion or LiFePO4 batteries last longer, but come at a higher upfront price. Implementing Lithium-Ion or LiFePO4 batteries therefore has to come with optimized design and higher upfront investments - a risky business.

Most of the SHSs in the future will rely on crystalline silicon panels. Cheaper and more efficient solar panel technologies are being developed but are far away from entering the SHS market. The conventional technologies are thus likely to dominate the SHSs the upcoming years. Proven technologies are favourable as reliability is key for SHSs.

TRENDS

SHSs are getting smarter. Wireless technologies are being implemented in some SHS for monitoring purposes. These systems can be controlled and monitored on distance. Software can get updated and performance data can be communicated. (Kamworks, 2016) Furthermore, some SHS are equipped with wireless technology for payment services, such as Pay-as-you-go (PAYG). PAYG compromises a set of different technolgies, payment rules and financing structures that enables payment in affordable installments, for example by scratchcards or mobile phone money transfer. In most cases, the SHS company can remotely disable systems if payments are overdue or not done. Several firms that have made the switch from cash sales towards PAYG have indicated a growth in the uptake of their products. (Lighting Global, 2015)

For more trends, see the trend study in Appendix G.

2.2.8 TECHNICAL CHALLENGES

This section will describe the main challenges that SHS are facing currently.

MATCHING ENERGY SUPPLY AND USER DEMAND

The solar panels only generate energy when the sun shines, while in general most energy is consumed at night. This is when lighting is needed and the TV is playing. This mismatch is the reason for a battery as storage. As the battery is one of the main cost components, it is necessary to estimate the mismatch correctly and reduce if possible. With changing demands, different system sizes need to be designed. One of the reasons for unsatisfied customers are undersized SHSs. (Urmee et al., 2016) It is therefore important to keep (future) energy demands in mind.

REDUCING COSTS

SHSs come at high upfront costs. This is for many households a barrier. (Urmee et al., 2016) Decreasing the upfront costs is therefore a important in the challenge to provide more rural households with a SHSs.

IMPROVE DURABILITY AND ASSURE QUALITY

Lowering the price of SHSs and appliances should not affect the quality. The Dutch saying 'Goedkoop is Duurkoop' (freely translated to "buy cheap and waste your money") expresses the problems that will occur if one compromises at quality. Durable products will result in less maintenance and more satisfied consumers. (Global Off-Grid Lighting Association, 2015)

EASING INSTALLATION AND MAINTENANCE

Poorly installed solar panels, oriented in the wrong direction, can result in lower energy yields. Secondly, if a systems fails, the right maintenance should be performed. The installer should have knowledge about the system.

2.3 LOADS: APPLIANCES

This section discusses appliances.At the moment, SHS for the BoP can satisfy energy needs up to Tier 2 (see Table 2). This includes low power-appliances such as LED lighting, TVs, fans and mobile phones.

Table 6 displays the results from a survey of Global LEAP (2015). It is a ranking of appliances by estimated customer demand. The survey is based on expert opinions and was held amongst stakeholders worldwide, that have knowledge about the off-grid market. The survey respondents were asked to rank top 5 household/SME off-grid appliances based on anticipated off-grid consumer demand and clean energy access impact potential for the next 3-5 years. (Global LEAP, 2015)

#	APPLIANCE
1.	LED LIGHTING APPLIANCES
2.	MOBILE CHARGING BANKS
3.	TELEVISIONS
4.	RADIOS
5.	REFRIGERATION
6.	FANS
7.	LAPTOPS
8.	SOLAR WATER PUMPS
9.	TABLETS
10.	RICE COOKERS
11.	CLOTHES IRONS
12.	GRINDERS
13.	HAND POWER TOOLS
14.	HAIR CLIPPERS
15.	SMALL SPEAKER SYSTEMS
16.	RICE MILLS
17.	SEWING MACHINES
18.	SOLDERING IRONS
19.	TEA KETTLES

Table 6: Ranking of appliances by estimated consumer demand, based on expert opinions from industry, policy, and development stakeholders all over the world. (Global LEAP, 2015)

Many of the listed appliances in Table 6 require more energy than SHS can supply. This makes it impossible for households to use them. The challenge to match energy supply and demand (see 1.4) is therefore also a challenge that should be approach from the demand side. The next section will discuss how appliances can be designed so that the appliances will better meet the needs of the user.

2.3.1 APPLIANCE REQUIREMENTS

A SHS delivers the best performance when appliances are used that are specifically designed for off-grid customers. On a technical level, appliances should be designed to function at the provided voltage (usually 12V). Furthermore, appliances should be energy efficient, since SHSs have a limited capacity. Next to this, appliances should switch off or in stand-by mode when are not in use, so that zero energy is consumed. Energy efficiency is important, but should not affect the value of a product by delivering lower quality. (Global LEAP, 2016)

Besides these technical requirements, there are various other design parameters that can make or break the adoption of a product. Products should be durable and reliable, as servicing might be difficult due to a limited supply chain and limited repair expertise. In general, costs should be held low to make the appliances affordable.

Where physical dimensions can be an important aspect in the choice of a battery, it might not matter to rural households. Lightweight and small lithium-ion batteries are important for smartphones as they need to be carried, but for rural households it is usually not a problem to make space for a big lead-acid battery. Physical dimensions of appliances can also be less of importance for rural households. For example, fridges: more isolation results in bigger fridges, but will lead to higher efficiencies. On the other hand, bigger refrigerators result in higher cost of production and reduce portability. (Global LEAP, 2016)

Appliances that are made for the off-grid market are available on the world market. However, households generally do not have access to the "world market". They have to deal with appliances that are available.

SYSTEM	TOTAL DAILY LOAD (WH/DAY)	TOTAL CONNECTED LOAD (W)	PV MODULE SIZE (WP)	BATTERY SIZE (AH)
2009 – SHS WITH STANDARD APPLIANCES	354	88	123	126
2014 – SHS WITH STANDARD APPLIANCES	349	86	121	125
2014 – SHS WITH OFF-GRID APPLIANCES	77	18	27	28

Table 7: Comparison of standard appliances vs. off-grid appliances. (Phadke et al., 2016) System size is based on a system powering lighting (600 lumen, 4 hours/day), a TV (19 inch colour, 4 hours), radio (small portable radio, 6 hours) and charging a basic mobile phone (1x per day).

2.3.2 OFF-GRID APPLIANCES

Multiple manufacturers are working on appliances dedicated for the off-grid, BoP market. These appliances are efficient and work on DC power, resulting in lower energy consumptions. In the remainder of this report, the term *off-grid appliances* is used for these types of appliances.

Both batteries as well as solar panels work on DC currents. However, AC appliances have become the standard worldwide since electricity grids work on alternating currents. Converting DC to AC leads to significant, unwanted losses. (Phadke et al., 2015) Phadke et al. (2015) have made an estimation based on modeled data of the impact that off-grid appliances can have on SHS specifications. This is based on a system powering lighting (600 lumen, 4 hours/day), a TV (19 inch colour, 4 hours), radio (small portable radio, 6 hours) and charging a basic mobile phone (1x per day). See Table 7.

There is a slight difference in the Total daily load between 2009 and 2014 when using standard appliances. A similar sized SHS is necesarry to serve these needs. When using off-grid appliances though, the total daily load is reduced significantly to 77 Wh/day. This means that the same energy services can be delivered by a smaller, cheaper system. This shows the importance of adoption of off-grid DC appliances specifically targeted at the BoP.

The following sections give a short overview of televisions, fans and refrigerators, accompanied with some examples in Figure 16. The section is derived from the extensive research done by Global LEAP (2016).

Table 8 on page 41 shows examples of appliances and their power ratings. A comparison is made between standard and off-grid appliances.

TELEVISIONS

Recent technological advancements have made TVs compatible with SHSs. Compared to old CRT televisions, LED & LCD televisions can be 3x as efficient. However, old and second-hand CRT televisions are still dominating the rural market. Suitable TVs are around 15-23 inch and consume around 10-20 W, and are expected to become even more efficient. TVs are in some communities seen as a status symbol. Besides entertainment and communications, TVs can also serve to spread social messages through TV shows or provide education and information. (Global LEAP, 2016)

NIWA SOLAR LED TV
23.6"
15 W
12V

FANS

Fans are an efficient way of cooling a house. Airconditioners and air coolers consume much more energy and are therefore not suited for SHSs. Several types of fans are available for the off-grid market: ceiling fans, pedestal fans and table fans, all in different sizes available. (Global LEAP, 2016)

The off-grid fan market is well-served, but there are still design improvements needed in order to make fans more energy efficient.

Fans are popular in South Asia as the climate is hot and humid. The comfort that fans supply can increase productivity. (Global LEAP, 2016)

ME-103-DC
147.3 m3/min air delivery
35 W
12/14V

REFRIGERATORS

DC refrigerators still have a gap to bridge and are at the moment hardly compatible with SHSs. Refrigerators need power all day, as food can go bad when not cooled. This means that the system should not run out of power. Furthermore, Refrigerators require large amounts of energy initially to cool to the right temperature. Power cuts are thus unwanted.

In comparison to appliances currently used with SHSs, refrigerators consume a lot more energy daily. Energy efficient refrigerators do exist, but come at high upfront costs. However, it is likely that products with better efficiency will become available in the future (Global LEAP, 2016) Mass production could reduce prices in order to improve viability. (Global LEAP, 2016)

PHOCOS FR165R
165 liters
40 W
168 Wh/24 h @ 32°C:
12/24V
Cooling temperature: 2-5 °C

Figure 16: Examples of DC appliances target at the off-grid market

	NAME	POWER RATING	NOTES	REFERENCE
LIGHTS	IKEA RYET LED E27	2.8 W	200 LUMEN	[3]
	FOSERA LAMP 200*	1.56 W	180 LUMEN	[4]
FAN	AEG VL 5529	30 W		[8]
	NIWA ECO AIR 9*	6		[1]
TV	CRT 17"	80 W	+10 WATT CONSUMPTION FOR DTV	[11]
	NIWA SOLAR LED TV 15.6"*	10 W	+10 WATT CONSUMPTION FOR DTV	[1]
PHONE	IPHONE 7 PLUS	2900 MAH / CHARGE		[12]
	NOKIA 3310	1200 MAH / CHARGE		[12]
RADIO	LENCO SCD-24	9 W		[9]
	RADIO FOSERA*	1 W		[2]
RICE	ARENDO	400 W	1.0 L	[7]
	MINI RICE COOKER*	100 W	0.9 L	[10]
WATER	OKUK BKK-138	1000 W	0.8 L	[5]
	SOLAR DC KETTLE SE520*	400 W	0.8 L	[2]
IRON	BLACK & DECKER F150	1000 W		[6]
	SOLAR DC POWER IRON SL100S*	150 W		[2]
FRIDGE	SOLAR CHILL*	500 WH/24H		[2]
	PHOCOS FR165R*	@ 32°C: 168 WH/24 H		[2]

*Table 8: Examples of appliances in demand by SHS users. A comparison is made between standard appliances and off-grid appliances (indicated with *).*

REFERENCES

[1] (Global LEAP, 2016)
[2] (Gesellschaft für Internationale Zusammenarbeit, 2016)
[3] (Ikea, 2017)
[4] (Global LEAP, 2016)
[5] (Amazon, 2017)
[6] (Amazon, 2017)
[7] (Amazon, 2017)
[8] (Amazon, 2017)
[9] (Amazon, 2017)
[10] (Alibaba, 2017)
[11] (Hedge, 2003)
[12] (Phone arena, 2017)

Figure 17: House in rural Cambodia.

2.4 CASE: KAMWORKS, LTD. - CAMBODIA.

Only 1 on 5 persons on the country side in Cambodia has access to electricity. (The Worldbank, 2012) The contrast between urban and rural Cambodia is big. Roughly 80% of the people does not live in urbanized environment. (The Worldbank, 2012) Most people are in the countryside are self-sufficient and rely on agriculture. Working on the land in the sun is hard and exhausting. Chances for a more luxurious life are limited. Besides farming, there are little jobs on the countryside. Some people can find a job in hotels or micro-finance institutes. There is simply no choice for them, as there are no jobs and people are less educated.

Fortunately, the grid is expanding rapidly. The grid expansion is funded by Japanese, Australian and French organizations. The government has two major goals for rural electrification:

1) 100% of the villages should have access to electricity by 2020;

2) 70% of the households should have access to electricity by 2030. (Department of the Rural Electrification Fund, 2016)

When the grid reaches the village, it is seen as "having access to electricity". For this reason, some villages are "grid connected" without a single household having grid connection. Whether or not the government is meeting these targets, 30% of the households remain without electricity access by 2030. (Khim, personal communication , 2016) This is roughly 1 million households.

"IN 2030, IT MIGHT BE POSSIBLE FOR PEOPLE TO LIVE ON MARS, BUT 30% OF THE HOUSEHOLDS WILL STILL NOT HAVE ELECTRICITY IN CAMBODIA."
- BUNLENE KHIM, CAMSOLAR

Roughly 20-30 companies are active in the SHS market in Cambodia. (Bun, personal communication, 2016) Some of them design their own systems, some retail systems of other companies. The SHS market in Cambodia is a push-market. SHS suppliers have their own sales force that promotes their systems. The SHS suppliers have a set of provinces at which they target their product.

SHS companies in Cambodia face 4 major challenges:

- Costs: Upfront costs are still high for rural households, who often have an irregular income. (Tun, personal communication, 2016)
- Reliabilibity: Many people have heard stories about companies selling bad systems. This has polluted the market. Most people already know about solar energy, but need to be convinced about the trustworthiness of the systems due to bad experiences in the past. (Deloof, personal communication , 2016)
- Grid competition: The unpredictability of the coming grid can be a reason for people not to buy a solar home system.
- Sales: Selling solar home systems is resource intensive.

Kamworks Ltd. is active in the Cambodian SHS market. Kamwork's mission is to provide affordable sustainable energy to low income households by products as SHSs and pico-solar lamps. (Rijke, Diehl, & Schoormans, 2009) Kamworks' team is a mixture of expats and young Khmer. Kamworks' creates jobs for the locals in their design team, at the production facilities and in the sales field. Kamworks started off with the Moonlight, a small lamp powered by the sun. The SHS is based on a graduation project (Van Diessen, 2008) and has evolved over the years to the product as it is today. Kamworks' is offering 70 Wp, 100 Wp and a 130 Wp SHSs. The 100 Wp SHS is powered by a DuPont DA095-A5 solar panel and the energy is stored in a 12 V, 100Ah battery. The most recent systems are equipped with a GSMA pay-as-you-go unit. The lights are connected at the back of the box. The back of the box also hosts the connector for the solar panel. Three 12V cigarette lighter sockets at the front allow the connection of appliances. Kamworks gives adapters for USB and 5V connectors.

For more information about Cambodia, see Appendix A. For more information on the Cambodian SHS market, see Appendix B. For more a more detailed analysis on Kamworks and the Kamworks 100 Wp SHS, see Appendix C.

Figure 18: Living room of rural Cambodian house, with Kamworks' battery box (yellow) in the middle.

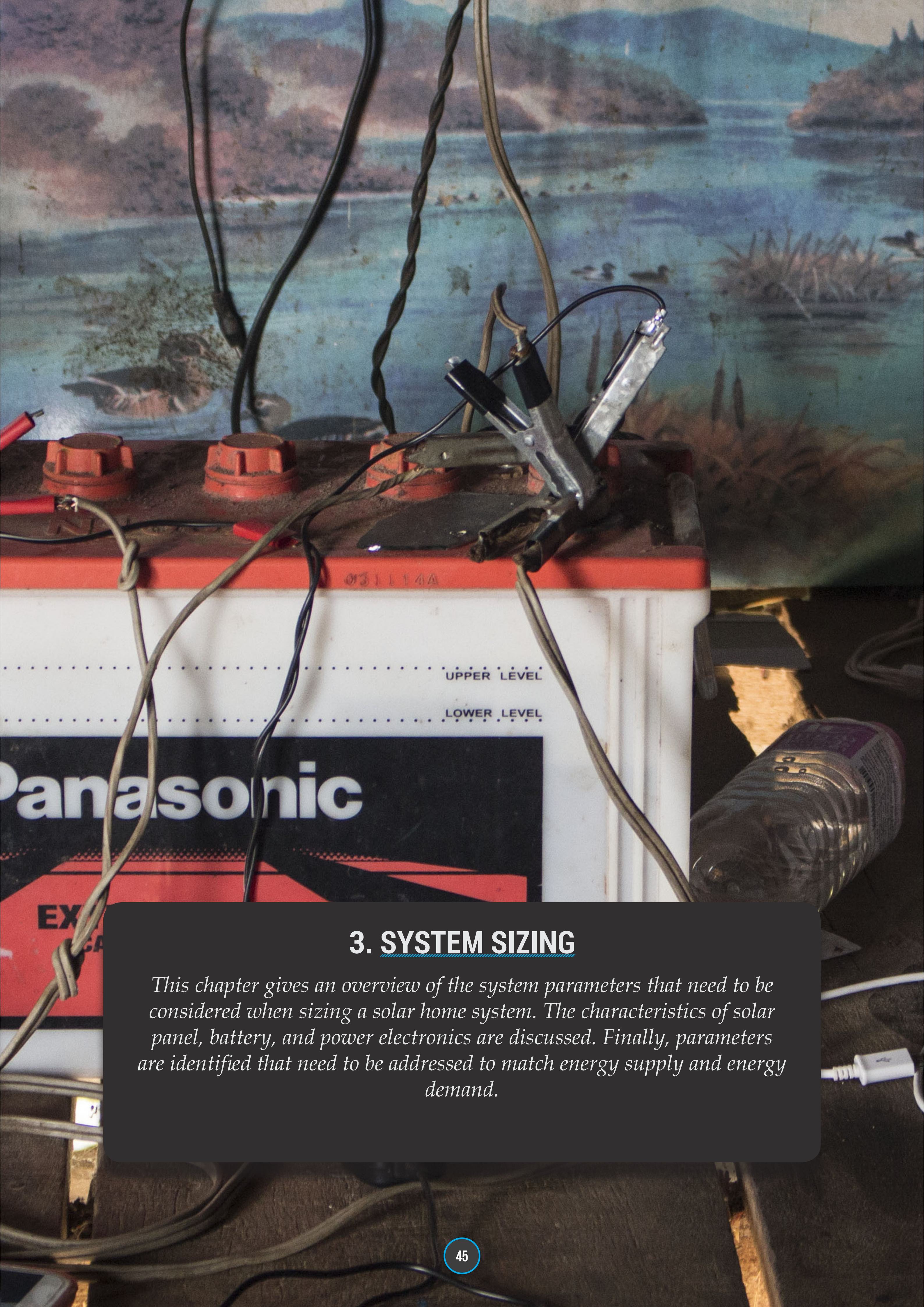
2.5 CONCLUSION

In this chapter, SHSs have been analyzed. The large population that remains unelectrified can well be served by SHSs. SHSs can help people using outdated energy sources to the first tiers of electrification access. This has social and economical benefits and is good for health and the environment. On short term, this is the best option for rural households. SHSs have contributed in solving energy poverty, but there is still a long way to go. The SHS market is rapidly developing with a lot of potential customers. In the future, SHSs will need to cater for high power appliances. The adoption of SHSs is, unfortunately, hampered by high upfront costs and limited capacity. Increasing system size at optimized costs should lower these barriers.

Matching energy supply and demand is crucial in tackling this challenge, as it will improve user satisfaction and reduce system costs. By sizing a system according to user needs, the user will experience less problems with their system. Furthermore, the user will be able to power more appliances. Secondly, by optimizing the system size according to user needs, the costs of the system can be reduced. Optimizing system size will also result in less maintenance.

The challenge to match energy supply and demand is also a challenge that should be approached from the demand side. Using off-grid appliances instead of standard appliances can already make a difference in system size, thus reducing system costs.

The next chapter will take a deeper look into system performance and describes the system parameters that should be considered when sizing a SHS in order to match user needs.



3. SYSTEM SIZING

This chapter gives an overview of the system parameters that need to be considered when sizing a solar home system. The characteristics of solar panel, battery, and power electronics are discussed. Finally, parameters are identified that need to be addressed to match energy supply and energy demand.

3.1 SIZING A SOLAR HOME SYSTEM

The challenges that will be adressed during the project is to match energy supply and energy demand. This chapter will go deeper into the technical details that are related to system sizing. The chapter adresses the following research question:

Q1. What system parameters are of importance for SHS sizing?

ENERGY FLOWS

The solar home system is build up by three blocks:

- Solar panel (discussed in 3.1.2);
- Battery (discussed in 3.1.3);
- Power electronics (discussed in 3.1.4).

These parts are responsible for the **energy supply.**

Attached to the solar home sytem are the loads. The load includes all the appliances connected to the SHS. This is the **energy demand** (discussed in 3.1.1). In this report, the loads are considered separately from the SHS.

Figure 19 shows energy flows through the system in a diagram. The following points describe how the energy generated by a solar panel is used:

- When the energy demand is equal to the energy generated by the solar panel, the energy can be consumed directly.
- When the energy demand by user is lower than the solar power input, the battery will be charged with the surplus of energy.
- When the energy demand by user is higher than the solar power input, the battery will have to supply power.
- When there is no demand for energy, but energy is generated by the solar panel and the battery is fully charged, the generated energy by solar panel is wasted.

EXISTING MODELS

Several models and calculation tools exist that support SHS designers in calculating the system size. (Homer Energy, 2017; Hankins, 2010; Leonics, 2013) The tools have the goal to support SHSs in the design process. The following section is an example of a process of steps that need to be taken when sizing a SHS.

First, it is necessary to calculate the daily energy demand. After this, the solar panel size necessary to generate the demanded energy can be calculated. When this is done, the battery size can be determined. This can be done by calculating how much energy can not be provided by the solar panel directly. Multiply this by the amount of days the system has to run without solar power. This determines the battery size. In the last step, the right power electronics should be chosen. (Leonics, 2013; Hankins, 2010)

This chapter will describe what system parameters influence the sizing in more detail, to get a better understanding of system sizing. Furthermore, this chapter explains why it is important to design a system with user needs in mind.

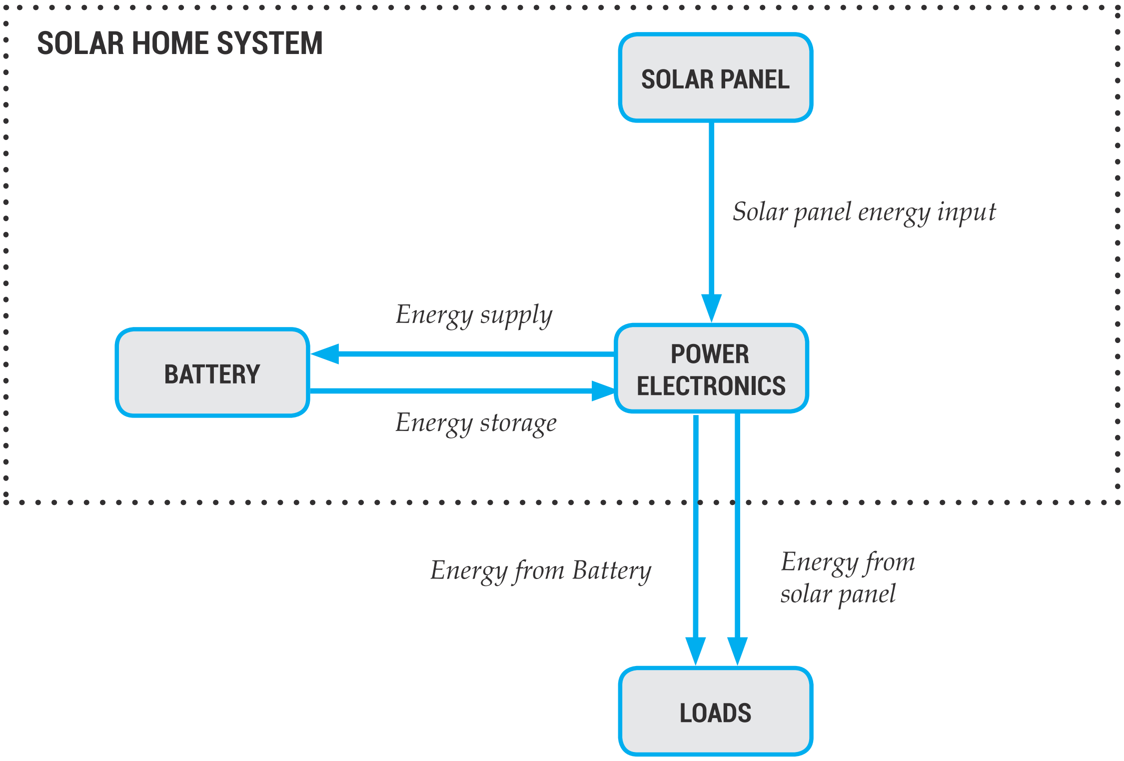


Figure 19: Energy flow diagram in solar home system. (Narayan, 2016)

3.1.1 ENERGY DEMAND: LOADS

For the developed world, several studies have been performed to analyse energy usage. One of the models developed is the *Behavioural model of residential energy use* by Van Raaij and Verhallen (1983), see Figure 22. The *Behavioural model of residential energy use* is made for residential energy consumption in the developed world. The model was initially made for energy-conscious behaviour studies. This model has to be adapted when applied to the SHS and the context.

For the SHS context, most interesting in the *Behavioural model of residential energy use* are the parts that directly influence the energy use. Especially the blocks *Household lifestyle* and *Characteristics of home and appliances* are interesting, as they directly influence the energy related behaviour (and thus energy use). *Climate, season and weather* might be interesting as it directly influences energy use, but this is true mainly for households with a heater or airconditioner. It is not possible to power airconditioners and heaters with today's SHSs, but e.g. a fan is possible.

Figure 21 is a simplification of the*Behavioural model of residential energy use,* suited for application in SHS sizing calculations. It is a diagram of the variables that contribute to the energy demand of a household using a solar home system. The main influences on the energy demand of a household using a solar home system are:

- Type of appliance;
    - Power rating of appliances;
    - Efficiency of appliances;
- Energy consumption patterns.

3.1.1.1 LOAD PROFILE

The electric energy consumption can be expressed in a *load profile*. The load profile is a graphical expression of the demanded energy over a specific period. The load profile is an important factor in determining a balanced, optimal system size for an SHS, as it influences panel size (see and battery capacity

3.1.1.2 LACK OF KNOWLEDGE

There is a need for more knowledge on energy demand. In the report *The State of the Global Off-Grid Appliance Market*: Global LEAP (2016) states,

"There has been little investigation into the real or specific usage patterns of off-grid consumers, leaving manufacturers unsure of consumer preferences and quality requirements."

Next to a lack of information about system usage and performance, there is also a lack of knowledge on current consumer demands. In the same report The State of the Global Off-Grid Appliance Market Global LEAP (2016) states, that there is a "*...lack of robustground-level consumer data...*" on the needs of off-grid consumers, including demand for off-grid appliances. Furthermore, they identify the problem of *"limited information on off-grid appliance products themselves, including product performance"*. These statements were made looking at the off-grid appliance market. Since appliances have a direct impact on energy demand, knowing more about appliance demands and preferences will lead to better understanding of energy demands. The changing market of appliances that can be used with solar home systems (Global LEAP, 2016) and the rising energy demand (Duveau, 2015) are a reason to investigate into the future needs of users.

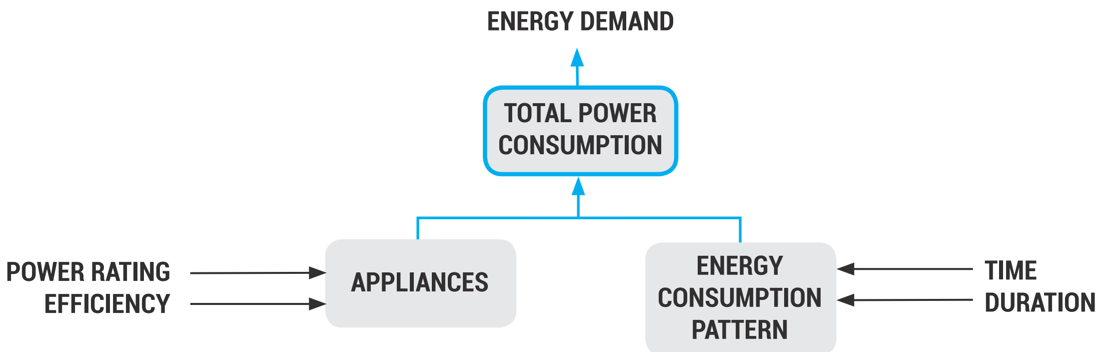


Figure 21: Energy demand in a SHS.

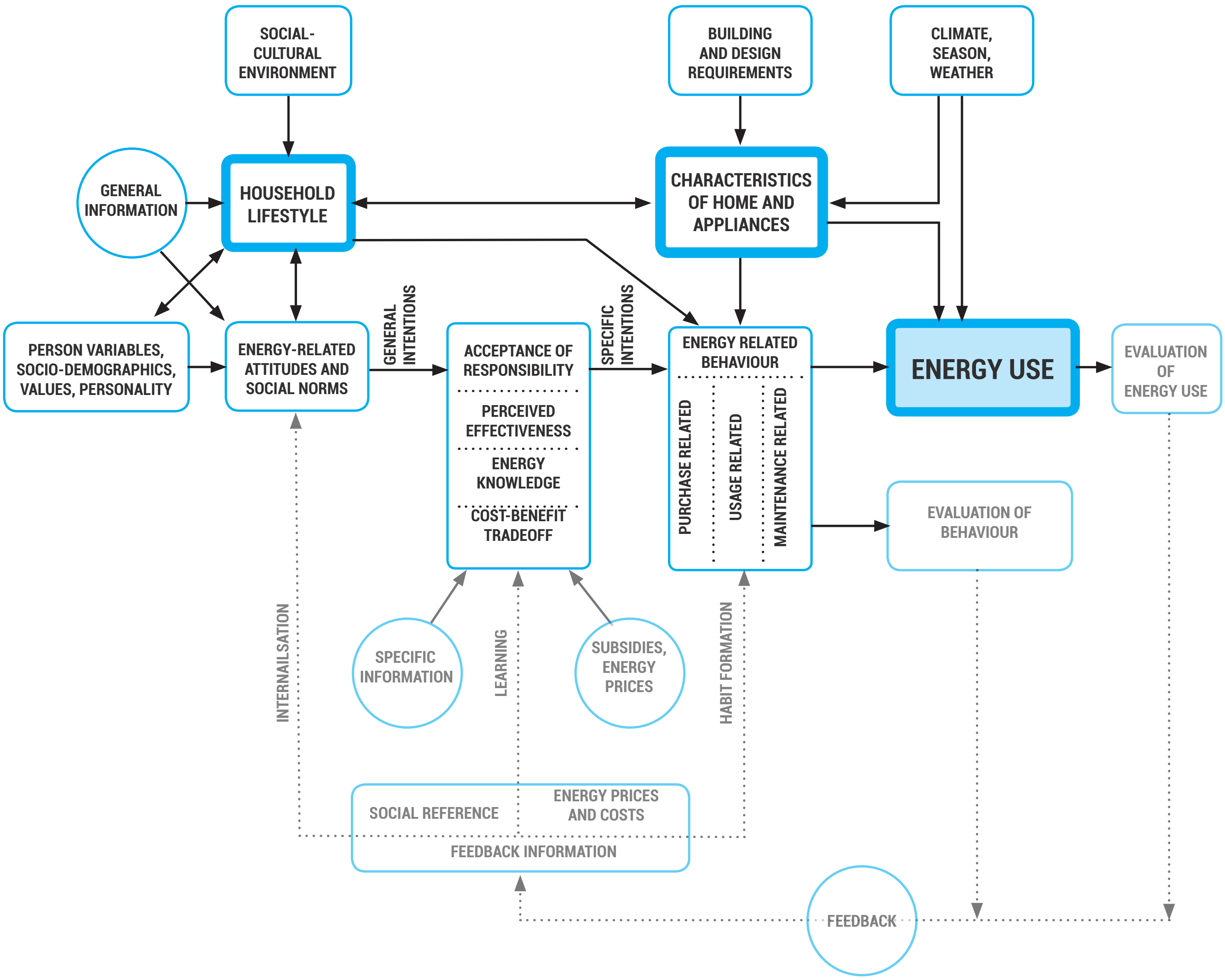


Figure 22: The behavioural model of residential energy use, Van Raaij, W. F., & Verhallen, T. M. M. (1983) Interesting blocks for solar home system loads are highlighted.

3.1.2 SOLAR PANEL

This section will discuss the parameters that influence performance of a solar panel. The solar panel in a solar home system has one function:

- *To generate electric energy;*

3.1.2.1 SOLAR PANEL PRODUCTIVITY

The productivity of a solar module is defined in watt peak (Wp). This is peak power that the module is expected to deliver under Standard Test Conditions (STC). The power output of a solar panel is variable. Some important characteristics that influence the output of a solar panel are:

- the amount of solar cells;
- the total surface area of the cells;
- the placement of the solar panel;
    - Amount of solar radiation (irradiance);
    - Orientation of panel;
- the efficiency of the solar panel.
    - Type of solar cells;
    - Module operating temperature;

(Hankins, 2010; Narayan, 2016; Isabella et al., 2016)

Since the solar panel is responsible for generating the energy, it is important to consider the expected energy demand and choose an appropriate panel size.

Figure 23 shows the variables that influence the solar panel energy input into a solar home system.

3.1.2.2 SOLAR POWER THROUGHOUT THE DAY

Figure 24 presents an example of solar power input by a solar panel throughout the day. Most of the energy is generated around noon.

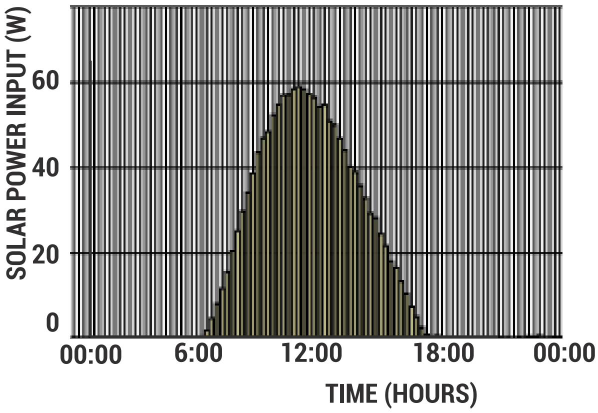


Figure 24: Example of solar power input by a solar panel throughout the day.

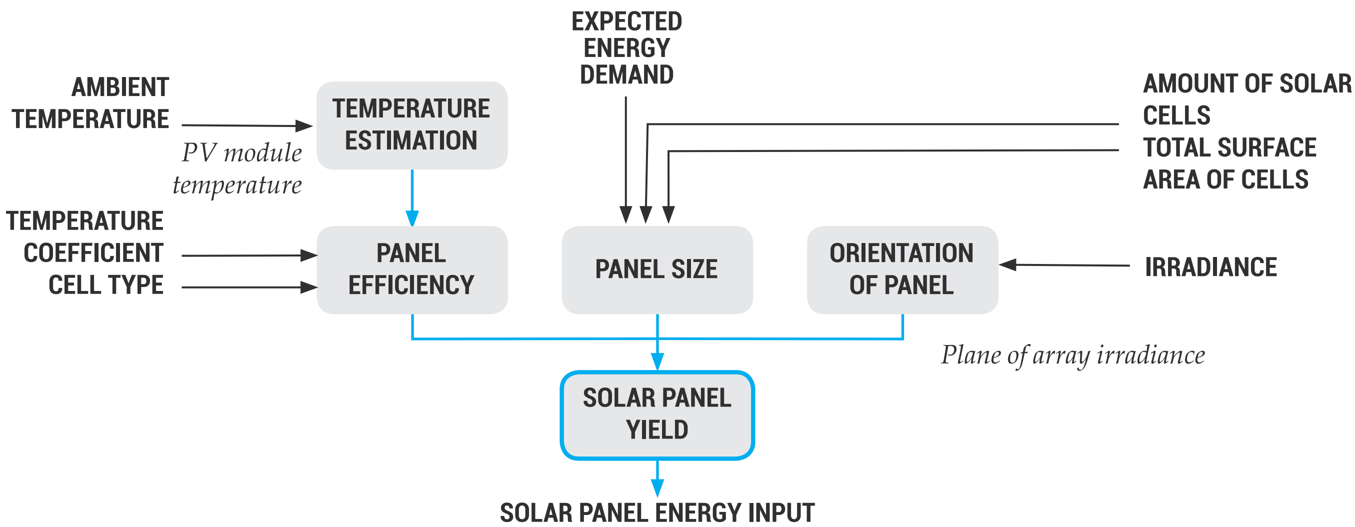


Figure 23: Solar panel energy input parameters.

3.1.3 BATTERY

The battery in a solar home system has two functions:

- *To store electric energy;*
- *To supply electric energy;*

When making the choice of battery for a solar home system, an optimum balance should be found of price and performance. Good batteries are expensive and lifetime is limited. A good match should be found between the expected usage and circumstances. Choosing the right type of battery is therefore crucial for the performance of the solar home system. The important battery characteristics that play a role when sizing a SHS, are discussed in 2.2.3. Figure 26 shows a diagram that displays how these battery characteristics influence battery performance.

3.1.3.1 EFFECT OF DEPTH OF DISCHARGE ON BATTERY LIFETIME

The Depth of Discharge (DoD) is the percentage of charge that is withdrawn from the battery per cycle. The DoD influences the lifetime of a battery. The various battery technologies have a different sensitivity to Depth of Discharge. In Figure 25, a graph is presented displaying the effects of DoD on a Ritar RA12-100SD battery, as used in Kamworks systems. When the battery is discharged to 100% everyday, the battery will last only ~300 cycles (days). When it is discharged for 50% only, the lifetime is ~800 cycles, more than doubled. As a SHS designer, the choice could be made to select a battery that suffices the demand while only discharging to 50% (instead of 100%). This will lead to higher upfront costs (as the battery size needs to be larger), but the battery will last longer and needs to be replaced later and less often. This will eventually be cheaper.

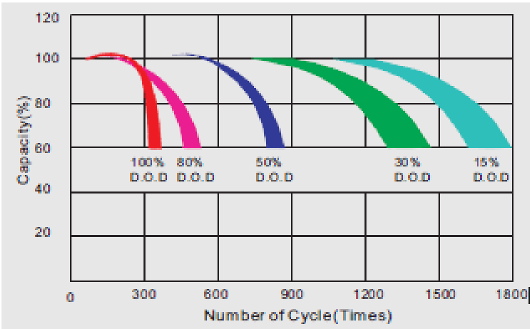


Figure 25: Effect of DoD on battery lifetime for a lead-acid battery. The battery is a Ritar RA12-100SD 12V 100 Ah, used in Kamworks systems. (Ritar, 2016)

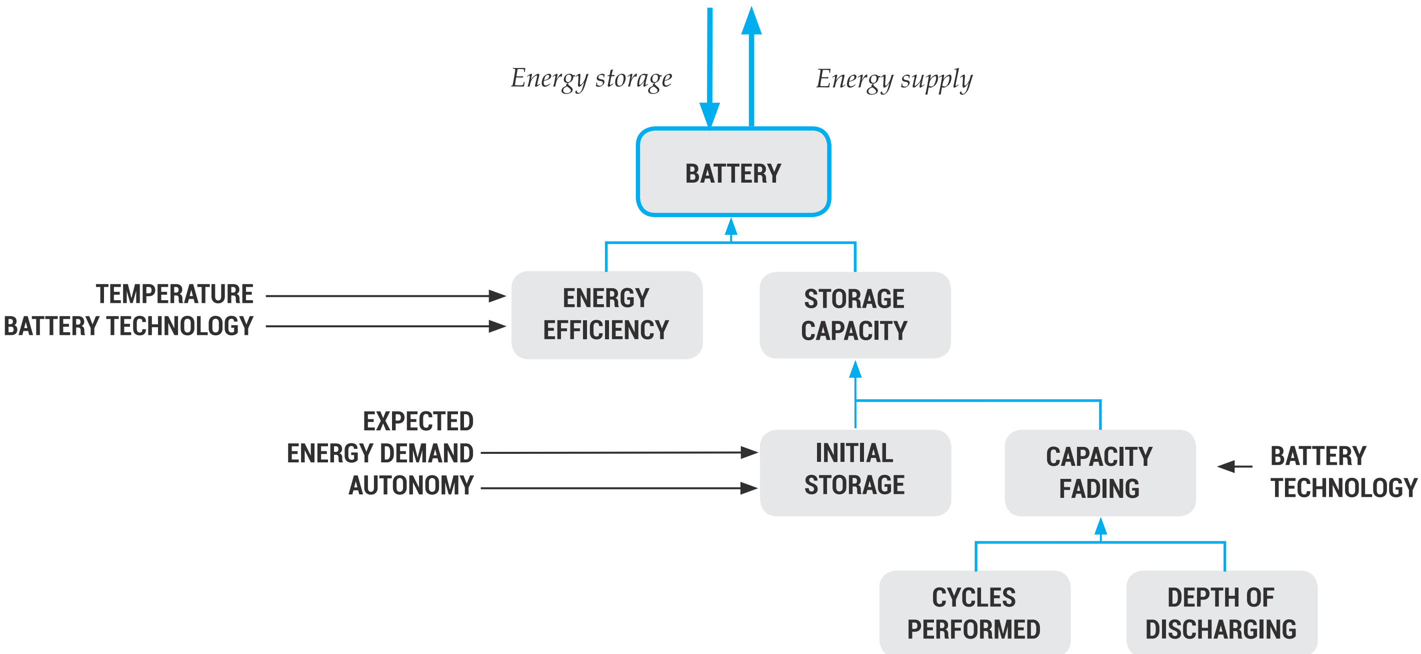


Figure 26: Battery performance parameters.

3.1.3.2 SIZING THE BATTERY

As listed in 2.2.3, there are multiple parameters influencing battery costs. As part of the overarching PhD-project, Marioleas (2016) has performed a study on the costs of batteries over the life cycle of a solar home system. The study assumed a solar home system lifetime of 20 years of operation, with an average daily consumption by the SHS user of 300 Wh. Marioleas (2016) has integrated the following costs in his calculations:

- upfront cost of battery;
- maintenance costs of battery;
- replacement costs of battery.

Figure 27 displays the estimated total costs of the battery for a solar home system that is 20 years in use.

By providing an oversized battery at an early stage, the DoD will be lower. With a reduced average DoD, the lifetime is extended significantly and the battery can be used more cycles. A reduced DoD directly also means that the battery has to be replaced less often. Replacement costs later in the life of SHS will be lower, but upfront costs are higher. This means that the right balance needs to be found to prevent excessive upfront costs versus excessive replacement costs.

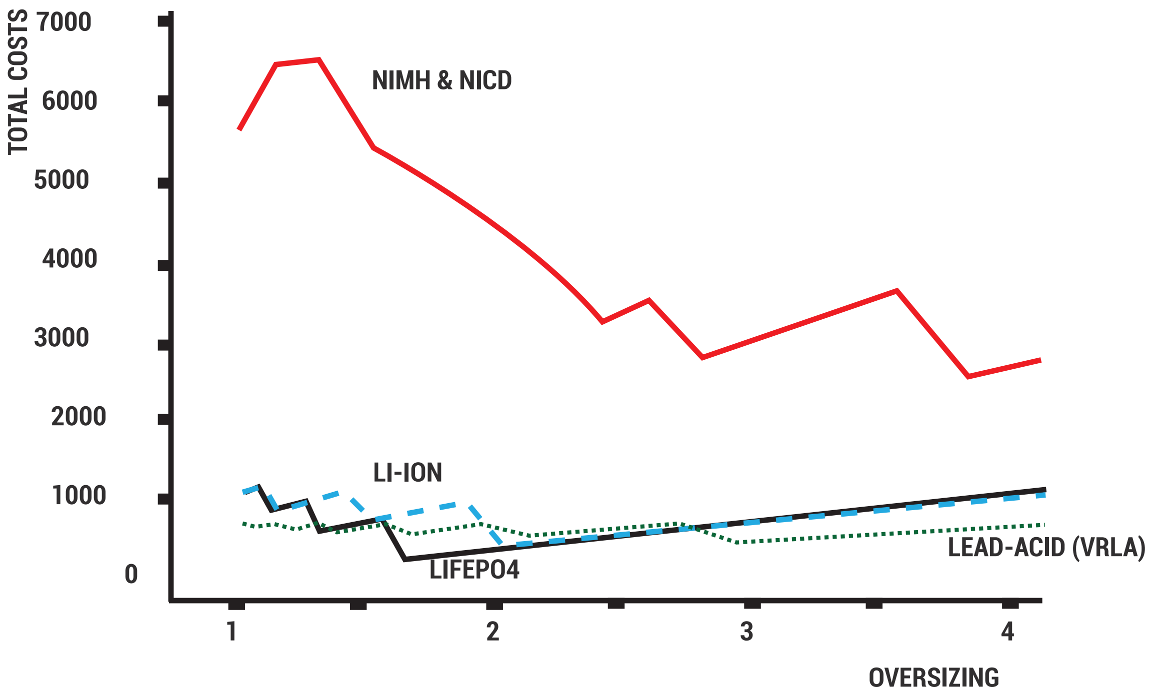


Figure 27: Total estimated battery costs for a SHS over 20 years of usage. Upfront, maintenance and replacement costs are included. The daily energy consumption by SHS user as used in the calculations is 300 Wh/day. (Marioleas, 2016).

3.1.4 POWER ELECTRONICS

This section will go into more detail on the power electronics that control the energy flows in the SHS. As discussed in 2.2.4, the majority of SHSs have a charge controller as the only component of the power electronics. The charge controller has an important role in optimizing the lifetime of the battery. The functions of the charge controller, as described in 2.2.4:

- *To prevent battery overcharging;*
- *To prevent battery from deep discharging;*
- *To control power flow between the battery, solar panel, and the load;*
- *To provide feedback to user;*
- *To monitor system performance.*
- *To optimize the amount of power generated by solar panel;*

The charge controller thus manages the flows of energy. Generically speaking, the main requirement for power electronics is that they should ensure electrical compatibility with loads, battery and solar panel. When performed correctly, it can increase the lifetime of the battery. For example, it can control the power flow such that the solar panel directly powers the load. This instead of first charging the battery and then the battery powering the load. Furthermore, it can prevent overcharging and deep discharges, which can damage the battery and shorten the lifetime.

There is a wide variety of choices for the charge controllers. Not all charge controllers are equipped with a MPPT.

CHARGE CONTROLLER FEATURES	DESCRIPTION
SYSTEM VOLTAGE	The charge controller must comply with the voltage of the system (e.g. 12V, 24V or 48V) (Urmee et al., 2016)
LOAD INPUT	The load input by solar panel should not exceed the rated load input of charge controller. (Urmee et al., 2016)
LOAD OUTPUT	The rated load output of a charge controller should match the sum of loads. (Urmee et al., 2016)
FUSE	Fuses or circuit breakers should be installed between charge controller, battery and loads to protect from short circuits. (Hankins, 2010)
LOW VOLTAGE DISCONNECT	If the battery drops below a predetermined level, the charge controller disconnects the loads automatically. (Hankins, 2010)
BATTERY TECHNOLOGY	The charge controller should be suited for the battery type used in the SHSs.
BATTERY MONITORING	Battery monitoring can be done by measuring currents and voltages of loads, batteries and panels. (Hankins, 2010)
ENERGY EFFICIENCY	The charge controller should consume as minimum energy as possible when in operation. Usually, this is below <1 W (Hankins, 2010)
USER FEEDBACK	Charge controllers often feature LEDs or even small LCD displays, which can provide feedback to the SHS user on e.g. battery SoC. (Hankins, 2010)
MAXIMUM POWER POINT TRACKER	Optimize the solar panel yield. Not all charge controllers are equipped with a MPPT. (Hankins, 2010)

Table 9: Power electronic features that should be considered in SHS sizing.

3.2 MATCHING ENERGY SUPPLY AND ENERGY DEMAND

This section will discuss why it is necessary to match the system characteristics (energy supply) to the user needs (energy demand).

3.2.1 MINIMIZING THE LOSS OF LOAD PROBABILITY

Loss of load occurs when the energy demand is higher than the energy supply from both the solar panel and the battery. Loss of Load Probability (LLP) is a value to measure when the user can not be supplied by the demanded power, throughout the year. An LLP of 5% indicates a 5% downtime throughout the year. (Narayan, 2016) From the perspective of the user, a 0% LLP is desirable. This is, unfortunately, not always achievable. Loss of load can occur for example:

- when systems are designed too small for user needs;
- on cloudy days when little energy is generated by the solar panel;
- due to system failure.

When a system is designed too small for the needs of the user, the user will experience loss of load frequently. This will negatively influence the lifetime of the battery, due to deep discharging of the battery. On the other hand, a system can be oversized for the needs of the user. When a system is oversized for the needs of the user, the user will almost never experience loss of load. Furthermore, it will be beneficial for the lifetime of the battery. However, when the system is excessively oversized, the costs of battery will be unnecessarily high. This illustrate the relationship between system performance, system costs and user needs, and the importance of finding the right balance.

Henceforth, the following parameters are referred to with the term *system performance:*

- Cycle life of battery.
- Loss of Load

3.2.2 IMPACT OF THE ENERGY DEMAND ON SYSTEM PERFORMANCE

As discussed in the previous sections of this chapter, there are several system characteristics that are influenced by the energy consumption. These system characteristics are presented in Table 10. For this section, it is assumed that conventional technology will be applied: crystalline solar cells and lead-acid batteries.

SYSTEM CHARACTERISTICS	RELATIONSHIP WITH ENERGY DEMAND BY USER
PANEL SIZE	The more energy the user consumes, the more energy that needs to be generated by the solar panel.
STORAGE CAPACITY	When the user consumes energy that can not be supplied by the solar panel directly, this has to come from the battery. This energy has to be generated when the sun shines, and stored in the battery.
DEPTH OF DISCHARGE (DOD)	When large amounts of energy are consumed before the battery can be charged by the solar panel, the battery will discharge deep.
CYCLE LIFE	When the SHS user discharges the battery deep during every cycle, the lifetime of the battery will be shorter.
STATE OF CHARGE (SOC)	When the battery fluctuates around a low SoC during every cycle and never gets charged to the optimal level, it will negatively effect the battery life.

Table 10: System characteristics and the relationship with energy demand by user.

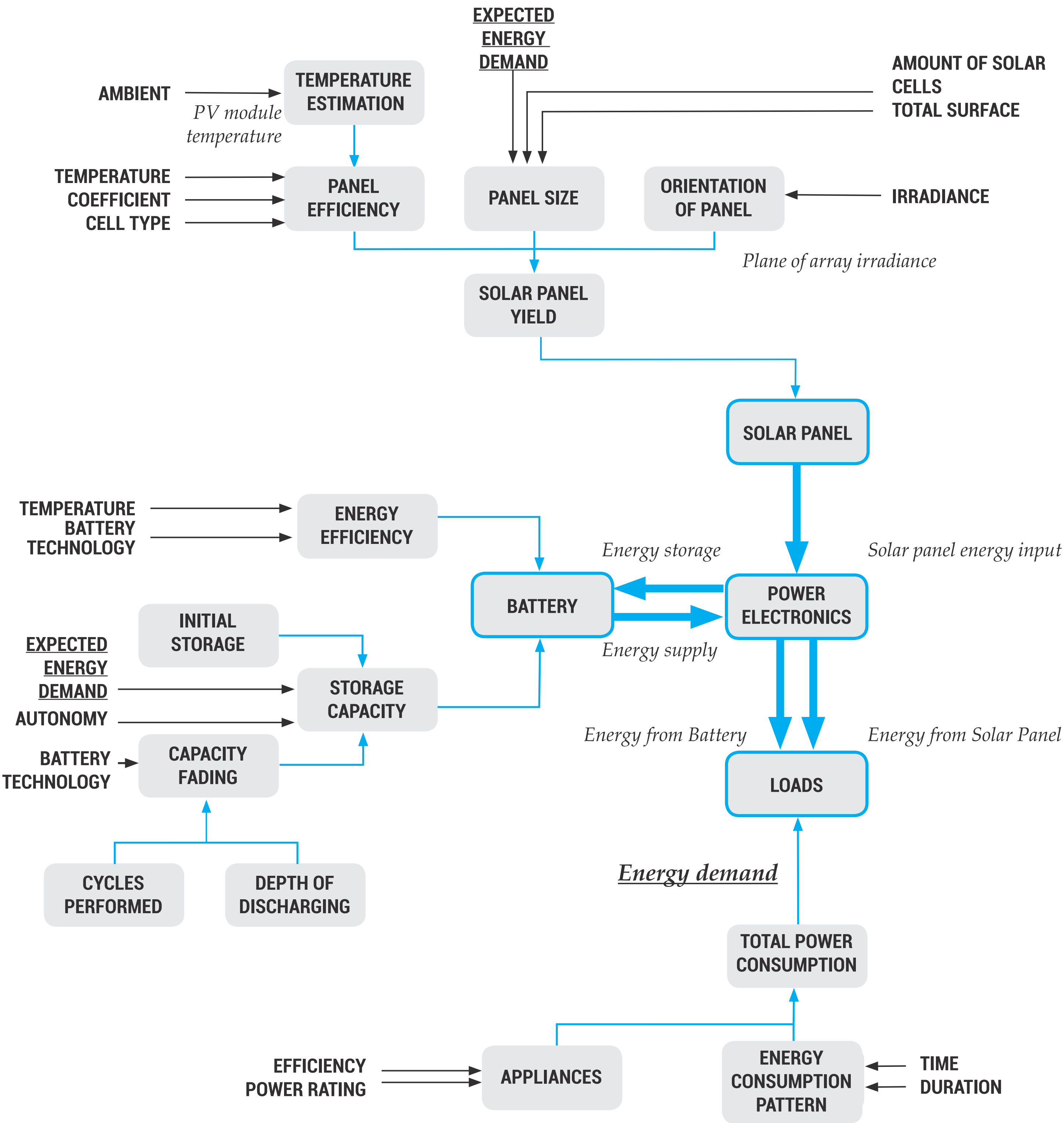


Figure 28: Overview of system of system components and the variables that influence the performance of the system.

3.3 RESEARCH OBJECTIVE

Figure 28 is an overview of what is discussed in this chapter and presents a diagram of system components and the variables that influence the performance of the system.

As discussed in 2.5, the focus of this project is on the challenge to match energy supply and energy demand. This chapter has discussed the system components that play a role in this challenge:

- **energy supply**: solar panel, the battery, and power electronics;
- **energy demand**: loads.

The research focus will be on the demand side of the project challenge, and what the relation is with system performance. This research has 2 drivers, as discussed in 3.1.1:

- lack of knowledge;
- changing demand.

3.3.1 RESEARCH QUESTIONS

The following research questions are defined:

Q2 What is the current energy demand?

Q2.1 What appliances are powered by the solar home system?

Q2.2 When are the appliances used, and for how long?

Q2.3. What is the relation between current energy demand of SHS users and system performance?

Q3. What are the future energy needs?

Q3.1 What appliances will powered by the solar home system?

Q3.2 When will these appliances be used, and for how long?

Q4. How can future SHSs serve future electricity demand?

Both questions will be adressed through a case study in rural Cambodia. Question 1 & 2 will be adressed chapter 4. Question 3 will be adressed in chapter 5. Question 4 will be adressed in chapter 6.

4. CURRENT ENERGY DEMAND OF SOLAR HOME SYSTEM USERS: A CASE STUDY IN RURAL CAMBODIA

What is the current energy consumption of SHS-users? And what impact does this have on system performance? This chapter will answer these questions by a case study on rural Cambodia. Households are visited and a data analysis is performed on the actual use of SHS. One household is presented in detail (4.5), comparing data and real life.

4.1 INTRODUCTION

The chapter focuses on the current energy consumption by SHS users. Goal was to gain more knowledge on load profiles and what impact current energy consumption has on system performance, as this is crucial input for system size modelling in the overarching PhD-project. At the moment, there is a lack of up-to-date knowledge on energy consumption. Global LEAP (2016) states:

"There has been little investigation into the real or specific usage patterns of off-grid consumers, leaving manufacturers unsure of consumer preferences and quality requirements."

Several studies on energy demand have been performed. Unfortunately, the studies are barely useful for today's SHS designers. This because these studies are:

- outdated (Adeoti, Oyewole, & Adegboyega, 2001; Gustavsson, 2007; Reinders et al., 1999)
- not focussed on developing nations; (Hayn, Bertsch, & Fichtner, 2014)
- focussed on a single geographical area (Adeoti et al., 2001; Gustavsson, 2007; Reinders et al., 1999)
- low amount of participants (Gustavsson, 2007)
- lack analysis on the impact of energy consumption on SHS performance. (Adeoti et al., 2001)

Taking into account the limited time and other resources, it was decided to limit the research in this phase to the context of rural Cambodia. The results can later be extrapolated onto other contexts.

The focus was put on the relationship between energy consumption and system performance. Investigating this relation has resulted in information that can support SHS designers in making design decisions.

4.1.1 RESEARCH QUESTIONS

The research questions for this chapter were formulated as:

Q2. What is the current energy demand?

Q2.1 What appliances are powered by the solar home system?

Q2.2 When are the appliances used, and for how long?

Q2.3 What is the relation between current energy demand of SHS users and system performance?

4.1.2 METHODOLOGY

In order to find answers on the research question, two methods were used:

- Data analysis on usage of SHS;
- Household visits;

The data analysis had the goal to provide detailed information on energy consumption and system performance. The household visits had the purpose to validate the data analysis and identify what appliances are in use by owners of a SHS.

The two methods will be described in more detail in the following section. Focus, with both methods, will be on owners of Kamworks' SHSs in rural Cambodia. The SHSs used for the analysis have the following components:

- 95Wp or 100Wp solar panel;
- 12V, 100Ah battery;
- GSMA pay-as-you-go unit.

The Kamworks SHS is depicted in Figure 29.

Figure 29: Kamworks 100Wp SHS.

4.2 DATA ANALYSIS ON USAGE OF SHSS

The goals of the data analysis were to find out how much energy is consumed and at what times energy is consumed. Secondly, the relation between energy consumption and system performance will be analysed. Furthermore, differences between households were investigated.

To reach these goals, multiple variables of the dataset were analysed. These variables are presented in Table 11.

4.2.1 DATASET

For data input, a dataset was used containing information about system usage of 788 Kamworks SHSs in rural Cambodia. This was a unique opportunity, as it would have never been possible to gather so much data within the timeframe of this master thesis. Furthermore, there is only a couple of SHS companies gathering this data at the moment. Moreover, companies are not likely to share data for two reasons: 1) the data contains confidential information about users and 2) the data is valuable for designing and is therefore a competitive advantage.

Besides general information on e.g. users, time, and SHS, the dataset gathered performance information. The following system parameters are used for this analysis:

- **Power input (W)**. The power supplied by the PV panel.
- **Power output (W)**. The power that is

DATA	ANALYSIS GOAL
LOAD PROFILE	Reveal at what times during the day energy is consumed.
DAILY ENERGY CONSUMPTION	As described in chapter 3, knowing this is crucial for determining solar panel and battery size.
MAXIMUM PEAK POWER (W)	Investigate the maximum power consumption on one day.
INFLUENCE OF SEASONS	Other studies have shown a correlation between temperature and energy consumption, due to weather-dependent appliances. (Van Raaij & Verhallen, 1983)
INFLUENCE OF HOUSEHOLD SIZE	Previous literature has indicated a positive correlation between energy consumption and household size in Europe. (Hayn et al., 2014) Goal is to verify if this is true for SHS as well. Other demographic variable can influence energy consumption as well, but are unavailable in the dataset.
DIFFERENCES BETWEEN WEEKENDS AND WEEKDAYS	Van Raaij and Verhallen (1983) define household lifestyle as one of the parameters that influence energy use. Other lifestyle variable can influence energy consumption as well, but days of the week are the only available variable in the dataset that might have a relation to lifestyle.
ENERGY CONSUMPTION AFTER SUNSET	Energy that is consumed after sunset has to come solely from the battery. It is thus important to know how.
ENERGY CONSUMPTION OVER TIME	Investigate if consumption increases over the course of time.
BATTERY SoC	Investigate the Battery SoC over the course of the day. Reveal how often SHS run out of battery.
ENERGY INPUT BY SOLAR PANEL	Investigate the energy generation by panel over the course of time.

Table 11: System characteristics and the relationship with energy demand by user.

consumed by the user.

- **Battery State of Charge (%)**. The state of charge of the battery.

The data was collected through performance logs. These logs were sent by each SHS through SMS on a 20 minute interval, starting on April 14th, 2014 until April 12th, 2016. A total of 9.776.091 performance logs was registered in the dataset. Information about users is limited to name, place of residence, gender and amount of household members. Information about payment methods and payment behaviour is also included in the dataset.

IBM SPSS V22.0 (IBM, 2013) was used to create output. A filter was applied on the dataset to select the most valuable datalogs and eliminate erroneous logs. The following filters were used to select the SHSs for further analysis:

- Households with at least 1 year of data.
- Only 100 Wp SHSs are included in the data analysis. 40 Wp and 60 Wp were responsible for 13,3% of the systems in the dataset and are not included. This in order to make comparisons on energy consumption clear, as 40 Wp & 60 Wp SHSs will be used differently than 100 Wp.
- SHSs that were marked in the dataset as demo models or prototype are not included.
- Households with 0 (unknown) household members are not included. These could for example be entrepeneurs.
- SHSs with faulty data due to broken sensor are not included.
- SHSs with incomplete data are not included.
- SHSs that were sold two or more times with the same identification number (IMEI).

Applying these filters resulted in a dataset of 111 SHSs (14,2% of initial dataset), and 3.402.677 performance logs (34,8% of initial dataset).

The households in the dataset varied in amount of household members. Figure 31 displays this variety in household size of the households in the dataset. The used dataset has a mean of 4.86 members per household.

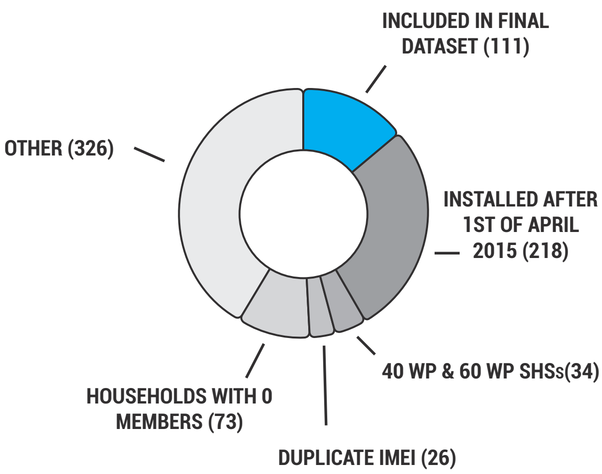


Figure 30: SHSs deleted from dataset.

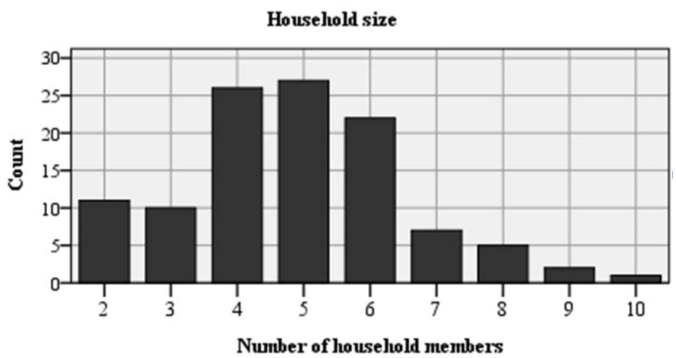


Figure 31: Households size of households in final dataset.

4.3 DATA ANALYSIS RESULTS

This section presents the results of the data analysis.

4.3.1 LOAD PROFILE

Figure 32 presents the mean power output (W) over time, which represents energy consumption (see 4.2). The graph displays the mean for all 111 solar home systems, regardless date.

Between sunrise and sunset, energy consumption is low. Cambodians spent their time outside the house, for example working in the rice field. A small peak is found aroundnoon. This occurred during lunch, when households power, for example, a fan.

The most energy is demanded between 18.00h and 23.00h. This peak is caused by the usage of multiple appliances at the same time. After sunset, households will turn on their lights. Furthermore, the family will be at home and use the TV for entertainment purposes. Occasionally, the fan is turned on.

During the night, many households power one light. In the mean load profile, this is reflected in the relatively stable power output between 11 PM and 5 AM.

When looking at the mean (Figure 32), it seems as if there is some appliance continuously on during the morning and afternoon. However, when looking at the median (Figure 33), one can see that this is not the case. In reality, many households will use some appliance (e.g. fan, lights, phone, TV) for a short period between 6 AM and 6 PM. During the rest of the time intervals between 6 AM and 6 PM, the do not consume energy. This results in a low mean consumption of all households, with some households powering appliances and most households not powering appliances. The median for each time interval is 0 W, as most households do not consume energy(Figure 33)

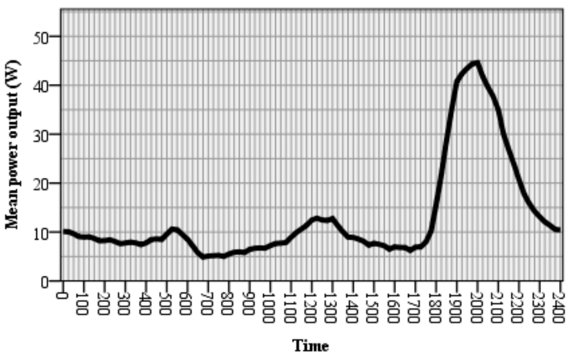


Figure 32: Mean load profile. The peak energy demand is at night, when the TV, fan and lights need to be powered.

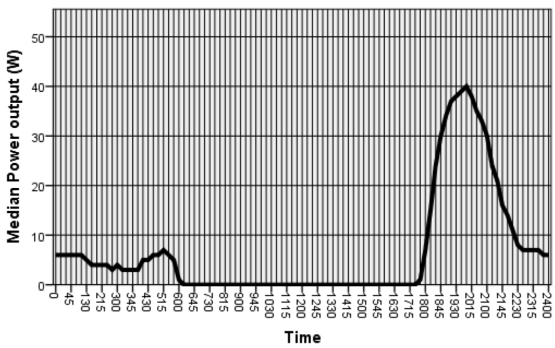


Figure 33: Median load profile. Most energy is consumed at times when the sun does not shine.

Figure 34 presents a boxplot of the power output of all SHSs in the households on one day in 2016. A boxplot of the power output is made for every hour of the day. The blue bar represents the values in between the lower quartile and the upper quartile. The horizontal black lines in the blue bars represents the median. The vertical black lines are the values between minimum and maximum values, excluding the outliers. The dots and asterisks represent values of the outliers. Outliers with a power output higher than 110 W are not included in the graph. A wide diversity in energy consumption can be observed. Each household has its unique load profile shape, which can change from day to day.

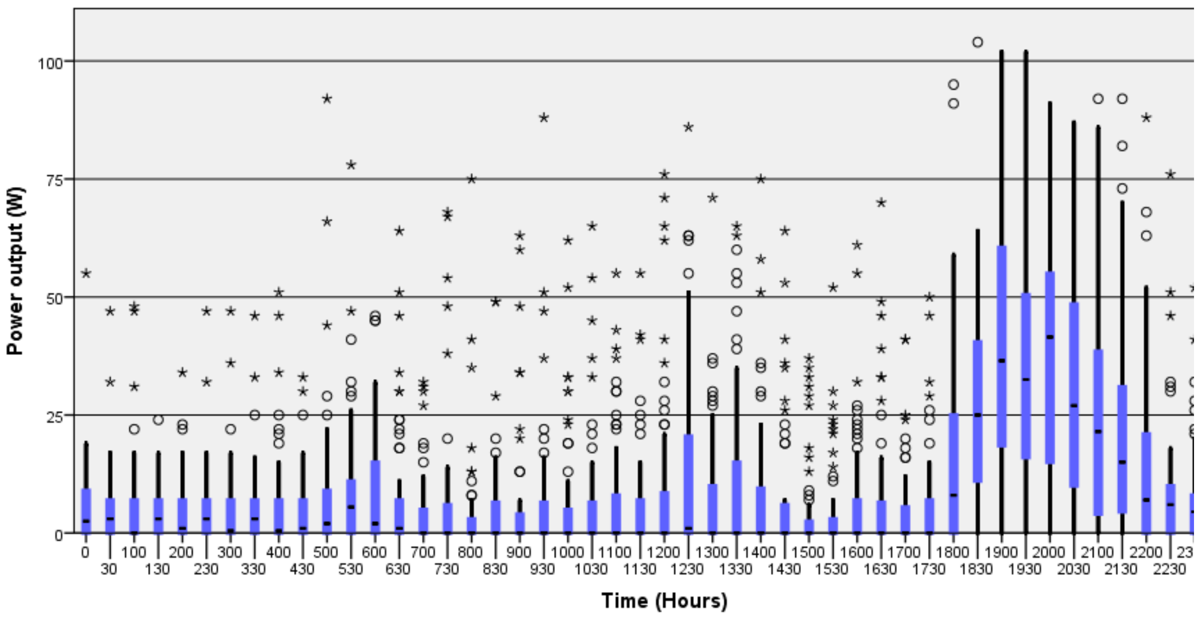


Figure 34: Boxplot of power output in all households, on January 1st, 2016. A boxplot of the power output is made for every 30 mins of the day. The horizontal black lines in the blue bars represents the median. The blue bar represents the values in between the lower quartile and the upper quartile. The vertical black lines are the minimum and maximum values (excluding the outliers). Dots and asterisks are outliers.

4.3.1.1 DAILY ENERGY CONSUMPTION

Figure 35 show the mean energy consumption per household, per day. The mean energy consumption for all users is 310 Wh/day, with σ = 159 Wh. The biggest group of users (42 users) consumes between 300-350 Wh/day.

While most users consume less than 400 Wh/day on average, there are 7 users that use significantly more. The maximum mean power consumption found in the dataset is 1162 Wh/day. This extreme SHSs is an outlier, and it is likely that something is wrong with the performance logs or the system. It is practically impossible to generate so much energy with a 100 Wp panel in rural Cambodia.

For SHS designers, it is important to know what the mean energy consumption is, since the solar panel needs to be able to generate enough energy to serve the daily energy consumption, and the battery needs to be able to store the required energy at night (see chapter 3). Since all analysed SHSs are of the same size, they are not tailored for the diversity in energy consumption. Section 4.3.8 analyses if this diversity in mean energy consumption has an impact on the loss of load for clusters of users.

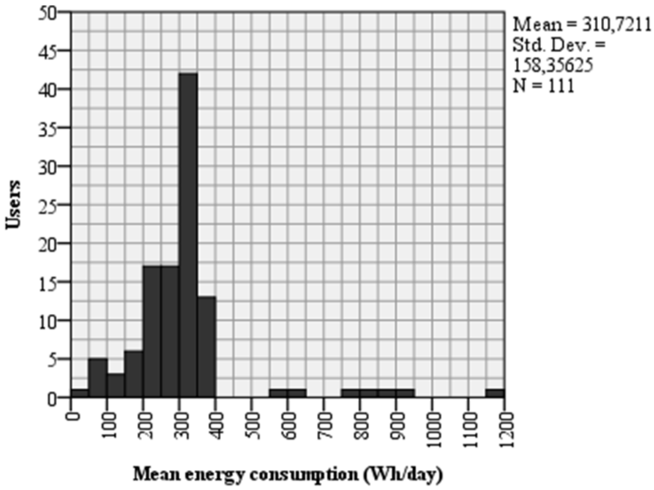


Figure 35: Mean energy consumption per household. The most of the analysed households consume between 300-350 Wh/day.

4.3.2 MAXIMUM PEAK POWER

The mean power output at the highest point (peak) of the day is calculated, for each household. First, the highest power demand is calculated for each day, per household. In the second step, the mean was calculated, per household.

The mean peak power output is displayed in Figure 36. The mean is 62 W, with a standard deviation of 27W. There is a wide diversity of peak power output. The biggest group of households has a mean peak demand below 110 W. There are 2 households with higher average peak power loads. No explanation for these two outliers was found in the dataset or the field research.

As described in 4.2.2.1, these peaks occur mostly at night. It happens when the TV is turned on. In addition, some lights and a fan might be turned on. Since most of the peaks occur at night, the loads at this peak need to be powered fully by the battery. During high power demand, C-rates will high, negatively influencing the battery lifetime. Therefore, the total peak load should be reduced as much as possible. This can for example be done by shifting to off-grid appliances.

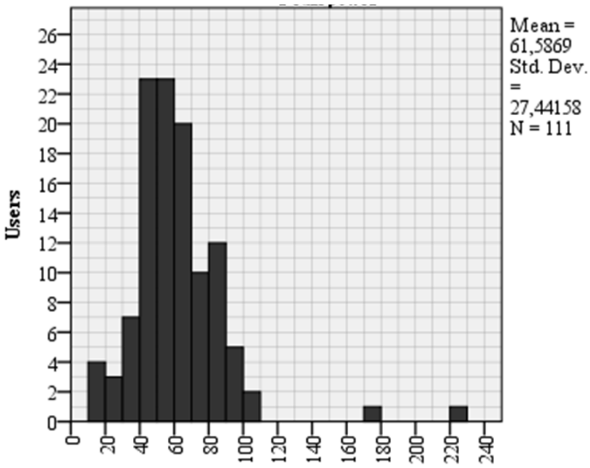


Figure 36: : Mean power demand at the peak of the day.

4.3.3 NUMBER OF HOUSEHOLD MEMBERS

In the analysed user group, no sigificant correlation between household size and mean energy consumption can be found. See Figure 37. A bi-variate Pearson correlation test resulted in a non-significant (p=0,533, 2-tailed) weak negative correlation (r= -0,060).

The reasoning that more household members result in a higher energy consumption might not apply to the rural households in rural Cambodia using a solar home system. Daily energy consumption is depending stronger on the amount of appliances and the appliance efficiency. What kind of appliances and how much the household own is largely depending on the household income, and less depending on the amount of household members as in Europe.

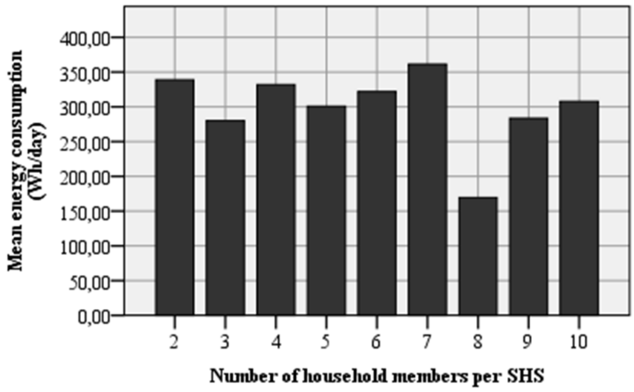


Figure 37: Energy consumption and household size.

4.3.4 SEASONAL DIFFERENCES

Figure 38 displays the energy consumption throughout 2015. It is the mean per day of all users. This appears to be very stable with very little differences between months.

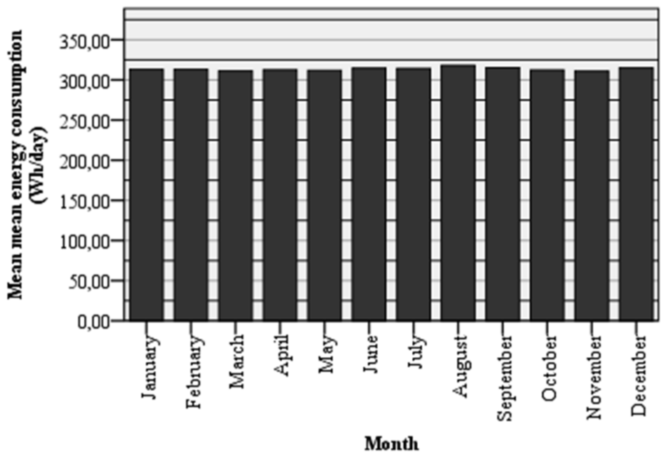


Figure 38: Energy consumption throughout 2015

4.3.5 WEEKEND AND WEEKDAYS

The mean energy consumption per day per household (Wh/day) is shown in Figure 39, comparing weekends (Saturday and Sunday) and weekdays. The mean energy consumption for all users during weekdays (Monday-Friday) is 307 Wh/day, and 315 Wh/day for the weekends. By means of a paired samples T-test, a statistical significant difference was found (p=0,002) Mean energy consumption on weekends is slightly higher.

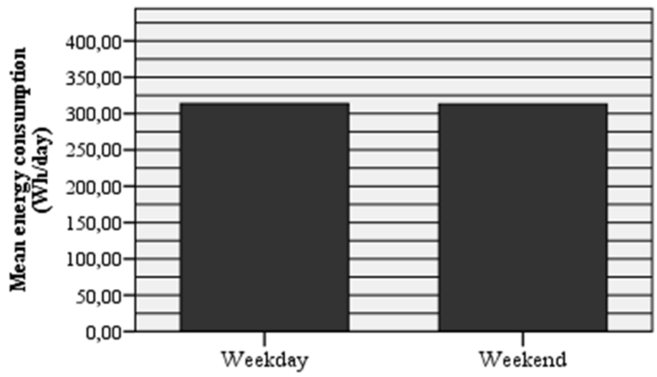


Figure 39: Energy consumption throughout 2015

4.3.6 ENERGY CONSUMPTION AFTER SUNSET

As can be seen in the load profile presented in 4.3.1.1, the biggest demand for electricity occurs after sunset. This power has to come solely from the battery.

A boxplot of the power output is made for 2 parts of the day: day (6 AM - 6 PM) and night (6 PM - 6 AM). The blue bar represents the values in between the lower quartile and the upper quartile of participants. The horizontal black lines in the blue bars represents the median. The vertical black lines are the values between minimum and maximum values, excluding the outliers. The dots and asterisks represent values of the outliers. Outliers with a power output higher than 500 W are not included in the graph.

Figure 41 displays the mean power consumption per part of the day. The mean power consumption during daytime is 100 Wh, while after sunset the mean power consumption is 212 Wh.

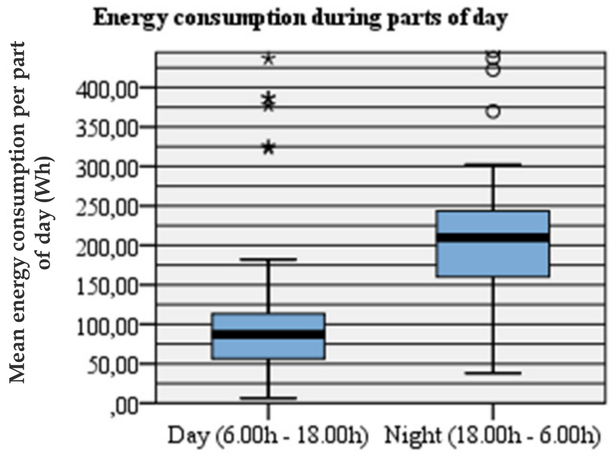


Figure 41: Energy consumption per part of day. The horizontal black lines in the blue bars represents the median. The most energy is consumed at times when the sun does not shine and no energy is generated.

4.3.7 ENERGY CONSUMPTION OVER TIME

Figure 40 displays the energy consumption over time, for the first year after the installation. As described in section 4.3.1.1, the mean energy consumption is 310 Wh/day. The energy consumption is stable throughout the year, beside a surprising peak in the first 2-3 weeks after installation. Employees from the solar home system provider indicate that users meet the limits of their system in the beginning. Afterwards they are more aware of the boundaries of the system and know how to cope with it. (Leleu & Verschilling, personal communication, 2016)

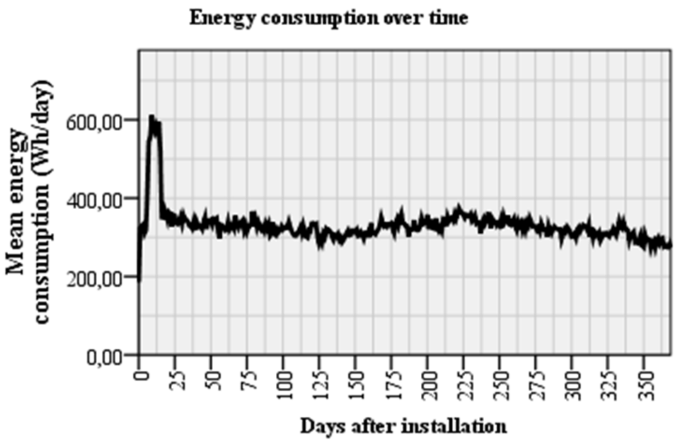


Figure 40: Energy consumption over time.

4.3.8 IMPACT OF ENERGY CONSUMPTION ON SYSTEM PERFORMANCE

This section will describe the relation between energy consumption and the performance of the system. Section 4.3.8.1 will discuss the solar panel performance, and section 4.3.8.2 will discuss the impact on the battery performance.

4.3.8.1 SOLAR PANEL

PERFORMANCE: POWER INPUT BY SOLAR PANEL

Figure 42 displays both the mean load profile as well as the mean power input (W) by the solar panel. The solar panel generates energy between 6 AM and 6 PM. At times when solar energy is generated the demand for energy is low; while at night the demand for energy is high. This is a mismatch. The need for a battery is clear: most energy is consumed at times when there is no solar energy generated.

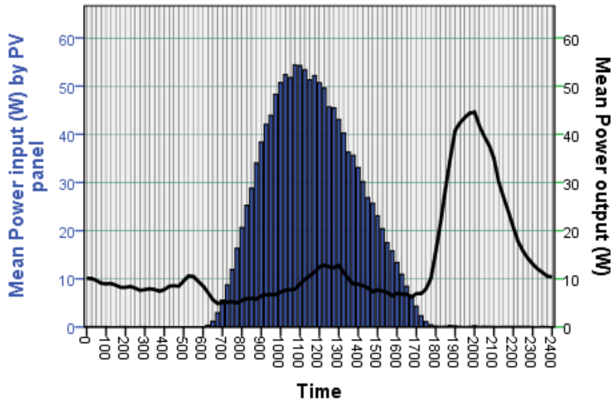


Figure 42: Solar panel power input and load profile.

Figure 43 shows a boxplot of power supply for all solar panels on January 1st, 2016. A wide variety is displayed. A boxplot of the power output is made for every half hour. The values in between the lower quartile and the upper quartile of participants are indicated by the blue bars. The median is indicated with the the horizontal black lines. The vertical black lines are the values between minimum and maximum values, excluding the outliers. Outliers are represented by the dots and asterisks. Outliers with a power output higher than 110 W are not included in the graph.

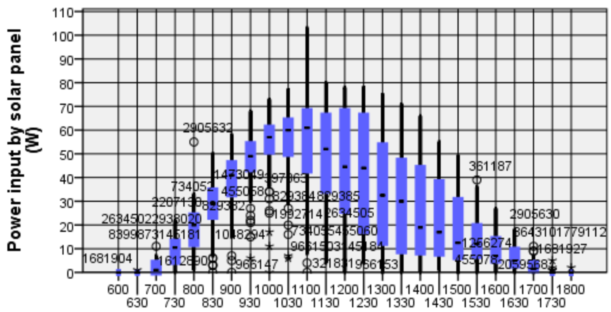


Figure 43: Boxplot of power generation by all 111 solar panels on Janury 1st, 2016, calculated in time intervals of 30 mins. The median is represented by the black horizontal lines.

PERFORMANCE: ENERGY INPUT PER MONTH BY SOLAR PANEL

Figure 44 presents the solar panel energy input per month for the year 2015. Cambodia is a very suitable location for solar powered electrification. This because Cambodia lies close to the equator. Insolation differences between seasons are therefore relatively small. Lowest power generation occurs between December and March. Highest yield in 2015 happened in May.

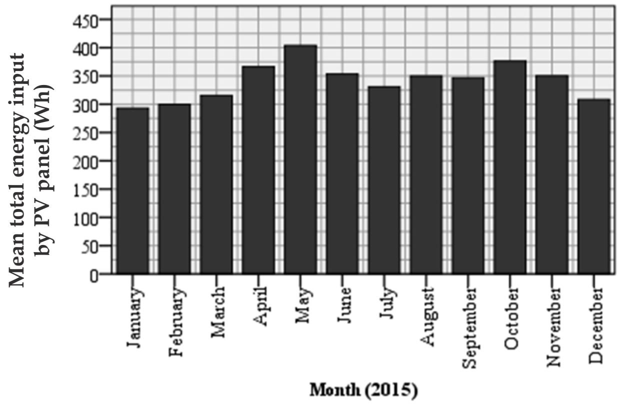


Figure 44: Solar panel performance per month

SOLAR PANEL PERFORMANCE: ONE YEAR

Figure 45 shows the mean total power input by the solar panel (Wh) per day, for all households.

A drop in solar panel performance can be seen after 1 year of usage. The mean energy input by panel (Wh/day/SHS) has decreased from 345 Wh/day/SHS to 300 Wh/day/SHS after 365 days, a decrease of ~13%. According to the manufacturers of the system, this effect is caused by a drop in capacity of the battery after a certain amount of cycles. The system simply cannot store more energy so there is no need for more generation of power. (Leleu & Verschilling, personal communication, 2016)

The peak around day 125 is most likely caused by erroneous data.

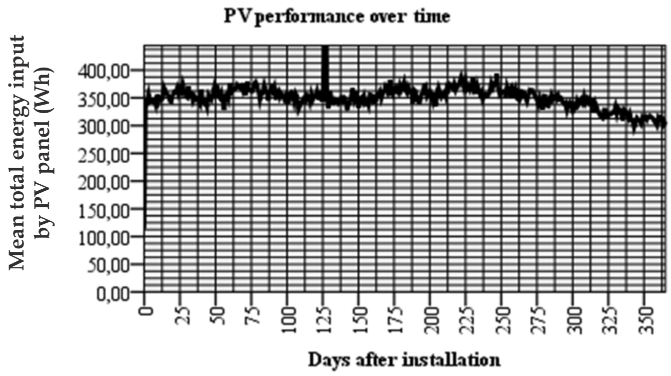


Figure 45: Solar panel performance: one year after installation. A decrease of ~13% can be noted after 1 year.

4.3.8.2 BATTERY

BATTERY STATE OF CHARGE

Figure 46 presents the mean state of charge (%) of the battery in the SHS. During the day, the battery gets charged by the 100Wp solar panel. This starts in the morning shortly after sunrise, at 6AM.

After 9.00h, there is a clear surplus in solar energy and the battery starts charging. The battery state of charge keeps rising until 18.00h, when the sun sets. After this, energy demand increases again and the battery SoC drops.

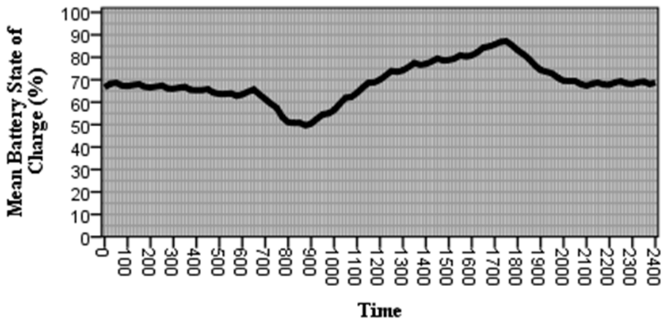


Figure 46: Mean battery SoC (%).

4.3.9 USER CLUSTERS

This section will describe the creation of user clusters. This has the goal to investigate differences between users, based on system usage. The cluster are defined by using a two-step cluster command in SPSS. This two step cluster command is an algorithm designed to reveal natural groupings within a dataset that are otherwise not apparent. (IBM, 2011) The clustering is done based on the following variables:

- mean battery state of charge;
- mean minimum battery state of charge;
- mean maximum battery state of charge.

These 3 parameters are chosen, as they influence the cycle life (life time) of the battery. Furthermore, they indicate loss of load.

The cluster analysis resulted in the identification of 3 clusters of households in the dataset. The cluster characteristics are presented in Table 12. There are some clear differences between the clusters. Cluster 1 consumes the most energy on average per day and also has a higher peak power demand than the other clusters. A fully discharged battery occurs on 28,2% of the days for these users. Furthermore, their battery only gets charged 32,3% of the days. In contrary, cluster 3 charges their battery fully on 82,9% of the days and only on 1,8% of the days has to deal with an empty battery.

	CLUSTER 3 LOW USERS	CLUSTER 2 MEDIUM USERS	CLUSTER 1 HIGH USERS
CLUSTER SIZE (NR. OF HOUSEHOLDS)	32	49	30
CLUSTER SIZE (%)	28,8	44,1	27,0
MEAN ENERGY CONSUMPTION (WH/DAY)	258,8	309,0	386,4
MEAN PEAK POWER DEMAND (W)	50,1	63,0	74,7
MEAN BATTERY STATE OF CHARGE (%)	82,6	67,3	54,1
MEAN MINIMUM STATE OF CHARGE (%)	55,7	34,7	21,3
MEAN MAXIMUM STATE OF CHARGE (%)	97,5	92,2	82,5
BATTERY FULLY CHARGED (% OF DAYS)	82,9	52,5	32,3
BATTERY FULLY DISCHARGED (% OF DAYS)	1,8	9,3	28,2
LOSS OF LOAD (% OF TOTAL TIME)	0,17	0,69	4,03

Table 12: The characteristics of three clusters of households.

For further reference, the three clusters are indicated as:

- Cluster 1: High consumption users. This group consumes the most energy (386,4 Wh/day mean energy consumption) and has a loss of load of 4,03%.

- Cluster 2: Medium consumption users. This group has a mean energy consumption of 309 Wh/day and a loss of load of 0,69%.
- Cluster 3: Low consumption users. This group has a mean energy consumption of 258,8 Wh/day and a loss of load of 0,69%.

See Table 12 for more detailed information.

BATTERY STATE OF CHARGE PER CLUSTER

The differences between the clusters in battery SoC are graphically displayed in Figure 47. The mean profiles have similar tendency throughout the day. Cluster 1 has the lowest mean SoC. Cluster 2 is the biggest cluster with 44,1% of the users and lies between cluster 1 and 3. Cluster 3 has the highest mean SoC for their solar home systems.

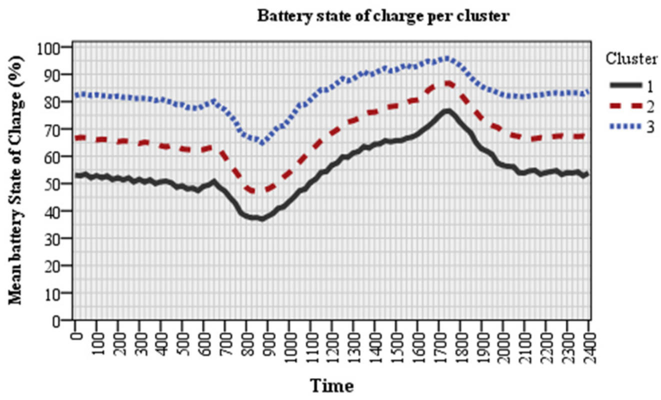


Figure 47: Mean SoC per cluster.

LOAD PROFILE PER CLUSTER

The differences between the clusters can also be seen in Figure 48 where their corresponding load profiles are plotted. The load for the users in cluster 1 is higher between 6.00h and 18.00h. Furthermore, the peak around noon is more intense. Final difference is the higher consumption at peak at night.

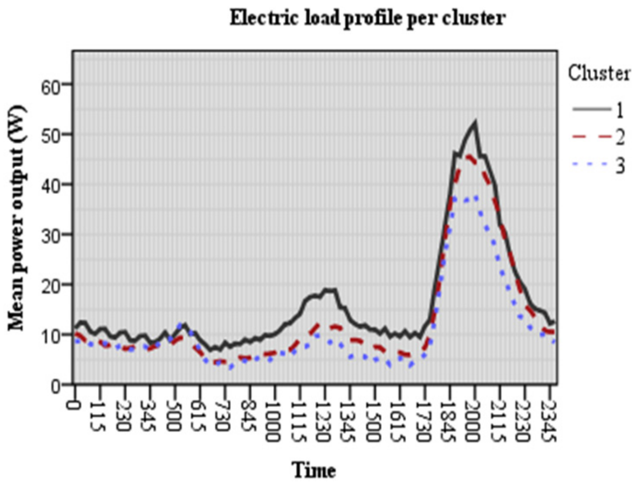


Figure 48: Load profile per cluster.

4.4 HOUSEHOLD VISITS

4.4.9.1 METHODOLOGY

Households in rural Cambodia were visited. Goals:

- Identify which appliances are powered by the SHS.
- Investigate consumption patterns:
    - When these appliances are used.
    - How long the appliances are used.

Furthermore, the households that participated in the field research were asked what appliances they would buy in the future, if they would have more money and more power. This research on future energy consumption is presented in chapter 5.

Seven households with a SHS in the province of Kampong Chhnang (central Cambodia) participated. This is the location where Kamworks has the most customers. The visited households are in possession of a Kamworks 100 Wp SHS. Of these seven households, five households also were part of the data analysis. The data of these five households can therefore be compared with the findings during the household visits. Paragraph 4.5 will show a detailed study on participant 1, in which data from the data analysis are compared with findings from the household visits.

Two methods will be used during the household visits:

- Structured interviews
- A booklet

During the structured interviews, SHS users were asked about their current energy consumption. The users were asked:

- What appliances the household powers with the SHS.
- When the household uses these appliances;

The full list of questions can be found in the Research manual, in Appendix D.

The participants are asked to fill in their answers in the booklet. The participants could fill in when they expected to use the appliances on a time line. See Figure 59. The booklet can be found in Appendix E.

Figure 50: Map of Cambodia. Kampong Chhnang lies at the bottom of the Tonle Sap, in the middle of the country. The capital of the province is also called Kampong Chhnang.

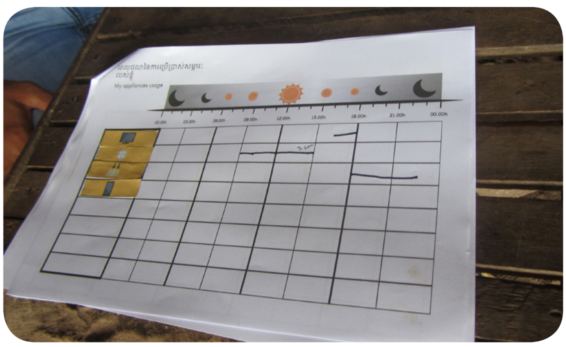


Figure 49: A booklet was used during the household visits. This picture depicts the time line on which participants could indicated their consumption patterns.

4.4.1 RESULTS

4.4.1.1 APPLIANCES POWERED BY THE SOLAR HOME SYSTEM

The amount of appliances that off-grid rural households posses is limited. The following appliances were frequently found in rural Cambodian households owning a Kamworks' SHS:

- LED lighting (included in the kit: 4 LED bulbs are installed by Kamworks);
- Fan
- Television;
- Phones;
- Speakers;
- DTV receivers, amplifiers, DVD players.

There were some remarkable findings in the field research. First of all, many households had an audio system, that was either used very little (e.g. 30 mins per 2/3 days) or not at all. The speakers were surprisingly big.

The second remarkable finding were smaller, supporting appliances. With a television come other appliances that also consume energy, such as an amplifier (used for the audio system) a DVD player (used with the television) or a digital TV receiver (used with the television). These appliances also consume energy. For example, the DTV receiver provided by Kamworks has a power rating of ~10 W.

The final remarkable finding were inverters. Although forbidden by Kamworks on penalty of loss of warranty, most households own an inverter.

Figure 51: A rural Cambodian residential interior. Highlighted are the appliances frequently found in rural Cambodian households.

4.4.1.2 CONSUMPTION PATTERNS

Table 13 displays the responses of the participants on the question: *"At what time do you use the appliances that you own?"* The users were asked to fill in their answers on a time line. The marked boxes are the times when the user indicates to normally use the appliances. This section will describe per appliance when the appliances are used.

Lights are used before and after sunset. Some households also have a light in the toilet. Two households leave one light on at night. One of these two household indicated that the reason to leave the light on during night, is to keep an eye on their cow.

Fans are used around noon and after sunset. Two participants indicated they would only use the fan during the hot dry season, running from November to May. Furthermore, one household indicated that one of their ceiling fans was only used when they had guests visiting the house.

Most ***phones*** are being charged irregularly. Nearly all phones that were observed during the visits were older "dumb" phones, of which the batteries lasts multiple days. The phones are thus connected to the solar home system when the battery is dead. However, smartphones are not uncommon in Cambodia. In one household, a child was playing games on his large smartphone that was just charged up.

Televisions are used daily. They are primarily being used at night. During the household visits, in some houses older, energy consuming CRT televisions were found, while other households were in possession of newer, more efficient TVs (LED/LCD). Furthermore, not all the visited households own a television. One household (participant 1) indicated a change of usage in the weekend, when boxing was broadcasted on Saturday afternoon.

Audio systems are barely in use (participant 1 & 6), or not at all because they are broken (participant 2). Participant 3 has a audio system that is not compatible with the Kamworks solar home system. Participant 6 indicated to use the speakers about 30 mins per 2 days. Participant 1 only uses the speaker once per week.

Appliances such as ***digital tv (DTV) receivers, amplifiers, DVD players*** are used simultaneously with other appliances. For sake of simplicity, the participants are not asked to indicate when these appliances are used.

APPLIANCE	PARTICIPANT	00H - 01H	01H - 02H	02H - 03H	03H - 04H	04H - 05H	05H - 06H	06H -07H	07H - 08H	08H - 09H	09H - 10H	10H -11H	11H -12H	12H -13H	13H -14H	14H - 15H	15H - 16H	16H - 17H	17H - 18H	18H - 19H	19H - 20H	20H - 21H	21H - 22H	22H - 23H	23H -00H
LIGHTS	1				■															■	■	■	■		
	2	■	■	■	■	■	■											■	■	■	■	■	■	■	■
	3	■	■	■	■	■	■													■	■	■	■	■	■
	4																			■	■	■	■	■	
	5					■	■													■	■	■			
	6					■	■													■	■	■			
	7																			■	■	■	■		
FAN	1	FAN IS BROKEN																							
	2																			■					
	3	NOT IN POSSESSION																							
	4										■	■	■	■	■	■									
	5																			■	■	■	■	■	■
	6													■						■					
	7	NOT IN POSSESSION																							
PHONE	1	THE PHONE OF A FRIEND WAS CHARGING AT TIME OF VISIT.																							
	2	DOES NOT USE A PHONE																							
	3																								
	4	PHONE IS CHARGED IRREGULARLY																							
	5																								
	6	SON OWNS A SMARTPHONE. THE SMARTPHONE IS CHARGED FREQUENTLY																							
	7	5 PHONES ARE CHARGED DAILY.																							
TELEVISION	1																			■	■	■	■		
	2																		■	■					
	3	NOT IN POSSESSION																							
	4																	■	■						
	5																			■	■	■			
	6																■	■	■	■	■	■			
	7																			■	■	■	■		
AUDIO SYSTEM	1	USED ONCE PER WEEK.																							
	2	AUDIO SYSTEM IS BROKEN.																							
	3	NOT FUNCTIONING WITH A 12V SYSTEM, ONLY 220V PLUG																							
	4	NOT IN POSSESSION																							
	5	NOT IN POSSESSION																							
	6	30 MINS IN 2 DAYS.																							
	7	NOT IN POSSESSION																							

Table 13: The responses of the participants on the question: "At what time do you use the appliances that you own?" The marked boxes are the times when the user indicates to normally use the appliances.

4.5 CASE STUDY: COMPARING DATA WITH REALITY

Figure 52: Living room of participant.

PARTICIPANT 1

BROKEN BARELY USED

HOUSEHOLD MEMBERS:	2
AGE:	52 YEARS 55 YEARS
OCCUPATION:	RICE FARMER
VILLAGE:	THNAL TA SAENG, KAMPONG CHHNANG, CAMBODIA

"I HAD TO MOVE MY HOUSE TO MAKE SPACE FOR THE GRID"- PARTICIPANT 1

The grid arrived at this village one month before the research visit. The participant stated that the house had to be moved 5 meters backwards to make space for the grid. The household unfortunately did not have the money to get grid-connected, because the participant had to pay for her fathers funeral and had spent all their money. One of their dreams was to have a houses like she has, but then with closed walls.

The household paid the system in cash money. There was an inverter connected to the system. This household had remarkably big speakers, which were only used rarely. The participant indicated the speakers consumed too much power.

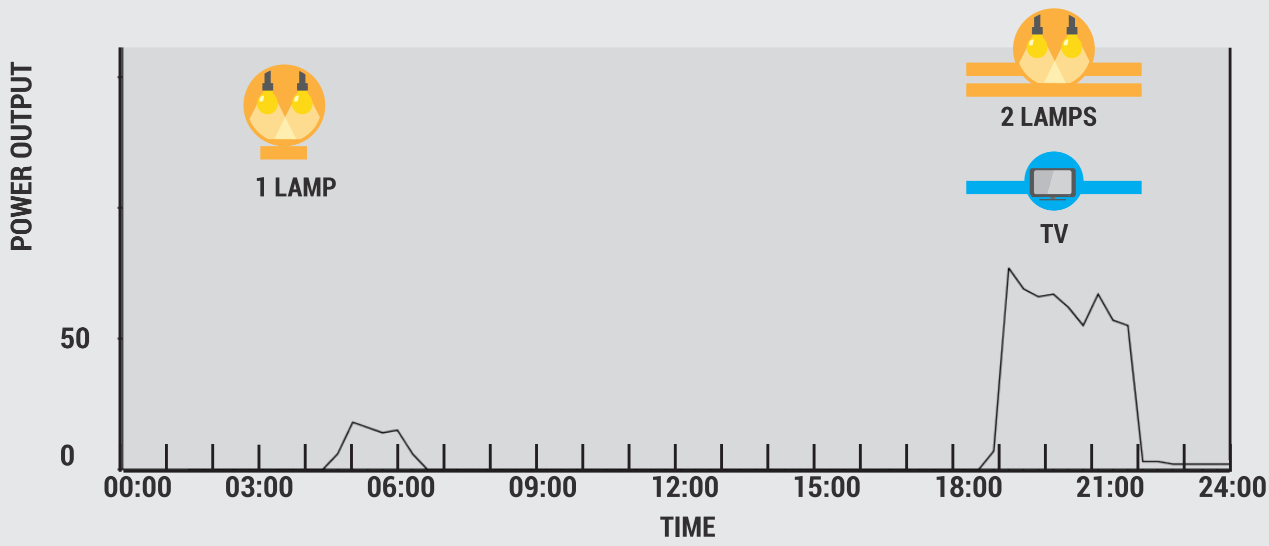


Figure 53: Load profile of participant on March 7th, 2016.

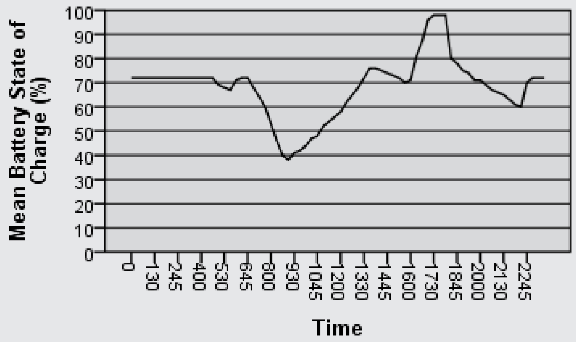


Figure 55: SoC on March 7th, 2016.

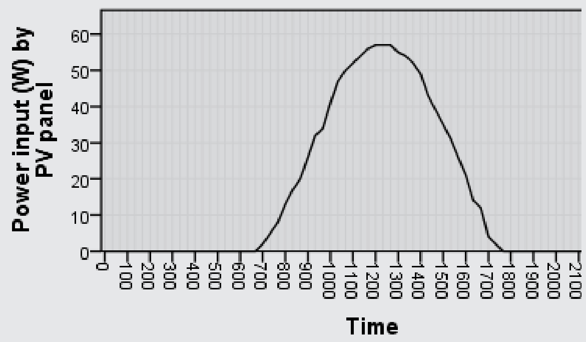


Figure 56: PV input on March 7th, 2016.

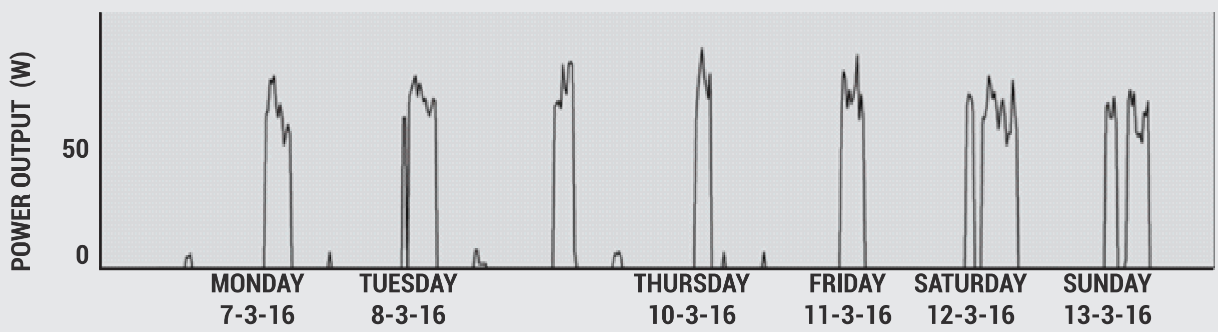


Figure 54: Load profile of participant of 1 week.

Figure 53 displays the load profile of the particpant on Monday, 7th of March. In the early morning, the participant prepares the rice for breakfast and turns on the light. The time she mentions does not match the load profile of the chosen date. In the evening, the family watches television and has two lights on. This explains the peak after sunset.

Figure 54 displays the load profile for one week. A similar energy consumption pattern can be found on the weekdays, while there is more consumption in the weekend.The husband mentioned he enjoyed watching boxing during the weekends on television. This explains the peak on saturdays and sundays in the afternoon.


TVSTAR
KAMWORKS


KAMWORKS


professional karaoke amplifier DM-880W
GMG
POWER
EVD
EVD-888

4.6 CONCLUSION

Although all the households that were part of the research own the same type of system, (100 Wp), there is a wide variety in energy consumption patterns.

The mean energy consumption for all users is 310 Wh/day, with σ = 159 Wh. Most energy is consumed at night, when the sun does not shine. This is when the lights are on and when the fan and TV are in use. This is also the time when the peak energy demand occurs. The mean energy demand at the peak of the day is 62 W, with a standard deviation of 27W.

The battery status is the lowest after a morning peak demand around 06.00h. After this the sun will start to shine and energy consumption will go down, resulting in charging of the battery.

The 100 Wp system provided by Kamworks is not sufficient for all users. Three clusters of users were identified: high consumption users, medium consumption users and low consumption users. High consumption users experiences an empty battery on 28.2% (!) of the days. This user cluster has a loss of load during 4,03% of the time.

Parameters that are relevant to energy consumption in the developed world are of less relevance in rural Cambodia.

From the data analysis, it seems that seasonal differences have very little impact on energy consumption. Energy consumption per day is similar during all the months. On the other hand, some users indicated they use their fan only in the dry season.

Secondly, no relationship between the size of the household and energy consumption was found. Furthermore, the differences between weekdays and weekends is, generally speaking, small.

The spread in energy consumption patterns is something that designers and other engineers should take into account during the design process of a future solar home system, to prevent high loss of loads, and high C-rates and deep discharges of batteries. Chapter 6 will present design

At the moment, there is thus a mismatch between energy supply and demand. This because:

- a large group of users suffer from loss of load;
- most energy is consumed at night.

Therefore, matching energy demand and energy supply is a suitable option to improve system performance. To better match energy supply and energy demand in future SHS, it is important to know:

- what appliances are in demand by the households;
- when the households will use the appliances;
- how long the appliances will be used;
- what the future energy consumption will be;
- what the differences in energy consumption will be between users.

Thes future energy needs will be explored in chapter 5.

5. FUTURE ENERGY NEEDS OF SHS-USERS: A CASE STUDY IN RURAL CAMBODIA

This chapter explores the future needs of SHS-users through a case study in rural Cambodia. Field research is performed to find out what appliances are demanded and what appliances can be expected to be used with SHS in the near future (2021). The results of a field visit are presented in the format of personas.

5.1 INTRODUCTION

This chapter will analyse the future energy needs, through a case study in rural Cambodia. Research has been done after demand for off-grid appliances, but knowledge about (future) energy consumption patterns is scarce. (Global LEAP, 2016) Estimating future load profiles has the aim to support SHS-designers in making design decisions for future system designs. This chapter will identify both demand for appliances and energy consumption patterns through expert interviews and interviews with SHS-users. The resulting load profiles will be presented in form of Personas.

5.1.1 RESEARCH QUESTIONS

The research question for this chapter is formulated as:

Q3. What are the future electricity needs of SHS users?

Q3.1 What type of appliances will powered by the solar home system?

Q3.2 When will these appliances be used, and for how long?

5.1.2 METHODOLOGY

In order to find the answers to these questions, the research is split up in two main components:

1) expert interviews;
2) household visits.

Focus within both research activities, will be on owners of SHSs in rural Cambodia. Interviewing experts has the aim to find out what appliances might be used with SHSs in the near future, keeping in mind the limitations and characteristics of SHSs.The household visits have the purpose to identify what type of appliances are demanded by owners of a SHS, and when they will use these appliances. The two methods will be described in more detail in the following section.

SHORT-TERM FUTURE: 2021

During this research, a look will be taken at the short-term future. The overarching PhD project is planned to finish in 2019. Consequently, the results of this research should still be relevant by that time. As a point of reference the year 2021 is chosen, 5 years after this master thesis research was performed.

Making scenarios for longer-term futures will result in less reliable input for the project.

5.1.2.1 METHODOLOGY: EXPERT INTERVIEWS

In total, 16 stakeholders from the SHS market in Cambodia were interviewed.

Goals:

- Indentify out what appliances in the future will most likely be used in combination with a SHS;
- Getting to know what will influence future energy demand;

Experts are interviewed from the following actors in the SHS market:

- SHS companies;
  - Kamworks: A. Luxwolda.
  - NRG: J. Pegler, S. Pha.
  - Camsolar: B. Khim.
  - Solar Partners Asia: J. Gramberg.
  - Entrepeneurs du Monde: L. Cochet.
- SHS programme financers;
  - Agence française de développement: G. André.
- Micro-Finance Institute (MFI);
- Non-governmental organisation (NGOs);
  - Picosol: B. Deloof, S. Tun.
  - SNV: K. Puth, P. Baudez.
- Rural Electrification Fund (Governmental institute): K. Loeung.
- Solar Energy Association Cambodia (SEAC): P. Ronteix.
- Institute of Technology of Cambodia (University): Professor B. Long.
- Impact Hub Phnom Penh: M. Mossard.
- Architect: S. Thim.

Figure 57: Interview with the executive director of the Rural Electrification Fund.

During the semi-structured interviews, the experts are asked about:

- their role;
- the current major challenges they face in the SHS market;
- their vision on SHSs and rural electrification;
- what type of appliances they expect to be used in combination with SHSs in the near future.

5.1.2.2 METHODOLOGY: HOUSEHOLD VISITS

Households in rural Cambodia are visited. The goal of the household visit is two-fold: 1) Identify what appliances in the future most likely will be used in combination with a SHS, and 2) investigate when these appliances most likely will be used, and for how long.

Seven households in the province of Kampong Chhnang (central Cambodia) participated. This is the location where Kamworks has the most customers. These seven households are representative for the households as analysed in the data analysis. The households are in possession of a Kamworks 100 Wp SHS.

Three methods were used during the household visit:

- Structured interviews;
- A booklet;
- Simulation.

The participants were asked what appliances they would like to use in combination with the SHS, and when they will most likely use these appliances. The Research manual can be found in Appendix D.

STRUCTURED INTERVIEWS

SHS users were first asked about their current energy consumption (See chapter 4).

Secondly, questions were asked about:

- what appliances the household would like to use in the future;
- when the household will use these appliances;
- why the household does not have/use the demanded appliances.

The list of questions can be found in the Research manual, in Appendix D.

BOOKLET

The participants are requested to fill in their answers in the booklet. The participants could fill in when they expected to use the appliances on a time line. See Figure 59. The booklet can be found in Appendix E.

SIMULATION

The households that participated in the field research were asked what appliances they would buy if they would have more money and more power.

This was done through a monopoly-like simulation, in which the users could virtually purchase appliances with fake money. During this simulation, the participants were restricted by time, money and energy capacity. The participants could purchase appliances that are meant for domestic use. The list of appliances that could be purchased during the simulation derived from the survey *"Off-Grid Appliance Market Survey"* that was performed by Global LEAP (2016). See Table 6. After the simulation, the users were asked to fill in at what time they would operate these appliances. This could be done on the time line in the booklet (Figure 59). The simulation was used as a discussion starter.

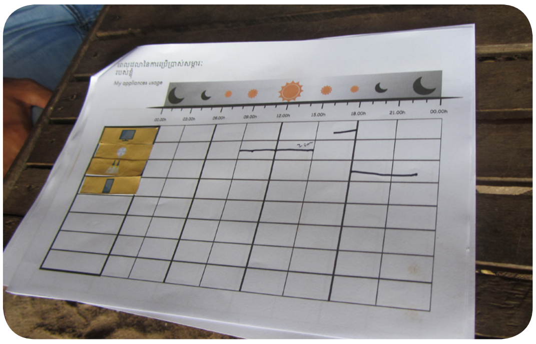


Figure 58: The time line.

Figure 59: The simulation.

5.2 DEMANDED APPLIANCES

This section will discuss what appliances are in demand by rural households in Cambodia. Goal is to answer research question *Q3.1: What appliances will powered by the solar home system?*

5.2.1 RESULTS

An overview of the demanded appliances can be found in Table 14. This table lists :

- Appliances that are already in use at the moment (in 2016);
- Appliances that are demanded by the users, resulting from user interviews during household visits;
- Appliances that are expected by experts to be used with solar home systems;
- Appliances that are currently available in rural appliances shops.

A reasoning why these appliances are likely to be used by SHS-users is provided in the following section. This will be done by means of analysing statements made by participants and experts during interviews.

From the user side, there is clearly a demand for more energy and more appliances. Households indicate that they would like to cool their food, iron their clothes and more. The appliances that were discussed during the household visit are listed in Table 14.

LONGER USE OF CURRENT APPLIANCES

"I would like to watch TV for a longer time" - *Participant 2*

Most participants indicated that they are satisfied with their SHS, but would like to power appliances for a longer duration. For example, participants stated they would like to use their TV more. Participant 2 mentioned that the household was able to watch TV for 3 hours on a sunny day, but only for 1 hour when it was cloudy.

APPLIANCES IN DEMAND

	ALREADY IN USE WITH SHS (2016)	DEMANDED BY USERS (2021)	EXPECTED BY EXPERTS (2021)	AVAILABLE IN VISITED RURAL SHOPS (2016)
AUDIO SYSTEM	x	x		x
FAN	x			x
FRIDGE		x	x	x
IRON		x	x	x
LAPTOP		x		
LIGHTS	x			x
PHONE	x			x
RADIO		x		x
RICE COOKER		x	x	x
SOLAR PUMP		x	x	
TABLET				
TV	x	x		x
WASHING MACHINE		x		x

Table 14: Appliances in demand.

AWARENESS

"I have a relative that is connected to the grid and has a ricecooker." - Participant 1

People are aware of the benefits that come with higher levels of electricity access. Participants indicated to have relatives that are grid-connected. Furthermore, there is mobile internet coverage practically everywhere in the country. Many people have access to digital news sources and social media. This results in a high level of awareness about the life of others, including the benefits that come with high levels of electricity access.

Another example is the usage of refrigerators. The use of refrigerators is already adopted in the lifestyle of more prosperous, urban Cambodians. It can thus be expected that rural Cambodians will also adopt refrigerators in their lifestyle, once they have financial means and if their systems are able to power refrigerators.

MORE APPLIANCES, FOR CONVENIENCE AND MORE

"I want to keep my vegetables cool for 10 days and not go to the market everyday"
- Participant 2

There are alternatives for electric powered appliances. Households can boil water or make rice on a fire, pump water by hand or go to the market every day for fresh food. Electric appliances can ease these tasks and bring more convenience in the life of the household.

It is, however, not only about convenience. Getting access to electricity reaching levels of Tier 3 and 4 (see Table 2) also results in other benefits, such as saving time. Replacing open fire with a rice cooker or a water kettle also has health benefits.

USAGE

"I would use an iron for special occassions like weddings, or Khmer New Year" - Participant 3

The appliances that are in use by SHS-users at the moment are powered daily, except for phones and audio systems. In the future, more appliances might be in use that are not used daily. This could also include appliances that were not investigated in the research, such as kitchen tools or other electronic appliances.

ADAPTION TO LIMITATIONS

"I will heat water in the morning and store it in a thermos flask" - Participant 6

Consumers will learn to adapt to the limitations of the SHS. When electricity supply is limited, alternatives need to be found. For example, non-electric alternatives can be used, such as a thermos flask for storing heated water.

AFFORDABILITY

"Fridges are not affordable, and therefore not demanded. If the prices would drop, then yes, people would buy fridges."
- Sotheara Tun, volunteer at Picosol

From the interviews it became clear that, although there is a demand for specific devices, not all of the devices are likely to enter the market. For example, there are at the moment no suitable solar pumps available for single household applications. They are either far too expensive, or are made for non-intensive usage.

Fridges are also not within financial reach of the households. At the moment, they come at high upfront costs and energy consumption is high. One grid-connected household that was visited indicated not to have a fridge due to the high energy prices.

The price of appliances and energy consumptions form major barriers for the adoption and usage of these appliances. Section 5.2.2 will discuss this in more detail.

5.2.2 BARRIERS: PRICE & ENERGY CONSUMPTION

There are two main reasons why households do not own the appliances they want to own:

1) the household can't afford the appliance;
2) the appliance does not match with SHSs, because it consumes too much energy.

PRICE

In general, the population in rural Cambodia is poor. Most of the visited households are rice farmers, a common job in rural Cambodia. Their income is low and season dependent. During the field research, three payment options for SHSs were frequently found:

- Financed through a loan. It is common in rural Cambodia to request a loan for a SHS at a micro-finance institute.
- In cash, for example after the rice harvest.
- In other cases, the system was paid by a more wealthy family member. This family member is for example a son send to work abroad, e.g. in Thailand

Appliances such as fridges and solar pumps are far out of financial reach when the households are not supported by a family member, or when they cannot get a loan at an MFI.

ENERGY CONSUMPTION

Households are aware of the limitiations of the SHS. They will not purchase appliances from their limited income if they know it is unusable. The barriers can be solved by

- making the appliances cheaper;
- by supplying more energy or make appliances more efficient.

Figure 61 has plotted the demanded appliances in a price-energy consumption matrix.

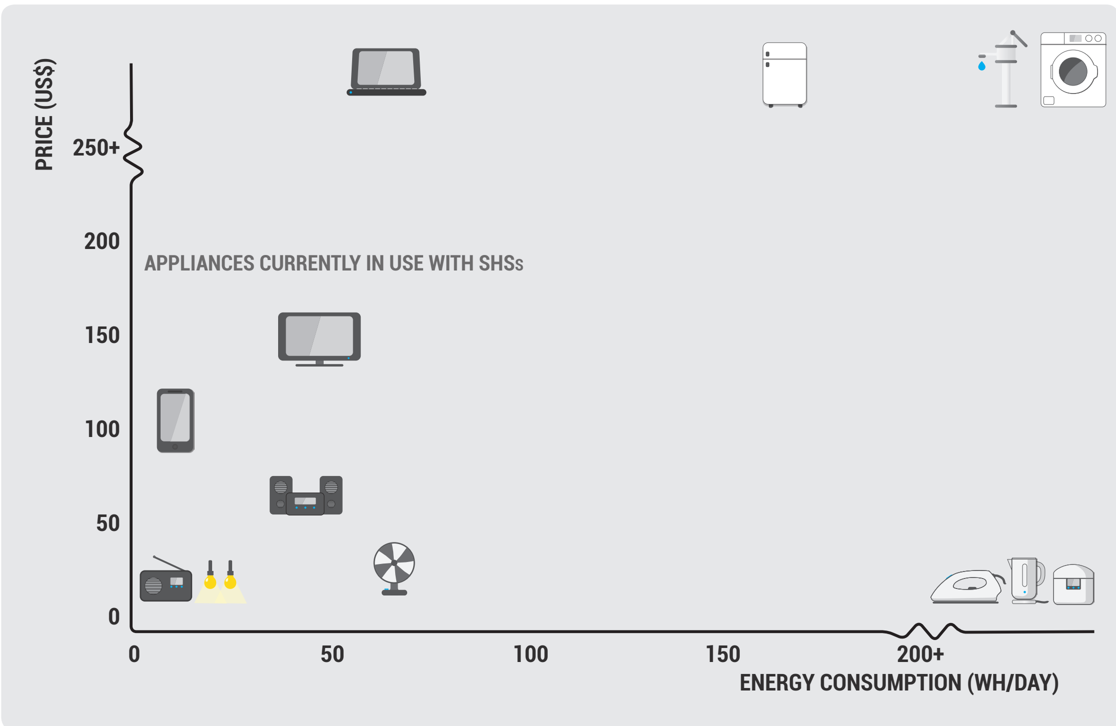


Figure 61: Price-energy matrix. Prices and energy consumption ratings are indicative. For more detailed information, see Table 8.

5.3 PERSONAS

To give a face to the solar home system of the users, the Persona method is applied.The definition of persona by Lidwell, Holden, and Butler (2010): ***"Personas are fictional characters created to represent the different user types that might use a site, brand, or product in a similar way."***

The personas presented in the following paragraphs are constructed based on the field research, the storyboard (5.3.4) and the data analysis (chapter 4).

5.3.1 LOW, MEDIUM, HIGH

At the moment, there is a wide spread in energy consumption by rural Cambodian households. See chapter 4. For future energy consumption, 3 different personas are created:

- low consumption household;
- medium consumption household;
- high consumption household.

The profiles are explained in the following pages.

5.3.2 INTERPRETATION OF PERSONAS

The load profiles are a realistic projection of future usage, based on current usage, discussions and field research results. The predictions are -by nature- uncertain. The predictions will have to be adjusted over time, if information and knowledge about demand has changed.

5.3.3 MODELLING THE LOAD PROFILES

The load profiles shown are constructed based on the following parameters:

- Appliance power rating;
- Operation times;
- Duration of usage;

A load profile will be made for:

- standard appliances;
- off-grid appliances.

The following simplifications are made:

- There are no seasonal differences;
- There are no differences between weekdays and weekends;

Included in the load profiles are the appliances

- that are in use at the moment,
- appliances that are demanded by the user
- expected by the experts.

Excluded from the load profile calculations are:

- washing machine. This appliances was not listed by Global LEAP (2015) *"Off-Grid Appliance Market Survey"* . During the field research, the demand for a washing machine was only mentioned by one SHS-user.
- solar pump; there are no suitable product available on the market at the moment. (Luxwolda, personal communication 2016)

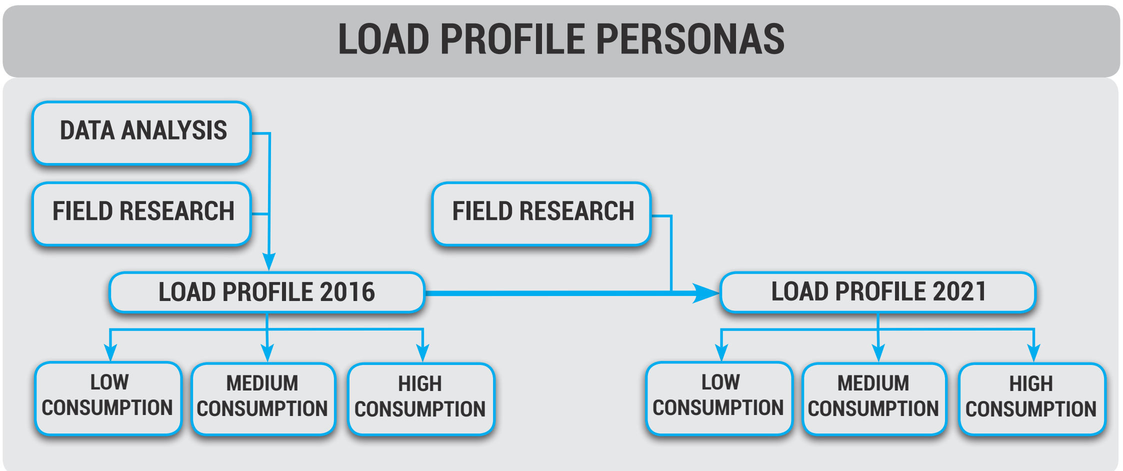


Table 15: Load profile personas.

The constructed load profiles of 2016 are compared and validated with the data analysis on the following criteria:

- Daily energy consumption;
- Peak power consumption;
- Day/Night consumption ratio.

The profile can be adjusted to fit any energy consumption pattern (any set of appliances, any power rating, any time). To create the profiles as displayed in the persona, the model is completed with insights from the field research about (future) appliance ownership and operation times.

The model is build based on parameters and can therefore be adjusted when over time knowledge about usage has changed, systems have changed or if one wants to compare different countries.

5.3.4 FUTURE APPLIANCES: A STORYBOARD

Figure 62 on page 86 is a storyboard that shows a scenario of a rural Cambodian household, that is in need for more appliances.

The storyboard is based on Kamworks modular system. (Siebinga, 2016) With a modular system, users can expand their system size. In this scenario, the households expands the system twice. Based on field research, the data analysis (chapter 4) and this storyboard, 3 personas are created:

- Low consumption household; this will not own more appliances than currently normal. Step 1 of the storyboard.
- Medium consumption household; up to step 5 of the storyboard.
- High consumption household; up to step 8 of the storyboard.

The appliances that are owned by the types of SHS user are presented in Table 16. The selection is based on the interviews with the experts and users.

APPLIANCES INCLUDED IN LOAD PROFILE PERSONAS

	2016	LOW CONSUMPTION PROFILE 2021	MEDIUM CONSUMPTION PROFILE 2021	HIGH CONSUMPTION PROFILE 2021
LIGHT	x	x	x	x
FAN	x	x	x	x
PHONE	x	x	x	x
TV	x	x	x	x
RADIO			x	x
AUDIO SYSTEM			x	x
WATER KETTLE			x	x
RICE COOKER			x	x
IRON			x	x
REFRIGERATOR				x

Table 16: Appliances included in the load profile personas. The personas are presented on the next pages.

Figure 62: Future appliances demand - a storyboard.

5.3.5 PERSONA 1

LOW CONSUMPTION HOUSEHOLD

The low consumption household is poor. The parents are rice farmers and have 4 kids who go to school. This household does not have the financial means to upgrade their system in the future. The family lives in a house build of thatch and iron. The mother makes baskets out of bamboo to make a bit extra money.

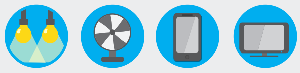
2016

APPLIANCES IN USE BY HOUSEHOLD:

The family has bought the SHS to replace their kerosene lamps. Furthermore, they have a fan. There is no money for a television. The phones are old and charged irregularly.

2021

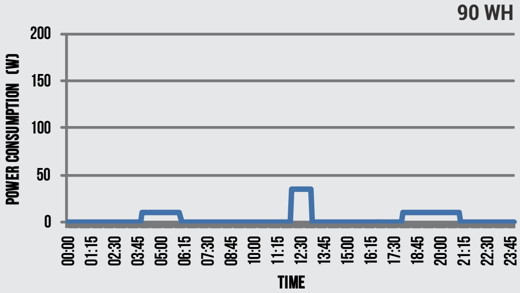
APPLIANCES IN USE BY HOUSEHOLD:



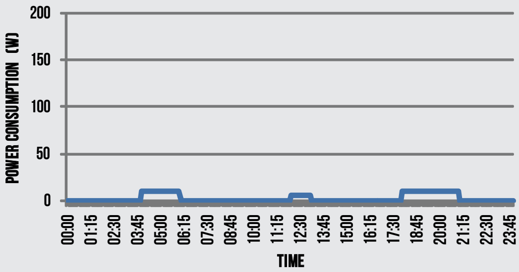
The household will be able to save for a television in the following years, but does not have the money to expand their system. Consumption will shift towards the medium consumption load profiles of 2016.

LOAD PROFILE 2016

STANDARD APPLIANCES — DAILY POWER CONSUMPTION: 90 WH

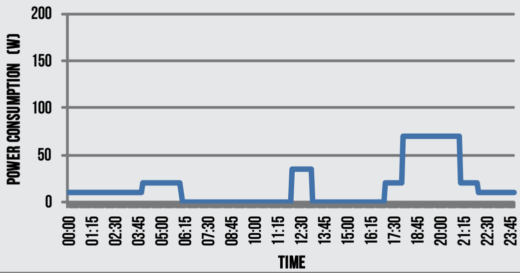


OFF-GRID APPLIANCES — DAILY POWER CONSUMPTION: 58 WH

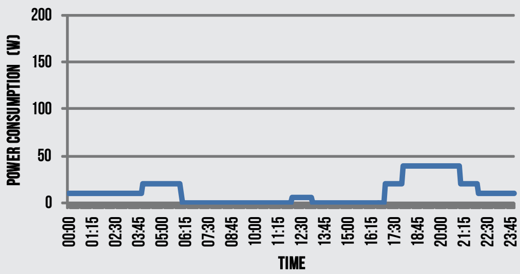


LOAD PROFILE 2021

STANDARD APPLIANCES — DAILY POWER CONSUMPTION: 394 WH



OFF-GRID APPLIANCES — DAILY POWER CONSUMPTION: 270 WH



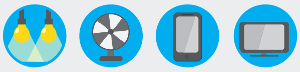
5.3.6 PERSONA 2

MEDIUM CONSUMPTION HOUSEHOLD

This family of 5 is not rich, but the oldest kids works abroad and sends some money every month. The parents are rice farmers. The kid living abroad is able to finance their second solar home system.

2016

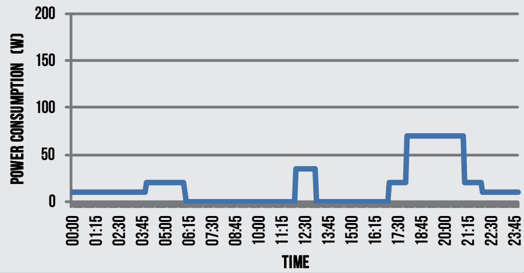
APPLIANCES IN USE BY HOUSEHOLD:



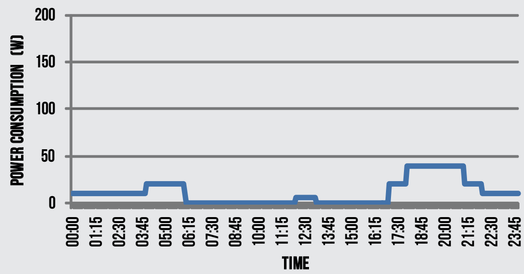
The household leaves one lamp one during the night to keep an eye on their cow and other belongings outside. At lunchtime, they turn on one fan. In the evening, they watch television.

LOAD PROFILE 2016

STANDARD APPLIANCES — DAILY POWER CONSUMPTION: 394 WH

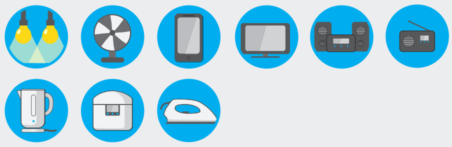


OFF-GRID APPLIANCES — DAILY POWER CONSUMPTION: 270 WH



2021

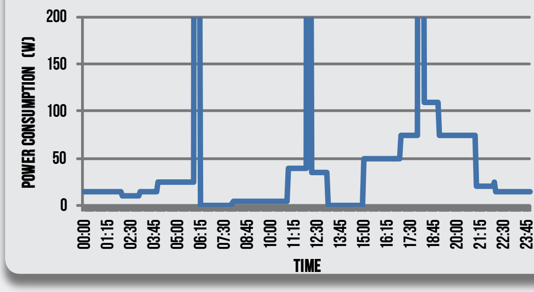
APPLIANCES IN USE BY HOUSEHOLD:



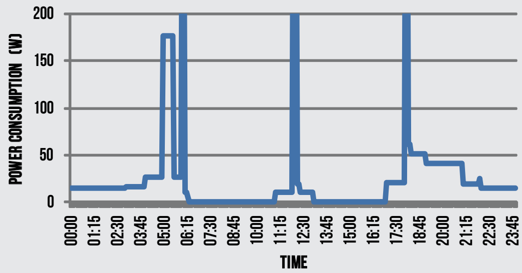
Users have a larger SHS. They own a water kettle, rice cooker and an iron. Multiple phones have to be charged on a daily basis. Furthermore, they own a larger audio system for listening music and a small radio for outside.

LOAD PROFILE 2021

STANDARD APPLIANCES (NO USAGE OF IRON) — DAILY POWER CONSUMPTION: 1244 WH



OFF-GRID APPLIANCES (NO USAGE OF IRON) — DAILY POWER CONSUMPTION: 975 WH



5.3.7 PERSONA 3

HIGH CONSUMPTION HOUSEHOLD

This family of 4 has more opportunities than other households, and can be seen as relatively rich. One household member is the village chief. This household consumes more energy than normal.

2016

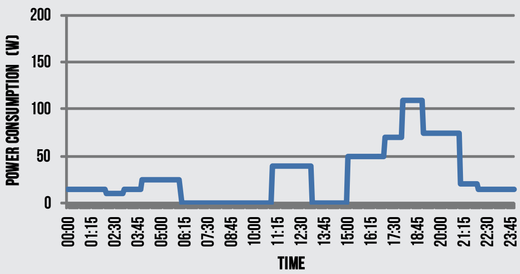
APPLIANCES IN USE BY HOUSEHOLD:

The high consumption is a result of longer usage of fan and television. The TV is larger than standard. They leave one light on during night. They have 2 fans.

LOAD PROFILE 2016

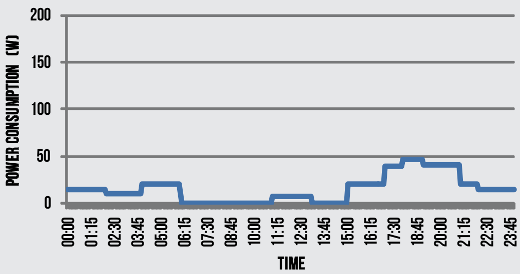
STANDARD APPLIANCES

DAILY POWER CONSUMPTION: 678 WH



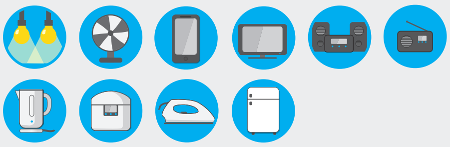
OFF-GRID APPLIANCES

DAILY POWER CONSUMPTION: 371 WH



2021

APPLIANCES IN USE BY HOUSEHOLD:

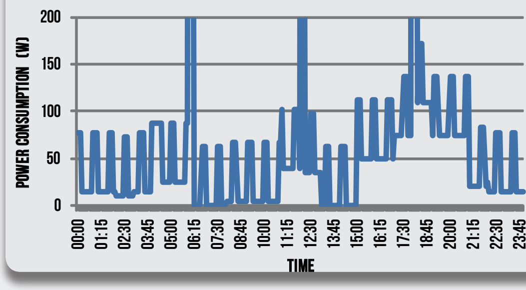


Users have a larger SHS. They own a water kettle, rice cooker and an iron. Multiple phones have to be charged on a daily basis. This user has the financial means to own a fridge and a compatible SHS.

LOAD PROFILE 2021

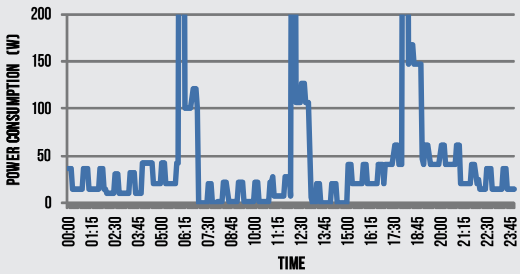
STANDARD APPLIANCES (NO USAGE OF IRON)

DAILY POWER CONSUMPTION: 1718 WH



OFF-GRID APPLIANCES (NO USAGE OF IRON)

DAILY POWER CONSUMPTION: 1134 WH



5.3.8 FUTURE LOAD PROFILES

Adding more appliances will have direct impact on the load profile, as can be seen in load profiles presented in the personas in 5.3.

Some appliances will be used daily and at specific times (water kettle, rice cooker), while other appliances might only be used every now and then (audio system) or perhaps once a week (iron). Fridges will need to be continuously connected, while water kettles, irons and rice cookers will cause high peaks for a short time in the profiles.

Figure 63 displays the total energy consumption per day for the various load profiles as defined in 5.3. There are large differences between the lowest consumption now (58 Wh/day), and the highest consumption in 2021 (2218 Wh/day).

Furthermore, it can be seen that appliance efficiency makes a differences on the energy consumption. Using off-grid appliances results in a lower energy consumption over the day, with a maximum differences at High consumption household during an iron day: 1234 Wh (off-grid appliances) versus 2218 Wh day when using standard appliances.

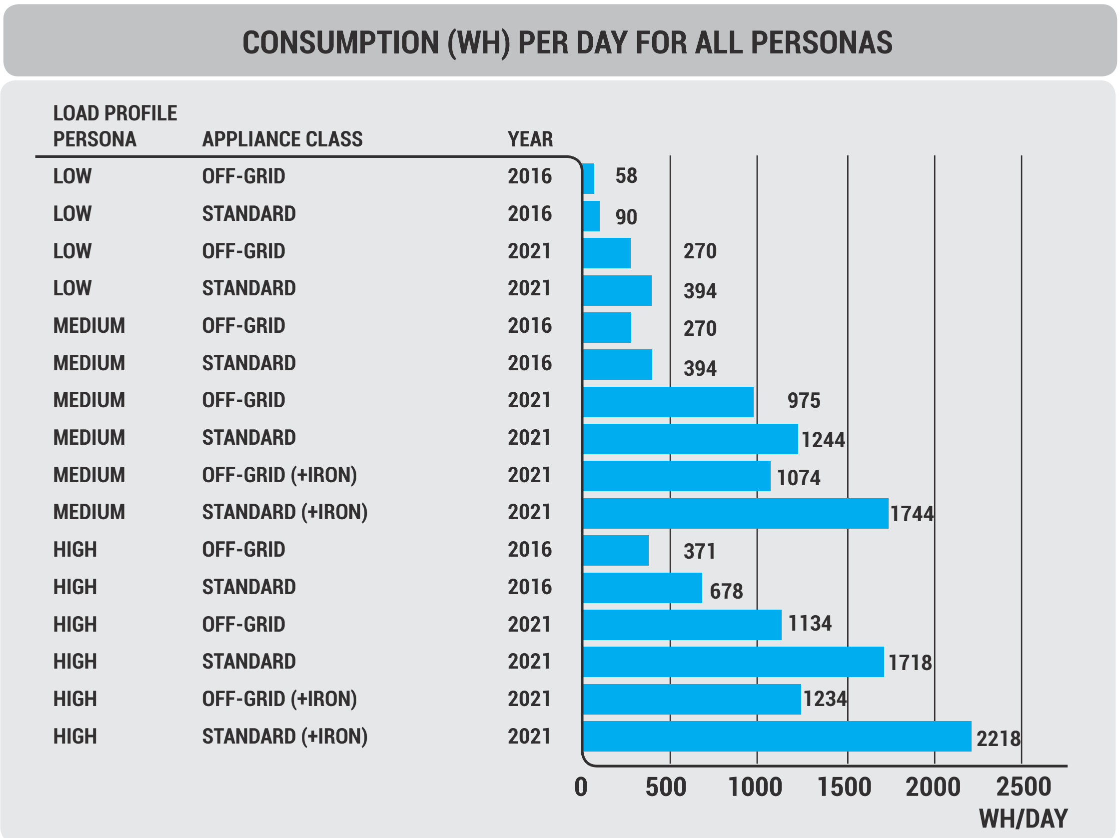


Figure 63: Total energy consumption per day for the different scenarios.

5.4 CONCLUSION

There is user demand for more electricity in rural Cambodia. Participants in the field research indicated to be satisfied with their SHS, but would like to use the TV longer and add more appliances, such as a rice cooker, water kettle, iron and a refrigerator. Main barriers at the moment are price of off-grid appliances and the limited enerygy production of SHSs. To overcome these barriers, appliances should become cheaper and be more efficient.

Three personas were created for the year 2021, based on household interviews and expert interviews. These personas display the variety in needs of the SHS users in rural Cambodia. Low consumption users will not be able to purchase more appliances and expand their SHS in size. As a result, they will use appliances similar to the appliances in use today: lights, fan, phone and TV. Medium consumption users will have the financial power to expand their SHS and purchase a water kettle, a ricecooker and an iron. High consumption users possess a larger SHS. On top of the appliances used by a medium consumption user, they possess a refrigerator.

These personas can be used for reference in future SHS design projects, such as the overarching PhD project.

In the future, load profiles will have more diversity. To accommodate future needs, larger SHSs are necessary. Furthermore, the additional appliances change the shape of the load profile. Irons, water kettles and rice cookers consume large amounts of energy during short periods. This results in high peaks in the load profiles.

Chapter 6 will discuss how future SHS have to be designed to cater for the future needs.

6. FUTURE SHS: MATCHING SUPPLY AND DEMAND

This chapter discusses what design choices can be made by SHS designers and companies in order to decrease costs and optimize system performance. This has the aim to support SHS designers in future SHS design. First, the Load Profile Tool is presented that can be used by SHS designers to calculate load profiles and thereby estimate future (mis)match with system design. Secondly, future system design is discussed. After this section on the supply side, the following part discusses demand side in two sections: 1) choosing the right appliances and 2) how demand side mangement can be benificial in SHS usage. Finally, a design direction is proposed for the overarching PhD-project.

6.1 INTRODUCTION

The previous chapters have described current energy consumption and future energy demand. It has become clear that current systems do not fulfil all user needs and that the demand for energy will grow in the near future. In order to cater for energy needs in the higher tiers (SeeTable 2), SHSs will need to be optimized in both price and performance.

6.1.1 MATCHING SUPPLY AND DEMAND: THREE COMPONENTS

Balancing performance and price in order to meet user needs is a delicate task. The challenge can be approached both from the supply side as well as from the demand side. On the supply side, the system size can be addressed. The demand side is affected by energy consumption patterns and the type and amount of appliances used.

Figure 64 is a visualisation of this challenge, displaying a triangle between system size, appliance and energy consumption patterns.

This chapter will argue why it is important to consider these three components in future SHS design, and describe what actions SHS designers can take in order to match energy supply with future energy demand in future SHS design.

The first section presents the Load Profile Tool that can support designers in calculating future load profiles. The second part of this chapter will discuss what actions can be taken by system designers to create better performing systems at optimized costs. The third part investigates how off-grid appliances should be incorporated in the SHS context. After this, it will be discussed how design can stimulate behaviour changes of SHS users in order to optimize the load profile. Finally, a design direction is proposed for the overarching PhD-project.

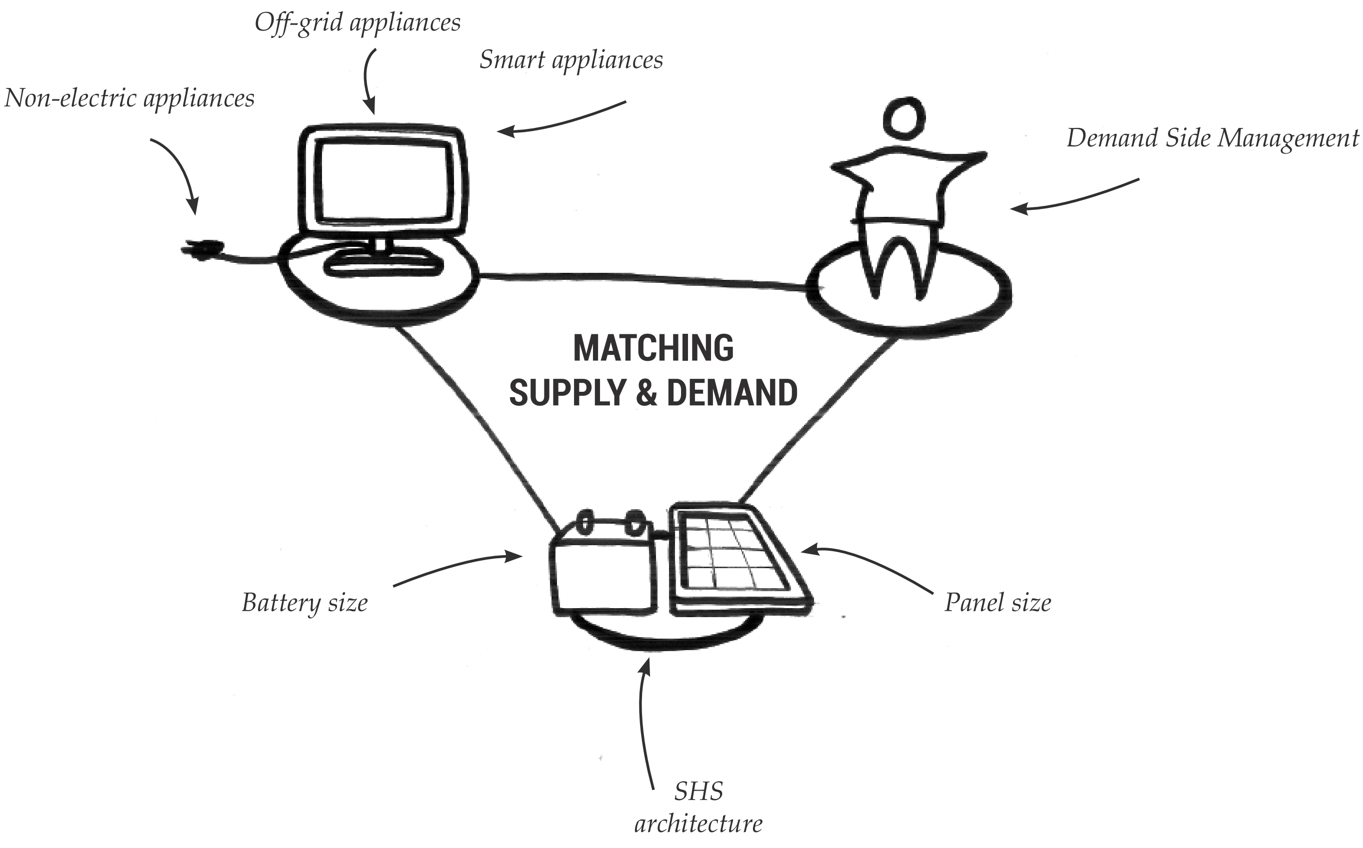


Figure 64: Matching supply and demand.

6.2 LOAD PROFILE TOOL: CALCULATING MISMATCH

Chapter 5 has described the research on future energy consumption through a case study in Cambodia. This section presents a Load Profile Tool that can support SHS designers in estimating future energy demand by constructing load profiles for other contexts, other moments in time or users with different energy consumption patterns.

The goal of the Load Profile Tool is two-fold: 1) it can be used to construct future load profiles and 2) it can be used to investigate the influence of appliances on future load profiles. The flexibility of the Load Profile Tool makes it perfectly suitable for application in other moments in time and environments. This is necessary, since lifestyles and demand of appliances can vary. These variations will result in different load profiles.

In the Load Profile Tool, multiple parameters can be adjusted. The user of the Load Profile Tool can select which appliances are owned by the SHS user, fill in the power rating of these appliances and the energy consumption patterns of the appliances. The Load Profile Tool will construct the load profile based on this input.

6.2.1 LOAD PROFILE TOOL: SYSTEM PERFORMANCE

Besides the load profile, the Load Profile Tool provides more useful outcome for the SHS designer. The SHS designer can insert basic system parameters (panel size and battery size), in order to estimate the system performance of future SHS.

The Load Profile Tool can estimate the battery SoC over time during one day. The SoC-graphs are suitable to analyze the relationship between energy consumption patterns and battery SoC. Next to this, the Load Profile Tool can show at what time of the day a deficit of energy supply occurs.

	Time 1		*Time 2*		*Time 3*	
Appliances	*On*	*Off*	*On*	*Off*	*On*	*Off*
Light 1	[illegible]:00	06:00	-	-	-	-
Light 2	18:00	21:00	-	-	-	-
Light 3	-	-	-	-	-	-
Light 4	-	-	-	-	-	-
Fan	12:00	13:00	-	-	-	-
Fan	-	-	-	-	-	-
Fan	-	-	-	-	-	-
Fan	-	-	-	-	-	-
TV	18:00	21:00	-	-	-	-
TV	-	-	-	-	-	-
Phone	-	-	-	-	-	-
Phone	-	-	-	-	-	-
Radio	-	-	-	-	-	-
Speakers	-	-	-	-	-	-
Rice cooker	-	-	-	-	-	-

	Power rating(W)	*Power rating(W)*
Appliances	*Low efficiency*	*High efficiency*
Light 1	10	10
Light 2	10	10
Light 3	10	10
Light 4	10	10
Fan	35	6
Fan	35	6
Fan	35	6
Fan	35	6
TV	50	20
TV	50	20
Phone	5	5
Phone	5	5
Radio	5	1
Speakers	30	10
Rice cooker	400	100

	User load profile
Consumption profile	High consumption
Appliance efficiency	High efficiency
Year	2021
Solar panel size	200
Battery 1 Capacity	1200
Battery 2 Capacity	0
Battery 3 Capacity	0
Battery 4 Capacity	0
Battery SoC (00:00)	69%
Total power consumption (Wh)	1134
Total power demand (Wh)	1134

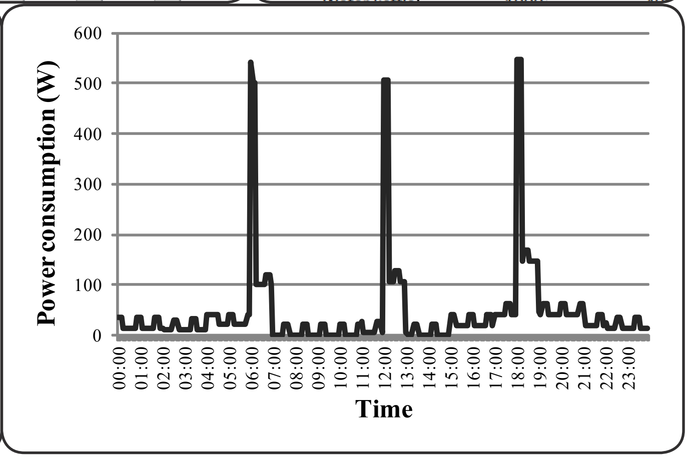


Figure 65: Screenshots of the Load Profile Tool.

6.3 MATCHING SYSTEM WITH FUTURE NEEDS

This section describes what design decisions SHS designers can make in order to better match energy supply with energy demand. First, system sizing is discussed. This is done by means of LLP (see 3.2.1). Secondly, the key SHS performance parameters are discussed. The implications of higher energy demand on the battery, the solar panel and balance of system are examined. Furthermore, the approaches of using modularity and interconnectivity to increase system level are discussed.

6.3.1 LOSS OF LOAD PROBABILITY (LLP)

As described in section 3.2.1, LLP is a value to measure the amount of time when the SHS is not able to supply the amount of power that is demanded by the user. LLP can thus be used as a method to assess a SHS on the fit with future needs. LLP must be seen as a tool to predict the performance of future systems, and not as one to evaluate current system performance. Narayan (2016) has developed a model that can be used to calculate the LLP for several predetermined system sizes. The mathematical model can determine for any moment in time whether the loads are satisfied. By doing this for small intervals in time, it can estimate the amount of time the system does not satisfy the loads.

The LLP can be used for optimization purposes. As an example, LLP can be used to calculate the necessary battery size corresponding with a specified solar panel size. Figure 66 presents an example of such a calculation. The battery size is calculated for 3 different sizes of solar panel. (Narayan, 2016) The LLP is calculated on a one minute resolution. For estimating the amount of energy generated by the solar panel, irradiance data from Meteonorm tool was used. (Narayan, 2016) For the calculations, the following load profile was used: medium power consumption persona using standard appliances (as presented in section 5.3). Usage of an iron is not taken into the calculation.

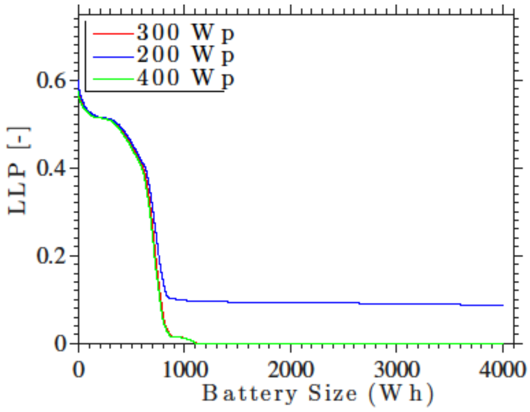


Figure 66: LLP for multiple panel sizes. Load profile: medium consumption 2021 with standard appliances (Narayan, 2016)

The results show that a 200 Wp panel does not generate enough energy to satisfy this load profile. The LLP never reaches 0 , regardless battery size (up to 4 kWh). The 300 and 400 Wp panel in combination with a battery of at least 1133 Wh is sufficient for LLP=0.

6.3.2 OPTIMIZING SYSTEM SIZE

An optimization study was performed by Narayan (2016). This was done in order to find the best suitable combination of solar panel and battery size for these load profiles. The requirement was set that LLP equals 0. The results can be found in Table 16 on page 94. For each future load profile, the minimum required battery size is calculated for 5 panel sizes. In this calculation, oversizing (see 3.1.3.2) is not taken into account. Furthermore, the weekly usage of an iron is not taken into the calculation.

In the empty boxes in Table 16, there is no solution for any battery size. This because the solar panel generates less energy than is consumed. In these cases, the requirement that LLP=0, cannot be met. In general, the calculations show that battery capacity and panel size need to increase significantly in order to fulfil the future medium and high power consumption load profiles.

6.3.2.1 SOLAR PANEL SIZE

In order to cater for the increased future energy demand, the amount of energy that is generated by the solar panel will need to increase. The Low consumption load profile persona can be served with a 100 Wp system, but it is clear that Kamworks' current 100 Wp system will not be enough to power the needs of a medium and high consumption household in the future. Of the panel sizes that were considered, the Medium consumption load profile persona (2021) using off-grid appliances, can only be satisfied with at least 300 Wp. The High consumption load profile persona (2021) can be served with a 300 Wp panel, if off-grid appliances are used. Otherwise, larger panels are necessary. The most demanding persona (High consumption 2021, standard appliances) will need a large, 400 Wp panel, and a battery of at least 1899 Wh.

In conclusion, there is a big difference between what the lowest profiles need (100 Wp) and what the most demanding households require (400 Wp).

6.3.2.2 STORAGE CAPACITY

The storage capacity needs to be increased in order to suffice the growing energy demand. The battery sizes displayed in Table 16 are the minimum required battery sizes for the respective load profiles. Even with the lowest load profiles, a battery remains necessary to serve the energy needs at night. The personas that consume more energy require a battery between 886 Wh (Medium, off-grid appliances) and 1899 Wh (High, standard appliances).

Besides increasing system size, it is clear that other solutions have to be used to match energy supply and demand, such as switching from standard appliances to more efficient off-grid appliances. It can be concluded that the diversity in energy demand between households requires different sizes of battery.

SYSTEM SIZING OPTIONS FOR DIFFERENT BATTERY-PANEL COMBINATIONS (LLP =0)

LOAD PROFILE PERSONA	APPLIANCE CLASS	YEAR	PANEL SIZE				
LOW	OFF-GRID	2016	50 WP	100 WP	200 WP	300 WP	400 WP
LOW	STANDARD	2016	65 WH	65 WH	65 WH	65 WH	65 WH
LOW	OFF-GRID	2021	65 WH	65 WH	65 WH	65 WH	65 WH
LOW	STANDARD	2021	-	445 WH	445 WH	444 WH	444 WH
MEDIUM	OFF-GRID	2016	3540 WH	329 WH	329 WH	329 WH	329 WH
MEDIUM	STANDARD	2016	-	445 WH	445 WH	444 WH	444 WH
MEDIUM	OFF-GRID	2021	-	-	-	888 WH	886 WH
MEDIUM	STANDARD	2021	-	-	-	1133 WH	1100 WH
HIGH	OFF-GRID	2016	-	408 WH	400 WH	398 WH	396 WH
HIGH	STANDARD	2016	-	-	660 WH	643 WH	635 WH
HIGH	OFF-GRID	2021	-	-	-	1014 WH	1013 WH
HIGH	STANDARD	2021	-	-	-	-	1899 WH

Table 17: Minimimal system sizing options, calculated for the load profile personas. Possible usage of an iron is not taken into the calculations. (Narayan, 2016)

6.3.3 BATTERY CHARGE & DISCHARGE PROFILE

This section will explore the impact of future load profiles on the battery. As described in section 3.2.2 and presented in Table 10, the following battery characteristics have an important role during the design process of a SHS:

- storage capacity
- DoD
- cycle life
- SoC
- C-rate

The storage capacity has been discussed in section 6.3.2.2. This section will discuss SoC, DoD and the C-rate by means of an example load profile. After the SoC, DoD and C-rate have been discussed, the impact of the load profiles on cycle life will be discussed.

To illustrate the effects of the future load profile, this section presents an example load profile and the corresponding battery SoC for one day. An extreme load profile is chosen: the high consumption load profile of 2021 on a day when the iron is used, using standard appliances. The resulting load profile is presented in Figure 65 on page 97. The battery SoC that corresponds with the load profile is presented in Figure 63 on page 87. The system used in the calculation has a 200 Wp solar panel and a 1200 Wh battery.

The battery SoC is can be described in four keypoints, which correspond to the numbers displayed in the graph:

1. At the start of the day, the battery is completely charged. The small peaks in the load profile throughout the day are the result of the refrigerator turning on and off. This causes ripples in the battery SoC.

2. In the early morning, the battery gets discharged rapidly to a deep level. This is caused by the usage of the iron, a rice cooker and the water kettle (the high peaks in the future load profile between 5.00h and 6.00h).

3. After this, the battery gets charged, until approximately 12.00h. Around 12.00h, lunchtime, the water kettle and rice cooker are used again. The battery gets discharged.

4. At the end of the day it is almost empty. This system is clearly not big enough to power the appliances demanded. There will not be enough energy for the next day. Furthermore, the levels of discharge are very deep, negatively impacting the battery lifetime.

The differences between the current and the future load profile should be considered in future SHS design. This because of two main reasons that affect the cycle life: high C-rates and deep DoDs.

In the current situation, the C-rates are low. In the future, the C-rate will be higher due to the high peaks in energy demands, caused by the usage of appliances as a water kettle, iron and rice cooker. The high C-rates will have a negative influence on the cycle life of the batteries.

Secondly, the higher energy demand during peaks will cause deep discharges. Furthermore, the large peaks in the early morning will result in deep discharges before the sun starts to shine. Deep discharges can be prevented by higher battery capacity.

Besides larger batteries, system designers can also opt for battery technologies that are less sensitive to deep discharges, such as li-ion technologies.

Another option is to make use of a hybrid battery system, including both a li-ion and lead-acid battery. In this manner, the lead-acid battery can serve the loads at low C-rates while the li-ion battery can accommodate high C-rates and have cycles with deep discharges.

HIGH CONSUMPTION HOUSEHOLD 2021 | IRON DAY | STANDARD APPLIANCES

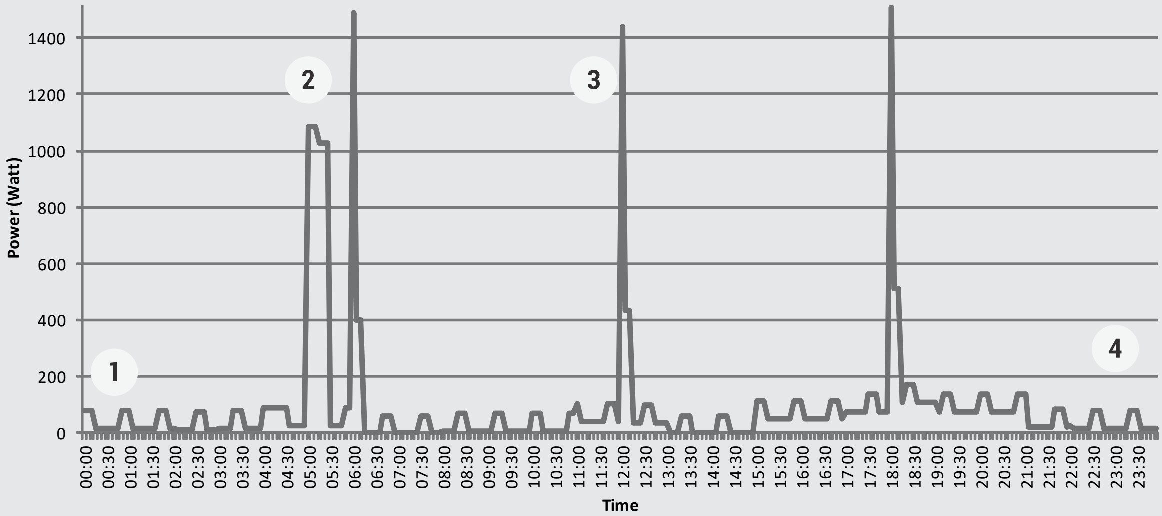


Figure 67: Load profile: high consumption household in 2021 on a day the iron is used, using standard appliances.

CORRESPONDING BATTERY SoC FOR LOAD PROFILE

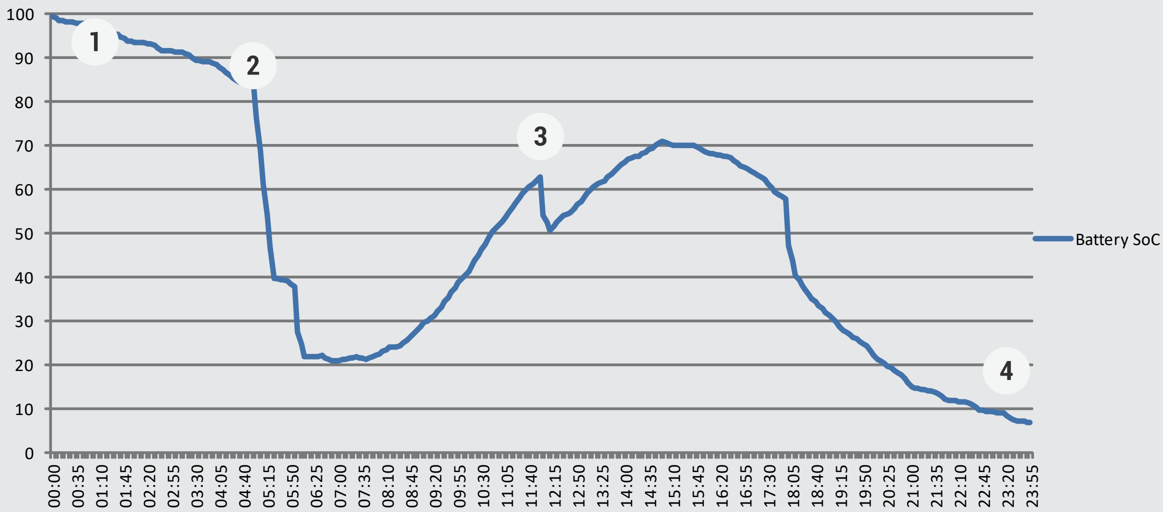


Figure 68: Impact of load profile on Battery SoC for a 200 Wp solar panel, 1200 Wh battery.

6.4 SYSTEM ARCHITECTURE

In order to suffice the future energy demand, there are several options for the system architecture. This section will compare three options for the composition of future SHS:

- Stand-alone non-modular systems;
- Modular systems;
- Interconnected systems.

6.4.1 STAND-ALONE NON-MODULAR SYSTEMS

Most rural off-grid systems available at the market today are not scalable. SHS companies offer a range of sizes (e.g. Kamworks), or one size only. The systems cannot be interconnected.

Drawback of this approach is that users will carefully have to select which system suits them best, as expansion is not possible. When the SHS user demands more energy, he/she can buy multiple systems when they can afford this. However, as the SHSs are not connected, the user will have to divide the loads itself over both SHSs.

The advantages of this approach are the advantage of an economy of scale. SHS companies can purchase components (e.g. battery and solar panel) in bulk. Furthermore, systems are less complex than interconnected and modular system and thus easier to design.

6.4.2 MODULAR SYSTEMS

Recently, the development of modular systems has gained more traction. Modularity can be expressed in various manners, but in essence comprises a system that can be expanded in panel size and/or battery capacity. In this manner, it can be configured to the needs of the household. Consequently, it can adapt to different needs and to growing energy demand.

Modularity of system size can be achieved through a variety of technological solutions. Systems can be integrally modular or components can be expanded separately.

In the first case, SHSs can be expanded by adding a complete additional SHS. In this way, the battery, panel and BoS components are expanded. A disadvantage is that the ratio between solar panel and battery is fixed. Users can only choose from a limited amount of options. Furthermore, BoS components will also be added, resulting in redundant components.

In the case of separately modular components, a solar panel can be added when more energy needs to be generated and the battery can be expanded when more energy needs to be stored. In this way, the system can be designed much more precisely to fit the user's needs. For example, different battery types can be installed to serve low energy demand (cheap lead-acid for e.g. TV and fan) and loads with high C-rates (li-ion for appliances such as rice cookers and water kettles).

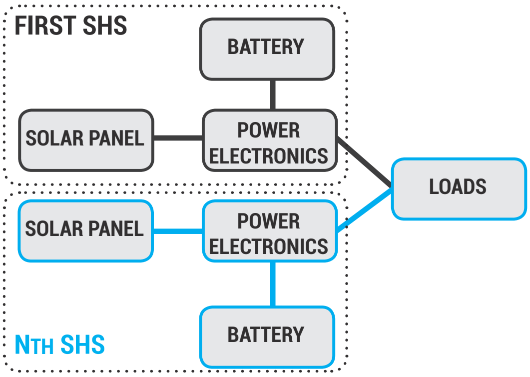


Figure 70: Integrally modular SHS.

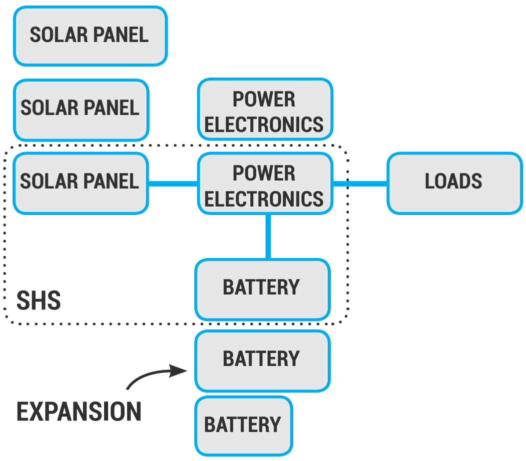


Figure 69: Modular SHS with separately expandable components.

A disadvantage is that the BoS components should be designed to handle larger system sizes while it is uncertain whether this is needed. This can result in redundant components that increase the costs. Another potential pitfall of modularity was found during the field research. During the household visits in the field research, modularity was discussed with the SHS users. Furthermore, virtual purchasing patterns of appliances between a modular SHS and large non-modular SHS were compared. The simulation in the research therefore involved two rounds; in the first round the ownership of a modular solar home system (up to 4 small systems) was simulated, and in the second round ownership of a large solar home system (equal to 4 small systems) was simulated. A certain pattern emerged during the simulation. After evaluating, it appeared that in round 1, only one participant had virtually bought a fridge. In the second round, there were 5 out of 7 participants who had bought a fridge. This raises the following issues:

1) If people have a modular system, users will consume more energy with each upgrade by adding more appliances. This will leave no power for appliances that consume more energy (such as a fridge or similar) in the end.

2) Will people expand their SHS to power appliances such as a water kettle or a ricecooker, if they have to pay a significant sum of money for a SHS?

These issues need to be adressed through smart business models that correspond with the right system architecture. For example, SHS companies can sell SHS modules in combination with off-grid appliances.

6.4.3 INTERCONNECTED SYSTEMS: MINI-GRIDS FROM THE BOTTOM-UP

In many BoP environments, mini-grids are a good solution to serve an energy poor village. However, one of the barriers for mini-grids as a concept is that the design has to be adaptable and fit a variety of community sizes, load demands and the available power resources. (Chattopadhyay et al., 2015)

Interconnected systems forming a mini-grid from bottom-up can solve some of the challenges. In this type of system architecture, SHSs are connected with each other and can exchange energy. With interconnected SHSs, energy can be divided over the households. By doing so, the mini-grid can accommodate variations in energy demand between households. Furthermore, not all the households need to possess a battery and/or panel. A good example of this interconnectivity is Solshare. (SOLshare, 2017)

Multiple architectures of interconnectivity are possible. For example, households can be connected to a centralized distribution network, alike a mini-grid. See Figure 71. Another option is to connect households in a swarm-grid, in which households are connected to multiple houses. (SOLshare,

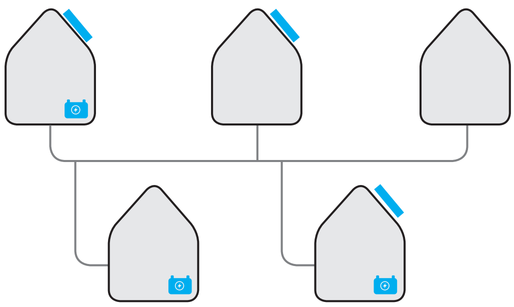


Figure 71: Interconnected households, connected through a centralized distribution network.

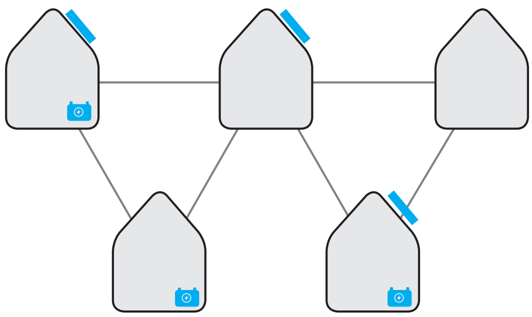


Figure 72: Interconnected households in a swarm. (SOLShare, 2017)

2017) See Figure 72.

Drawback of interconnectivity is that it requires additional technology and components, e.g. for power distribution, network controls and payment methodology. Furthermore, this approach is not suitable for every environment. Using interconnectivity is not a useful approach in for example rural Cambodia, since households are dispersed; the distance between houses is often very large. This requires a proper supporting infrastructure including long and expensive cabling. Interconnectivity is better suited for centralized villages.

The choice for system architecture decision that has to be made in an early phase of the design process. It has an impact on many technical and non-technical product aspects. A comparison between large non-modular systems, modular systems, and interconnected systems is presented in Table 18.

LARGER SYSTEMS: A COMPARISON

	LARGE NON-MODULAR SYSTEMS	MODULAR SYSTEMS	INTERCONNECTED SYSTEMS
ADVANTAGES	• Only one installation is necessary. • Non-modular systems are a proven technology.	• A modular system is scalable. It can thus fit the needs for users exactly. • Users can opt to increase their system size when they have more financial means.	• Energy can be distributed between households. • Not every households needs a battery and/or panel.
DISADVANTAGES	• System size is not adjustable to the users energy demand. • The households can buy a second system in the future, in case energy demand increases. However, this second SHS will not be connected to the system already owned. This has the drawback that users have to switch between systems if one of the loss of load occurs at one of the SHSs.	• Modular system will need multiple moments for installation. This results in added installation costs. • Modular systems are more complex. More components need to be managed and scalability should be taken into account in the design. • New technologies can lead to unforeseen problems.	• Interconnected systems are more complex. More components need to be managed and scalability should be taken into account in the design. • New technologies can lead to unforeseen problems. • Need for a power distribution infrastructure, control infrastructure and payment infrastructure.

Table 18: A comparison between non-modular, modular and interconnected systems.

6.5 CHOOSING THE RIGHT APPLIANCES

The previous section has described how the growing future needs can be met by increasing energy supply. This section will describe the same challenge from the supply side: by reducing energy demand. Approach of this section is to discuss how energy demand can be reduced by changing the kind of appliance.

As the amount of energy that a SHS can provide is limited, energy efficiency of the connected appliances is critical. As described in section 2.3.2, using off-grid appliances specifically designed for the BoP context can be a manner to reduce energy consumption. Various manufacturers offer suitable products, that have a low power rating and come at an affordable price. The implementation of efficient LED lighting products has already proven to be successful. (Global LEAP, 2016)

While electric appliances come with many advantages and great convenience, it is not always the only solution to battle energy poverty. For many categories of appliances, alternatives exists that do not rely on electricity. One of the arguments for not using electric powered appliances, are the efficiency losses that occur during the conversion of solar power to electric power and during the usage of appliances. Using irradiation directly to generate heat will eliminate electrical components. Several products are out on the market targeting off-grid consumers. A good example of such a product is a solar water kettle. Figure 73 depicts a SunRocket, which uses reflective panels to heat and boil water. (Amazon, 2017) Another example of a non-electric product that can substitute an electric appliance, is a solar cooker. Figure 74 depicts a solar cooker, which concentrates sunlight in order to heat up pots and pans. A solar cooker could be an alternative for an electric rice cooker and for a conventional, polluting stove. In the same direction, the use of clean cooking stoves could be promoted, such as the product from African Clean Energy (African Clean Energy, 2017)

Besides more efficient appliances, other technological advancements can stimulate a reduced demand for energy. For example, smart appliances can (semi-) automatically operate at times when this is most desirable, for example at times when the sunshines. (Kobus, 2016) This could for example be a refrigerator that cools down more than necessary during the day, so that it does not need as much power from the battery during the night.

The solutions discussed do not require much effort from the user, besides choosing for the right appliances. This is exactly where the problem is: adoption of these products is low. A key barrier for the development of the off-grid appliance market are financial challenges. Other challenges are policy challenges, product quality, product availability and distribution and lack of information and consumer awareness. (Global LEAP, 2016) SHS companies are trying to battle these barriers by offering SHSs in a package deal with appliances such as LED lighting and TVs. (Kamworks, 2016; Good Solar Iniative, 2017) As indicated by Global LEAP (2016), the market for off-grid appliances is huge. Selling appliances next to SHS could be an extra revenue source for the SHS companies. In the future, SHS companies should put more focus on offering energy efficient appliances in combination with the SHSs. In doing so, system size can be decreased, thus reducing costs. The money that is saved by this cost reduction can be invested in new, energy efficient appliances.

Figure 73: An example of a non-electric appliance on solar energy: Sunrocket.

Figure 74: Solari solar cooker. (Project Solari, 2017)

6.6 CHANGING THE LOAD PROFILE

This section will present a short introduction on Demand Side Management (DSM) and what value it could have for SHSs, based on literature study. Secondly, a short study is presented that evaluates the possible benefits of DSM for SHS users. This paragraph concludes with the description of the design process that has resulted in ideas for DSM in combination with SHSs.

6.6.1 DEMAND SIDE MANAGEMENT

DSM includes every measure that is taken on the demand side of an energy system in order to keep the right balance between supply and demand. (Palensky & Dietrich, 2011) Although DSM-theory is primarily targeting grid-operators and grid-users, some methodologies and theories could well be applied on SHSs. First of all, it is important to understand in what way load profiles can changed. Goswami and Kreith (2015) have illustrated six load-shape-changing possibilities. These possibilities are presented in Table 19. In the same table, it is briefly described how these possibilities can be translated into opportunities for SHSs.

6.6.2 IMPLEMENTATION OF DSM

There is a large variety of methods that have the aim to implement DSM and change load-profile shape. The International Energy

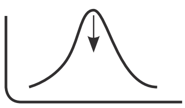
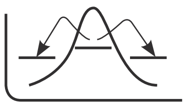
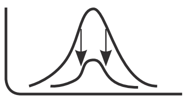
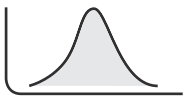
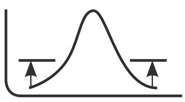
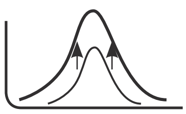
DSM STRATEGY	DESCRIPTION	APPLICATION IN SHSs
 Peak clipping	Reducing peak loads.	Spread loads over longer periods of time, to lower C-rates.
 Load shifting	Shifting loads from on-peak to off-peak periods.	Shifting loads to time when the sun shines.
 Strategic conservation	Reduction in consumption and change in pattern of use.	Reduce energy demand.
 Flexible load shape	Changing the load depending on the supply.	Appliances that (semi-) automatically operate at optimal times or at limited power, responding to supply.
 Valley filling	Stimulating extra energy use during off-peak periods.	Operate appliances when excessive energy is available.
 Strategic load growth	Increased usage of products/ appliances that require electricity.	Anticipate on growing future energy needs by optimizing SHS design.

Table 19: Possibilities for changing the load-profile-shape. (Goswami and Kreith, 2015)

Agency (2003) has divided them in two categories: system-led and market-led.

System-led methods enable the energy supplier to alter demand when market or system condition require this, for example in the case of energy shortages. This can be done for example with loads from grid-users that participate based on agreements made on beforehand. (International Energy Agency, 2003) An incentive to participate in such programs can be reduced energy tariffs. An example of a system-led method is direct load control. This requires controls that are installed on interruptible appliances, such as electric heaters or air conditioning. These appliances can then be controlled remotely by grid-operators. While system-led methods are grid-oriented, the principles can well be translated to SHSs technology. Directly controlled appliances (e.g. refrigerator) could be automatically controlled when necessary, e.g. when not enough energy can be supplied.

Market-led methodologies are generally based on agreements between electricity retailers and electricity customers. In these agreements, rates are decided for certain parts of the day. Examples are Time-Of-Use pricing and Real-time pricing. (International Energy Agency, 2003) As SHSs are stand-alone and energy tariffs do not play a role, these pricing mechanisms will not have effect on the current SHSs. In the future, this might change when systems become grid-connected or interconnected.

Kobus (2016) describes two other smart energy methodologies that are often used: smart appliances and Energy Management Systems (EMS). With smart appliances, users can select the most desirable time for usage, for example by considering electricity rates and weather forecasts. In the case of SHS, smart appliances could turn on automatically if there is an abundance of sun, or turn off when necessary. An EMS (also Home EMS) is a system that can manage, monitor and provide (visual) feedback about energy consumption of appliances or households. (Van Dam, Bakker, & Van Hal, 2010) Besides real-time feedback, some EMSs include feed forward on for example electricity tariffs or weather forecasts. Furthermore, EMSs can include comparisons with historical or normative load profiles. (Kobus, 2016) Households can use the feedback and feed forward from the EMS to change their demand patterns manually, but some EMSs can also automatically turn appliances on or off. (Kobus, 2016) An example EMS, Toon by Eneco, is displayed in Figure 75.

Figure 75: An example of a Energy Management System: Toon. (Eneco, 2017)

In the BoP context with stand-alone systems, different solutions are required. The following section will describe the idea generation that was done to create solutions that can stimulate a change in demand patterns in order to match demand with energy supply.

6.6.3 DEMAND SIDE MANAGEMENT IN CAMBODIA

In order to implement DSM in SHSs, different solutions are required. As the load profile of SHS is depending on the used appliances and the energy consumption pattern (see section 3.1.1), changes should come from changing the appliances or the energy consumption pattern. Changing the appliances has been discussed in section 6.5. This paragraph will focus on changing the energy consumption patterns.

Figure 76 is presented by Kobus (2016), and is a decision tree that shows the appliances related opportunities to change the load profile. The following section will discuss these opportunities, applied to the context of rural Cambodia.

For SHSs, the biggest opportunities are there for appliances that are not perceived to be time-critical of which energy consumption patterns can be changed. For example, products could be used at times when the sun shines.Appliances that are perceived time-critical, are for example lighting. Energy consumption patterns of lighting cannot be altered as it is a necessity at night.

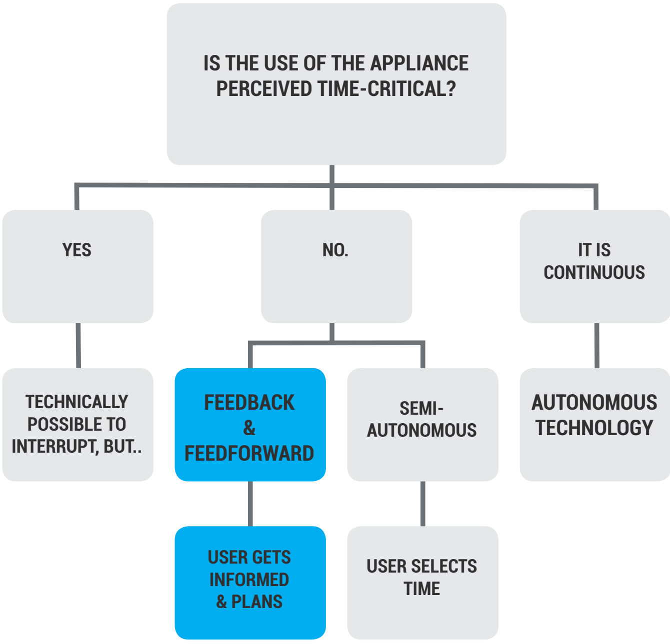


Figure 76: Opportunities to change the load profile. (Kobus, 2016).

In the present, there are no appliances used continuously. In the future, refrigerators might changes this. Integrating smart technology into these appliances can for example be used to create a flexible load shape or smart load shifting.

The following practical examples illustrate how this DSM can be translated to SHSs in rural Cambodia:

- Shift energy consumption as much as possible to times when the sunshines.
- Spread power peaks; do not operate multiple appliances at the same time.
- Shift time of ironing from morning to noon.
- Turn appliances automatically off when battery is running low.
- Boil hot water around noon and store water in thermosflask.
- Refrigerators can be cooled to minimum temperatures at times when the sun shines.
- Phones can be charged at peak power generation.

6.6.3.1 IMPACT OF DEMAND SIDE MANAGEMENT

To illustrate what this would mean in the usage of a SHS, a storyboard is created. See Figure 77. The storyboard depicts one day in the life of a rural Cambodian household. Two households are compared: one with DSM (right side), and one without (left). The storyboard "With DSM" displays the resulted interaction of a SHS user after it is coached to change its energy consumption behaviour. The storyboard is specific for the Cambodian environment. In a different country, different energy consumptions patterns will request a different way of DSM.

To estimate the effect of the optimized load profile, the Load Profile Tool is used (see section 6.2). Next to the Load Profile, the battery SoC is calculated. For the calculations, a SHS is considered with a 1200 Ah battery and a 300 Wp panel. As a load profile, the Medium energy consumption profile of 2021 is chosen, using standard appliances, on a day when the iron is used. The load profiles and corresponding battery SoC are present in Figure 78 on page 107.

The advantages of DSM are clear. Without DSM, the user will encounter an empty battery two times: 1) in the morning after ironing, and 2) at the end of the day.

Secondly, deep discharges at high C-rates are prevented. This because appliances are not used simultaneously. This ultimately results in a longer lifetime of the battery. A longer lifetime will lead to a reduction in costs.

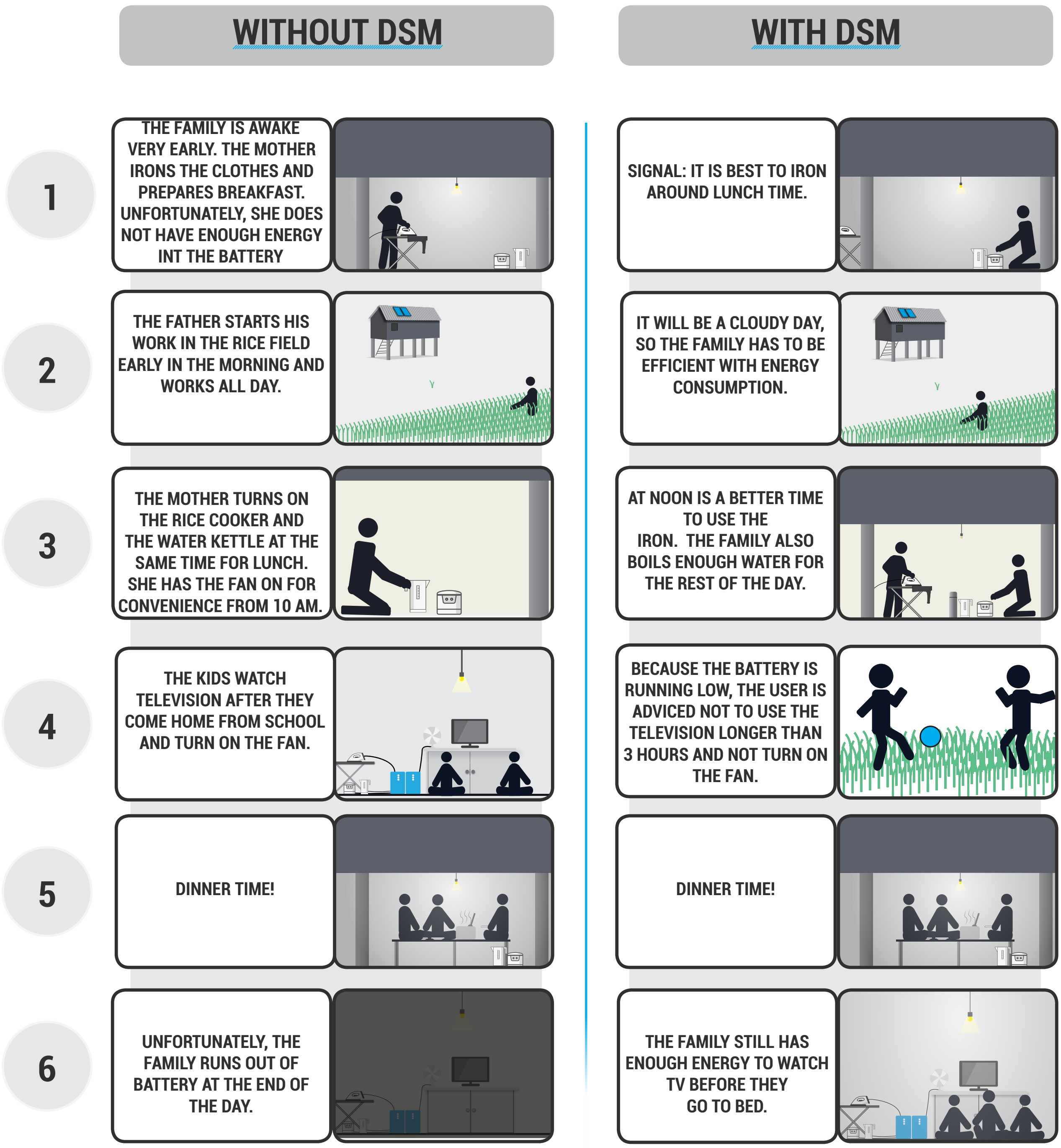


Figure 77: Scenarios for households without DSM (left) and with DSM (right).

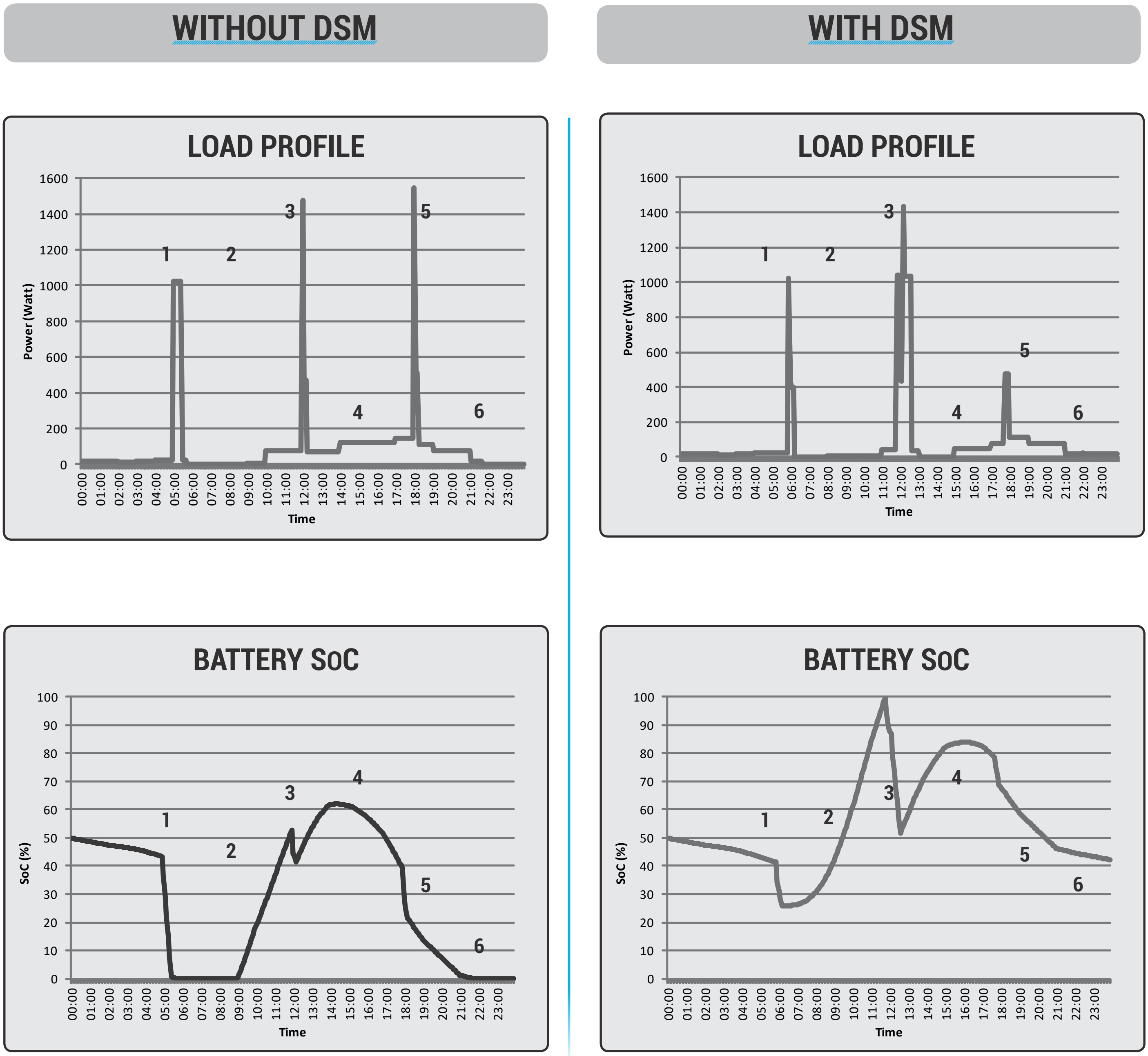


Figure 78: Impact of DSM on load profile and battery SoC. The load profile that is used for the calculation: Medium consumption 2021, standard appliances, on a day that the iron is used. Total energy consumption: 1074 Wh/day. The SHS has a 300 Wp panel and a 1200 Ah battery.

6.7 A CHANGE IN ENERGY CONSUMPTION PATTERNS BY DESIGN

Section 6.6 has presented the possible benefits of using DSM in SHSs. There are several options to achieve a change in load profile. However, the currently existing methodologies are not applicable to SHSs. The following section will describe the idea generation that was done to create solutions that can stimulate a change in demand patterns in order to match demand with energy supply.

It will be described how a change in energy consumption patterns can be achieved through design. Part of this phase was a brainstorm session, held to generate ideas. Afterwards, the ideas are categorized by means of a morphological chart. Finally, multiple concepts are presented.

6.7.1 DSM FOR SHSS: IDEA GENERATION

In order to generate ideas for DSM in combination with SHSs, a brainstorm session was held. The brainstorm session is described in this part of the report. The goal of the brainstorm session was to generate ideas that minimize a mismatch in energy supply & energy demand by changing the user-product interaction.

The brainstorm consisted of two rounds. In the first round, the participants were asked the following question: *How can we change energy consumption patterns?* In this round the participants sat around a table and wrote down their ideas on post-its. The participants were asked to discuss their ideas out loud to inspire others.

During the second round, the participants were asked to make a sketch of a SHS integrating smart technologies. Each participant was assigned a country for where the SHS had to be designed. After 3 minutes, the participants had to pass the idea on to the next participant. The next participant could then add ideas upon the initial sketch, guided by keywords.

Figure 79: Brainstorm session 14-11-2016

The brainstorm session was participated by:

- two students from Industrial Design Engineering (TU Delft), working on a SHS project in Rwanda;
- one recent graduate from Integrated Product Design (TU Delft);
- one graduate student at the TU Delft Electrical Sustainable Energy department.
- two PhD-candidates at the TU Delft Electrical Sustainable Energy department.

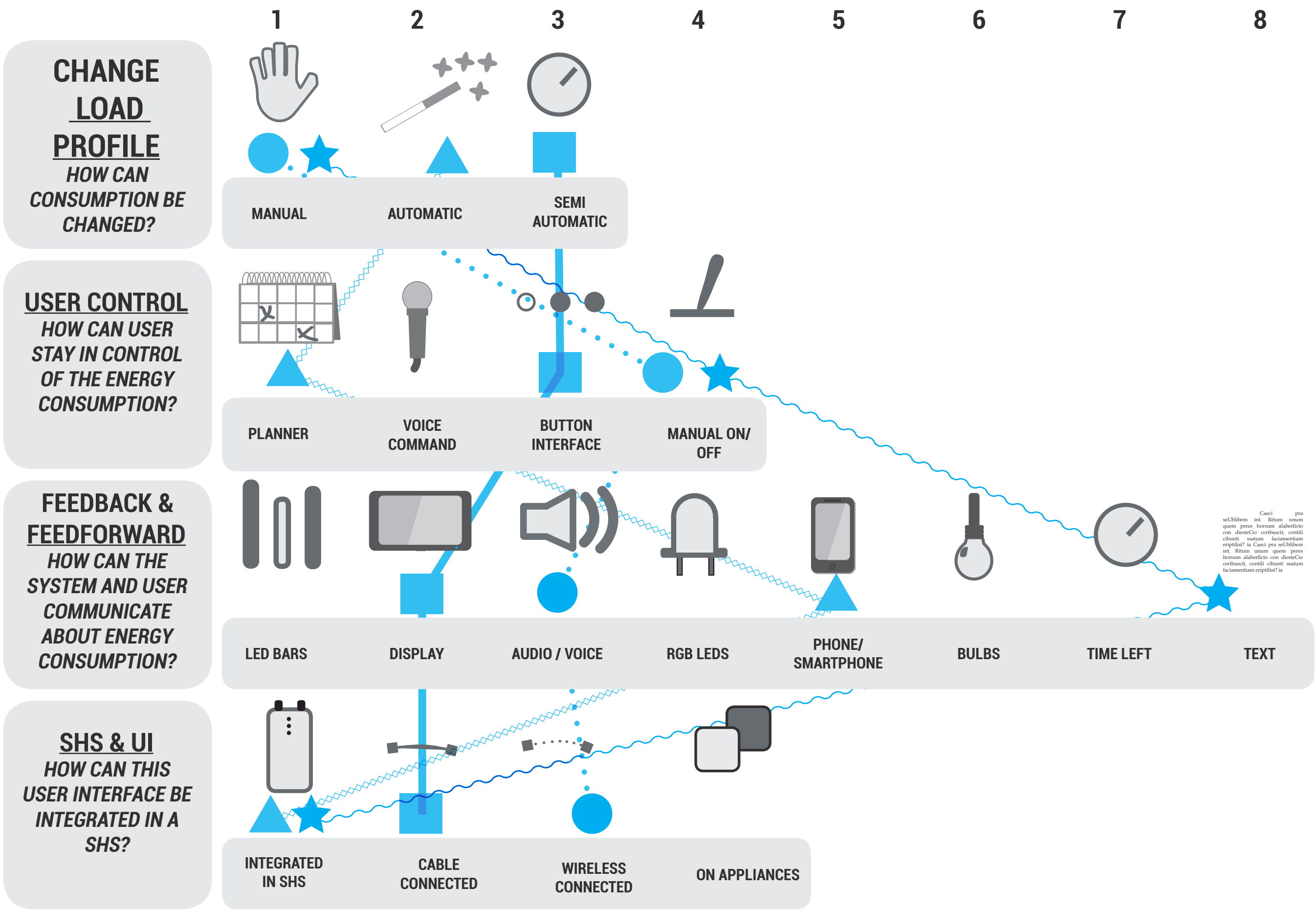
The brainstorm session has resulted in a wide variety of ideas. In order to create an order in this variety, a selection of these ideas was made and categorized according to the following questions:

How can load profile shape change?
How can the user stay in control of the energy consumption?
How can the system and user communicate about energy consumption?
How can a user interface be integrated in a SHS?

The morphological chart is presented in Figure 81. The morphological chart is used to create concepts, by combining ideas of sub-questions. The concepts are presented on page 110 and page 111.

The concepts presented on page 110 and page 111 should be seen as possibilities on how DSM can be implemented in the SHS context. For actual implementation, the concepts should be developed further and need better investigating. The concepts should be improved, tested and the effects should be researched. The functioning of concepts might depend on the type of SHS, environments, situations or users. The potential benefits, as discussed in section 6.6, seem to be worth more investigation.

MORPHOLOGICAL CHART



CONCEPT 1: DSM MANUAL

CONCEPT 2: MOBILE APPLICATION

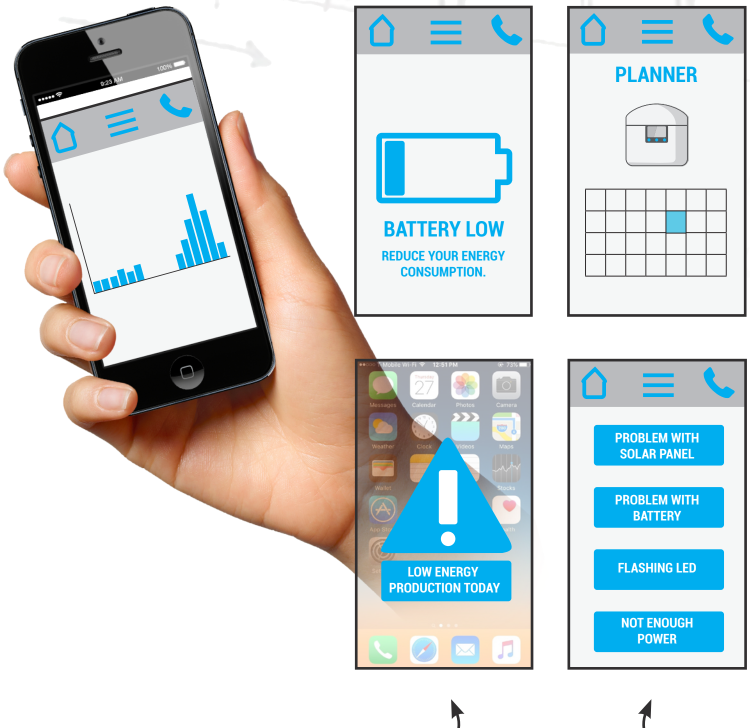
CONCEPT 3: ACTIVE COACH SPEAKER

CONCEPT 4: INTEGRATED IN SHS

Figure 81: Morphological chart.

6.7.1.2 DSM MANUAL

Stimulating user behaviour change can be done with simple means, for example by giving lessons or through an instruction manual. In this way, the user gets informed of the benefits of changes in energy consumption patterns. For example, through a manual on paper, the user is instructed on how and when to use specific appliances.



6.7.1.1 MOBILE APPLICATION

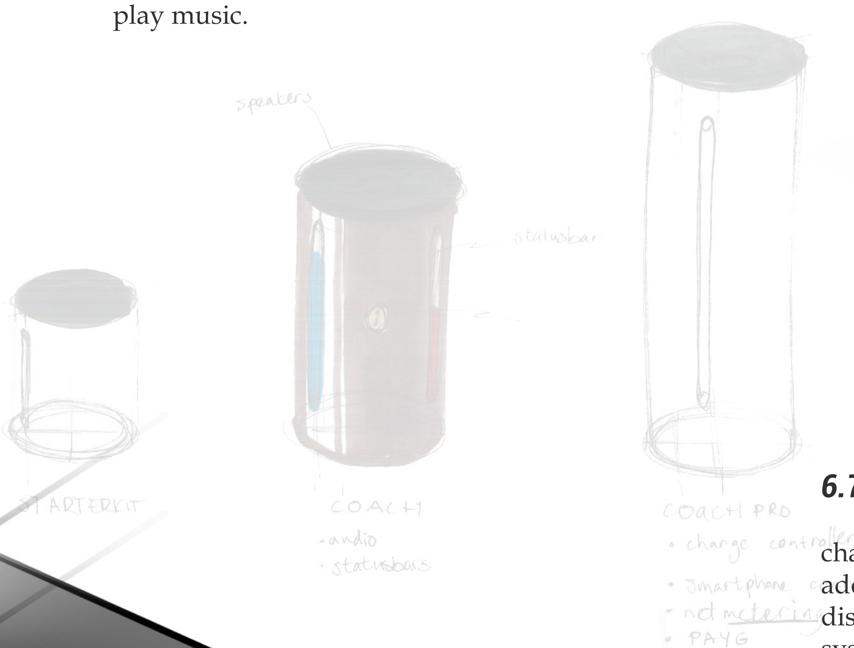
A more advanced option of stimulating user behaviour change, is by making use of already existing technology. For example, SHS users can connect to the (already existing) databases of SHS companies, such as Kamworks' database, through mobile devices.

The data will be presented in an accessible manner for the user. Users get alerts on their mobile devices when a change in behaviour is necessary. This can be a short or long-term consumption change. For the suggestions, the devices uses load profiles, weather forecasts, and system status. Users can compare energy consumption with neighbours. The planner gives suggestions what the optimal time is; for example to turn on a slow-cooker.

WARNING POP-UPS **PROBLEM SOLVING**

6.7.1.3 ACTIVE COACH SPEAKER

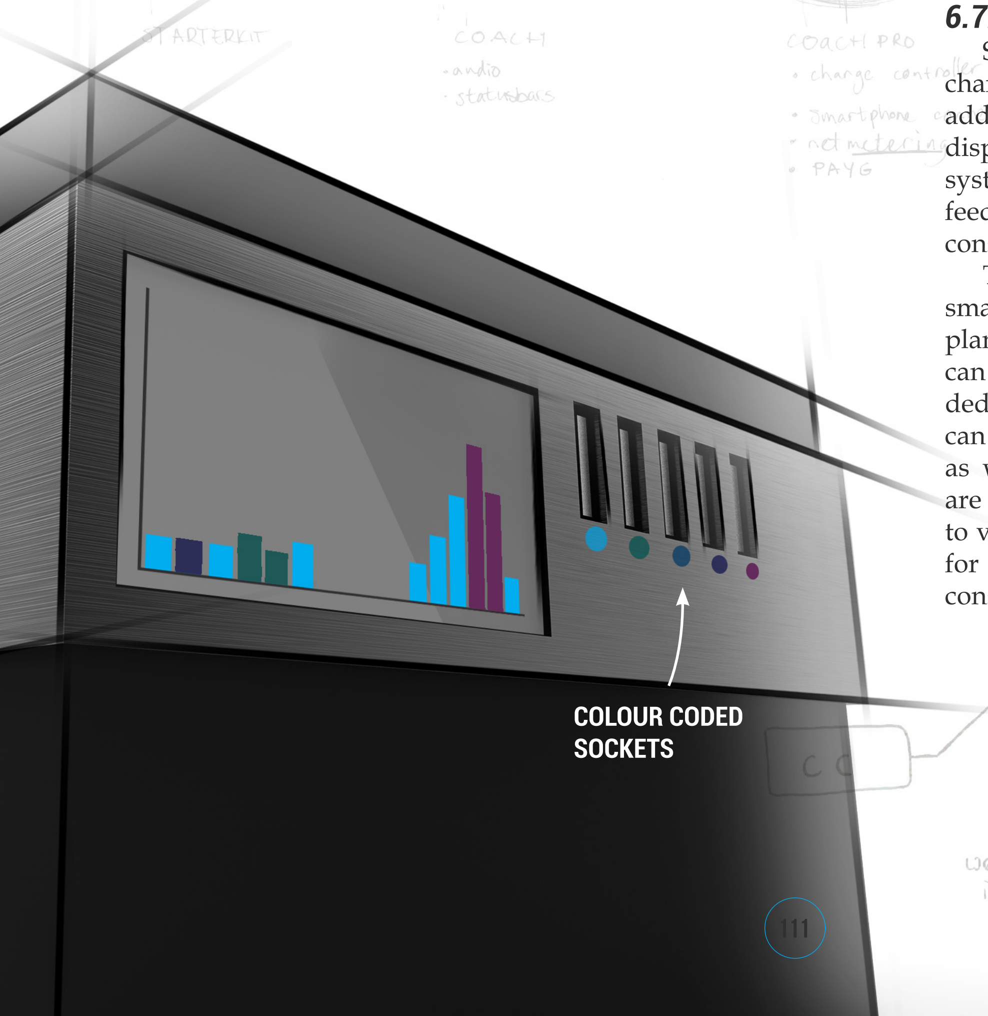
This device actively coaches the user to change behaviour. The device is connected to the SHS. The LED bars display solar generation, energy consumption and power consumption. This has the aim to inform the user so that it can plan accordingly. Based on consumption, audio feedback is given to the user by voice messages. These messages will coach the user to change their energy consumption behaviour. For the suggestions, the devices uses load profiles, weather forecasts, and system status. The device can be used both outdoors and indoors. In this way, the user always has access to the information. The speaker can also be used to play music.

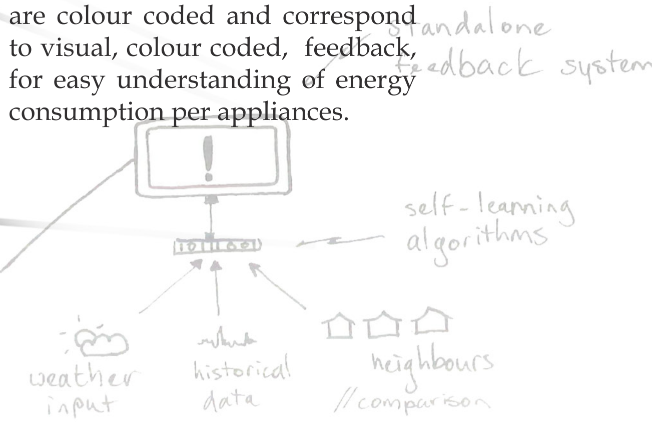


6.7.1.4 INTEGRATED IN SHS

Stimulating behaviour change could also be done by adding features to the SHS. A display provides feedback on system performance and gives feedback on the user about energy consumption.

The SHS is able to control smart appliances through a digital planner. With this planner, the user can turn on/off specific devices at dedicated times. Smart appliances can be controlled both manually as well as automatically. Sockets are colour coded and correspond to visual, colour coded, feedback, for easy understanding of energy consumption per appliances.





6.8 FUTURE SHSs

This section will describe how the proposed changes in SHSs can be integrated in future SHSs. A design vision for the overarching PhD-project is suggested. A concept is presented that can serve as a starter for the future work in the overarching PhD-project.

As described in section 6.1, three points of focus should be considered when matching energy supply and energy demand:

- system size
- appliances
- energy consumption patterns

It is suggested to focus on improving SHSs with an integral approach, in which the following points are considered:

- optimizing system capacity according to user needs (as discussed in 6.3)
- enabling the usage of off-grid appliances and non-electric appliances (as discussed in 6.5)
- integrating DSM (as discussed in section 6.6)

See also Table 20.

Only with an integral approach, the full potential will be unleashed of SHSs. However, the current SHSs are not ready for these changes. Especially power electronic components need to be advanced. Figure 82 is a visualisation of a concept vision for for future power electronics in SHSs. The figure serves to support the description below.

As described in 6.3, increased system size is necessary in the future to serve the higher energy demands. There are several alternatives for system architectures that can be chosen that can support these increased system sizes. In order to serve the growing needs and be adaptable for future needs, it is desired to make systems expandable. This could be done by incorporate modularity and/or interconnectivity features in the future SHS. These features require more sophisticated BoS-components than are used in stand-alone SHSs. For interconnectivity, energy has to be transferred between SHSs. This requires an electricity distribution network, as well as network controllers. The SHS should incorporate the connectors for such a grid.

The power electronics should be ready to work with a wide range of batteries and solar panels. As it can be expected that li-ion become in the future competitive with lead-acid batteries for SHS, the charge controller(s) should be ready for both battery technologies. The SHS should feature the connectors for multiple batteries. Furthermore, the power electronics should be prepared for different types and sizes of solar panels.

Where advanced power electronics sound like the optimal solution, there are several drawbacks. The main disadvantage is the increased costs that come with adding more (complex) components to the system. In the next stages of the project, the goal should be to develop power electronics supporting modularity and/or interconnectivity features at a minimal price. As modularity requires extra installations, it is necessary to make these installations as easy and quick as possible to reduce costs. Ideally, the user is able to install extra modules without help of the SHS company.

Inherent to advanced power electronics is advanced firmware and software. The system should be able to communicate with

POINTS OF FOCUS	DESIGN DIRECTION
SYSTEM SIZE	OPTIMIZING SYSTEM CAPACITY ACCORDING TO USER NEEDS
APPLIANCES	STIMULATING THE USAGE OF OFF-GRID AND NON-ELECTRIC APPLIANCES
ENERGY CONSUMPTION PATTERNS	IMPLEMENTING DSM FEATURES

Table 20: Design directions.

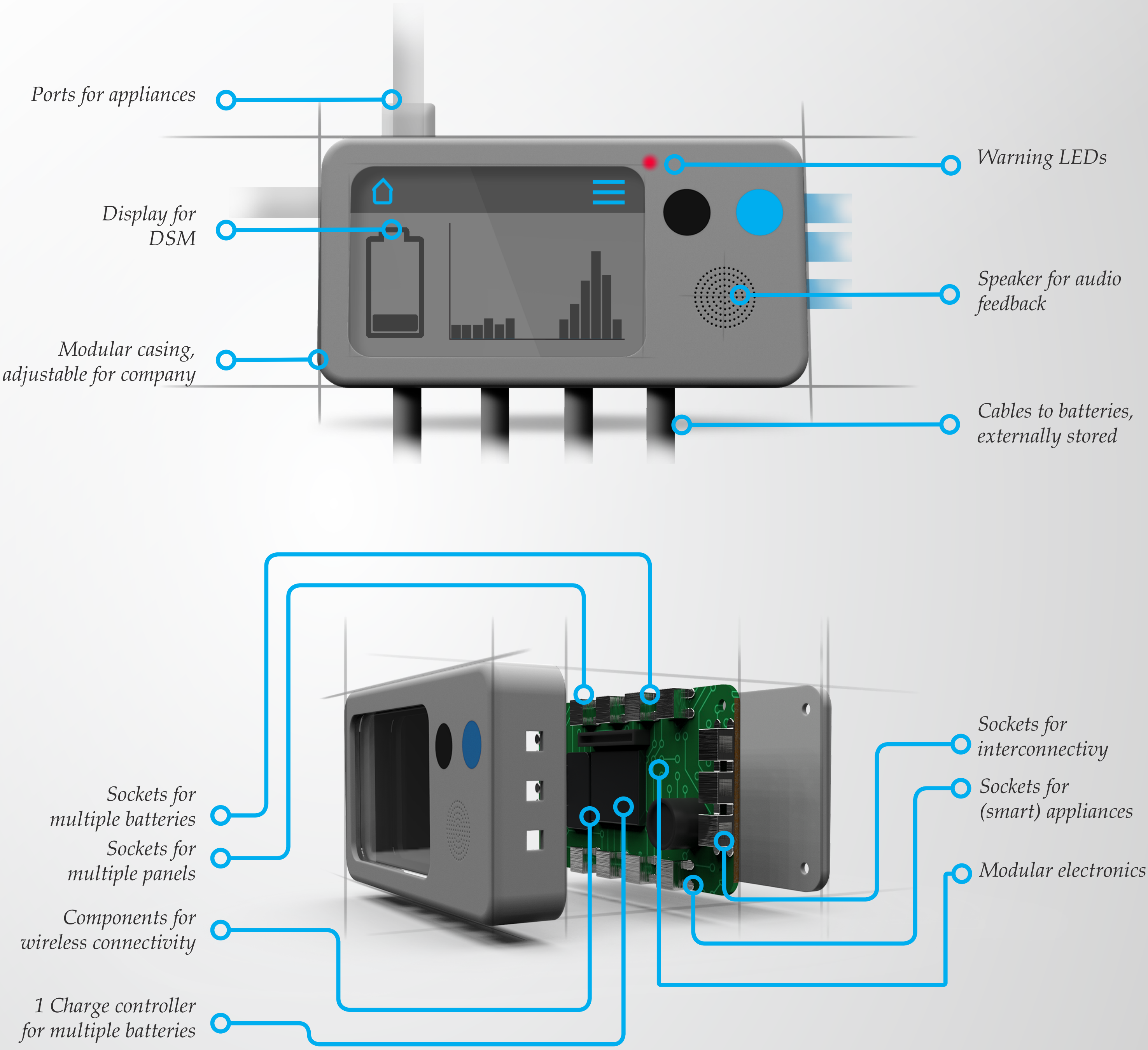


Figure 82: Concept visualisation of potential future power electronics in future SHS.

smart appliances, and turn them on/off when necessary. Furthermore, the firmware should be updateable. In this manner, it can adapt to system changes, for example when the system gets expanded in the future.

Both the firmware as well as the electronics should facilitate wireless monitoring of system performance. This supports the SHS companies in maintenance work, but also helps in future system design by providing feedback on system usage. Furthermore, the system should support DSM features. As described in section 6.6, implementing real-time DSM has potential benefits for the performance and the price of SHSs. Next to this, the user should be able to control smart appliances. The electronics, software and firmware should support this. In the continuation of this project, more research should prove if the idea of DSM for SHS is valuable. Secondly, it should be evaluated which alternative works best. Besides DSM, it is important that the system is understandable in usage for the user. This includes understanding of system status, such as battery SoC.

As found in the field research, many households use appliances with an inverter. Using (cheap) inverters causes many problems and results in energy losses. Future SHSs should prevent such usage. This comes with the drawback that the user might not be able to use all types of appliances.

Table 21 presents the design vision in key features for future SHSs. There are many design choices yet to be made in the project. The next step would be to create a set of concepts, which can be evaluated on a set of key requirements, including performance and price. The increased complexity and costs that come with developing such advanced power electronics should at least be counterbalanced by the benefits of optimized system design.

KEY FEATURES FOR FUTURE SHSs

TECHNOLOGY	USER	BUSINESS
• EXPANDABLE IN BATTERY CAPACITY	• PLUG & PLAY MODULARITY	• WIRELESS MONITORING
• LEAD-ACID & LI-ION READY	• FACILITATING USAGE OF OFF-GRID AND NON-ELECTRIC APPLIANCES	• OVER-THE-AIR UPDATABLE FIRM & SOFTWARE
• EXPANDABLE IN SOLAR PANEL SIZE	• SUPPORT DSM FEATURES	• SUPPORT PAYG, ALSO FOR APPLIANCES
• SMART APPLIANCE READY	• UNDERSTANDABLE FEEDBACK ON ENERGY CONSUMPTION	
	• UNDERSTANDABLE FEEDBACK ON SYSTEM STATUS	
	• PREVENT TAMPERING WITH THE SHS	

Table 21: Key features for future SHSs.

7. CONCLUSION & DISCUSSION

This section will conclude the master thesis. This chapter will present the conclusion of the project. Secondly, difficulties during the project will be discussed and recommendations for further research and development will be given. Chapter 7 will conclude with a personal reflection.

7.1 CONCLUSION

SHSs can well serve the basic energy needs for many of the 1.3 billion people in the world that lack access to electricity (International Energy Agency (2013). Unfortunately, the adoption of SHSs is unfortunately, hampered by high upfront costs and limited capacity. Three main challenges of SHSs were the starting point for this project: 1) high upfront costs , 2) limited capacity and 3) knowledge on current and future demand was limited, not relevant or outdated. This thesis has resulted in design directions for future SHS design with the aim to decrease system costs and improve system performance by focussing on matching energy supply with energy demand.

Matching energy supply and demand is crucial in tackling the challenge of matching supply and demand. By sizing a system according to user needs, the user will experience less problems with their system. Furthermore, the user will be able to power more appliances. Secondly, by optimizing the system size according to user needs, the costs of the system can be reduced. Oversizing can lead to unnecessary cost for the user and undersizing can lead to loss of load. Optimizing system size will also result in less maintenance. Knowing what the future energy consumption will be is therefore extremely important in system design. Battery capacity and panel size have to be chosen accordingly. Most important parameters to keep in consideration during optimization, are solar panel size, battery storage capacity, and the influence of DoD on the cycle life.

The research in this thesis, as presented in chapter 4 and chapter 5, has focussed on the demand side of the project challenge and the relation of load profiles with system performance. This is done in order to fill the gap in knowledge on energy knowledge and anticipate on future demand. Chapter 4 has presented the results of data analysis performed on actual usage of SHSs in rural Cambodia. It displayed a wide diversity in energy consumption patterns. The mean energy consumption for all users is 310 Wh/day, with σ = 159 Wh. Most energy is consumed at night, thus when the sun is not shining. For a large group of users, the current SHSs does not suffice their demand. There is a clear mismatch in energy supply and energy demand, that should be prevented in future SHS design.

Chapter 5 has presented the results of a field research performed in rural Cambodia. The research has resulted in insight on future energy demand. In the future, load profiles will be diverse. Participants indicated a need for more appliances. Some appliances will be used daily and at specific times (water kettle, rice cooker) , while other appliances might only be used every now and then (audio system) or perhaps once a week (iron). Fridges will need to be continuously connected, while water kettles, irons and rice cookers will cause high peaks for a short time in the profiles. The three personas presented in chapter 5 give clear guidance for future SHS designers and can be used in optimization models by SHS designers.

To accommodate future needs, bigger systems are necessary. As discussed in chapter 6, this can be achieved using features as modularity and connectivity. However, solely increasing system size will not be the optimal solution. The full potential of SHSs will be unleashed with an integral approach. Besides optimizing SHSs, future systems should facilitate smart off-grid appliances and DSM features. This will require advanced power electronics. In the next phase of the overarching PhD project, the focus should lay on creating multiple design concepts for the power electronics and evaluating them on key requirements, including price and performance.

7.2 DISCUSSION & RECOMMENDATIONS

This section will discuss difficulties during the project and recommendations for further research, development of SHSs, and the continuation of this project, and the overarching PhD-project. This part will be written from the perspective of the writer of this thesis.

At the start of the project, N. Narayan had two major questions: 1) *What is the current energy demand* and 2) *What will the future energy demand be?* With the work done during this thesis, answers have been found on these questions. More insight has been developed on the demand side aspects of SHSs. Before this thesis, little research had been published regarding the energy consumption of SHS users. Especially quantitative data analysis on such a large number of households was non-existing. Therefore, in my opinion, the research done during this thesis is a clear addition to already existing literature.

The insights on future energy demand will be the most useful for the remainder of N. Narayan's work. The Personas can be used for modelling the required battery capacity and solar panel size of future systems. However, the future load profiles should be used with careful consideration, and are primarily valid for the context of rural Cambodia. In future work, the same research can be applied to other environments. This was unfortunately not possible within the time scope of this master thesis. When looking into energy demand in other locations, the same methodology that is used in this project can be applied. If necessary, the methodology can be adjusted.

The Load Profile Tool is developed to support SHS designers and researchers in constructing future load profiles. The Load Profile Tool is in an early stage of development, and can be seen as a rough prototype. The Load Profile Tool could be developed into a web application, so that it is easily used by SHSs developers all over the world. Another option is to integrate the Load Profile Tool into software aimed at optimizing system size. Someone who can develop software or web-apps should be able to improve the Load Profile Tool in a short time frame. The effort would be minimal, but the benefits of such a tool would be great for many SHS companies.

The dataset provided by Kamworks was an important pillar in this work. As there were no similar analyses available for reference, it took time to get familiar with the dataset and framing the possibilities of the dataset. The initial dataset was full of erroneous data logs. Furthermore, it was relatively large and therefore hard to handle with the limited processing power available. Therefore, a selection of households and performance logs was made, as described in chapter 4. The selection resulted in a set of performance logs that was 34,8% of initial dataset. This means a large amount of data was excluded from the analysis. If more time would have been available, more careful selections could have been made. However, the remaining set of data was large enough for valuable results.

For further research, I recommend to do more analysis on the relationship between energy consumption and appliances, socio-demographic aspects, and/or socio-economic aspects. Unfortunately, Kamworks' database does not contain information that could be used for this. In order to do so, additional (field) research should be performed. The benefits of such research could for example be to clarify relationships with SHS usage and amount of appliances, time spent at home by household members, or the relationships between appliances and income levels. Gaining information on these topics could for example be done by extensive user surveys or household visits.

In future work, the same analysis can be done for other locations. In this way, good comparisons can be made between different locations. This could show what the differences in energy consumption patterns are between different locations and cultures. As the focus of the project is on South-Africa, India and Cambodia, it is recommended to first analyse these countries.

In future research on future energy demand, as described in chapter 5, the research methodology could be sharpened so that quantitative results are possible. This can for example be achieved by increasing the amount of participants and optimizing the research. By quantifying the methodology and results, more accurate predictions on energy consumption patterns can be made. However, this will cost significantly more time, since more households will need to be visited.

Additionally, up-to-date knowledge on the off-grid appliance market remains crucial for realistic results. It is necessary to have up-to-date information, because the market space is continuously evolving and appliance efficiency is increasing. The appliance efficiency and pricing play an important role in the outcome of the research and should therefore be as accurate as possible.

During the field research, electrical engineering student Bunheng Souy helped translating during the interviews with the rural households. I involved him in the research and explained him about the goals of the project. This had a positive impact on his cooperation in the project, as he got genuinely interested in the (future) energy consumption of rural households. At the end of the research, he even started questions by himself. I can recommend to find a translator has a background in a related field and is interested in the project. However, mr. Souy was not a professional translator. Therefore, it is likely that a significant amount of information was lost during the translation.

During the projects, connections have been made with stakeholders in the SHS market. These connections were very helpful during the project. It is recommended to keep in touch, for example by updating them on the project status. By doing so, there will be a lower barrier for asking for help, feedback or collaboration in the future. Some examples of these stakeholders are the Kamworks'employees and the contacts at Bboxx. Furthermore, it would be good to keep in touch with the staff at the Institute of Technology of Cambodia. This is also in line with the goals of the Delft Global Initiative to work in close partnership with local scientists. (Delft Global Initiative, 2017). Other stakeholders that should be kept in touch with, are for example Picosol and SNV, which could be useful in future work; for example, when testing needs to be done or when Cambodia-specific information is lacking. Morevoer, it is in my opinion necessary to collaborate closely with one or multiple SHS companies. This will increase the understanding of the challenges that these companies face today.

During the remainder of the PhD-project, I highly recommended to keep track of the latest trends and developments in the SHS field. Furthermore, knowledge about state-of-the-art technology continuously needs to be updated. This in order to finish with a result that is not already outdated at the end of the project (whatever the result of the PhD-project may be). Most important developments that should not be overlooked, are developments in the field of batteries, solar panels, modularity and interconnectivity. For example it can be foreseen that battery technology will improve and prices will drop, due to the rise of electric vehicles. The same accounts for solar panels and cell types. Solar panel technology improves over time and it can be expected that panels become more efficient and cheaper in the future. Other (third generation) cell types may become market ready.

Regarding modularity, I recommend Nishant Narayan to keep in touch with Kamworks. They are one of the first to implement this concept in their design. The lessons they learn during the development of the modular systems can be very valuable. Secondly, if it turns out to be successful it can be expected that other SHS companies will follow and develop their own modular systems.Similar recommendations can be made for developments in interconnectivity. To my knowledge, the most innovative company at the moment is Solshare. (SOLshare, 2017) However, building up grids from the bottom-up using interconnectivity is something that is not solely reserved for rural electrification. It is recommended to stay informed on relevant developments in similar fields as well.

At the moment, many parts of the project are research oriented and are of theoretical nature. This is definitely a strong point of this project, but the PhD-candidate and team should not lose sight of reality. As described in the first chapter, the SHS market is harsh and crowded. There are many aspects that should be considered with designing. Optimizing the battery, panel and power electronics is only part of the solution. It has to come with a matching business model.

It is not recommended for the PhD-project to develop yet another SHSs. Product development should not focus on batteries or solar panels, but on power electronics. Keeping in mind that the overall goal of the project is to reduce energy poverty, the aim of the project can be of best help by levering the knowledge through research. To achieve something that contributes to reducing energy poverty, it is in my humble opinion necessary to create smart power electronics, that can be used by SHS companies all over the world. Unique selling points for this project could be the implementation of features that such as DSM, smart appliance support and PAYG for appliance.

7.3 PERSONAL REFLECTION

In this section, I will reflect upon my work, the project, the field work and my experiences during the project.

This project has been a great learning experience for me. Before starting working on this thesis, the project brief attracted my attention because I was looking for a project where I could combine technology with design for well-being and sustainability. My aim as a designer is to make products that improve the life of people in need. This project fitted perfectly with what I want to achieve as a designer. I feel fortunate and am grateful for getting the opportunity to work on this project and in the field of SHS.

The initial focus of the project was wide. The project started with a design brief including a broad range of design-related topics, ranging from technical questions about topics such as (future) load profiles and modularity to socio-economic topics such as purchasing power and social acceptance. Many of these questions are already answered by others and documented in papers and reports. In my opinion, it was a good choice to put the main focus on load profiles and matching energy supply with energy demand.

I started this project with very limited knowledge on energy consumption and/or design for the BoP. I did not see this as a problem before starting, but it gave me some good headaches during the project. Fortunately, I got good support from my coaches. I have definitely come across some of my own limitations, and got to the realization that learning doesn't stop after a masters degree. Personally, I have learned a lot from the interdisciplinary teamwork with Nishant Narayan. The collaboration proved to me how important it is to work together with different backgrounds. The many small lectures on electrical engineering gave me a better understanding of SHSs.

The execution of the project has had its ups and downs. Some parts of the projects were straightforward and more easy to perform, where other parts took more time and were not clear-cut. For example, the data analysis took a substantial amount of time. This was due to a combination of a hardly manageable dataset and my lack of experience in data analysis.

Another part that took considerably longer than might have been necessary, was writing the report. I underestimated the amount of work that goes into this. Another reason for my struggles during this phase is the fact that there was a long time between my last university courses and the start of my thesis. I would not recommend anyone else to take such a break. If I would have the chance to do it again, I would spend more time on planning, keeping track of progress and setting clear goals for myself.

The field research in Cambodia was a very interesting experience. During this part of the thesis I have learned a lot, in many different fields. First of all, the field research requested a lot of my interpersonal skills. The field research was prepared before departure in Holland, but much of the appointments and visits had to be arranged during the short stay Cambodia. It showed to me how important it is to meet new people, make the right connections and expand your network.

Working together with a company like Kamworks has learned me a lot. Kamworks' database and the help of the company really boosted this project. Without their help, a lot of the results from this thesis would not have been possible. I had the opportunity to get to know Kamworks from the inside, since they offered me a desk to work at in their office during the field visit. This showed me how tough it is to operate a company in a country like Cambodia, where local employees are barely educated and competition is harsh and sometimes even unfair.

Furthermore, visiting the households during the field trip was a great experience. However, I have realized how hard it is to connect to the rural people without speaking the same language. This made it sometimes hard to get full understanding of statements in conversations. Visiting the rural households made me realize how different life can be, and it made me feel grateful for the good life I live in the Netherlands and the chances I get. Although the people in rural Cambodia do not live an easy life, the Khmer are friendly people and always welcome you with a smile. This is a good habit that I will try to adopt.

Without the help of my coaches, this project would have probably turned out completely different. During the project, there were many times where I had the urge to take a turn in another direction. I would like to thank my coaches for steering me in the right direction, keeping me focussed and putting me back on track where necessary.

Concluding, I think I can look back at a successful project. With the results of this thesis, I have contributed to the overarching PhD-project with the knowledge on current and future energy consumption. Furthermore, I have given clear advices on future SHS design in relation to user demand. I am looking forward to the final result and have full confidence that the overarching project will result in something that will contribute to the SHS market and be of support in the battle against energy poverty.

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