



Analysis and dimensioning of a large scale solar cooking system

A solution for the Base of the Pyramid market

OSCAR BLANCO FERNÁNDEZ

Analysis and dimensioning of a large scale solar cooking system

A solution for the Base of the Pyramid market

Oscar Blanco Fernández

2018-10-29

Master's Thesis

Company Supervisor
David Bauner

Academic Supervisor and examiner KTH
Justin Chiu

Academic Supervisor UPM
Luis Francisco González Portill

Abstract

This thesis introduces an analysis and dimensioning of a solar powered solution for enabling clean and sustainable cooking in developing areas. Access to clean cooking is a great challenge hindering human development, with significant health, environmental, and economic implications. The proposed solution is analysed and modelled in this work. Recommendations are given on the development of the project, reviewing the critical factors for its success.

The solution is a novel approach for providing power for cooking through solar energy. Targeted market segment is institutional cooking, where current cooking fuels are commonly based on firewood and charcoal. The system integrates a solar trough collector array, an oil heat storage, a heating unit for the cooking recipient, and two thermosiphons for transporting the heat between each component. The technology is under development, requiring an accurate analysis and further work in the design.

The work presented analyses the solution and its implementation in a specific case study. A modelling software was built as a tool for dimensioning the technology and observing its behaviour. Moreover, specific values were obtained on the dimensions for the case study. A structured critic of the system through a deep review allowed for observations on risks, future work, and additional recommendations.

Simulations for the case study enabled the first values on the dimensions of the system. Flexibility of the model was provided to repeat this exercise for future case studies. The analysis unexpected critical factors for the solution such as user behaviour and reviewed expected ones such as the insulation or the size of the heat storage.

There are still many challenges to overcome for the success of the analyzed project. This thesis gives a basis for future work and strong guidance for the development of the solution.

Keywords

Clean cooking; Institutional cooking; Base of the Pyramid market; Solar cooking; Simscape model

Acknowledgments

Thanks to David and Tom, for trusting me with the development of this work and giving me a good guidance. Thanks to the other members of this project, to Adam and Fredrik for their parallel efforts in building the system, and to Justine from the distance in Kenya for enabling a clear picture for the project that would otherwise be impossible to imagine. Thanks, as well to my academic supervisors, to Justin for his great involvement and attention and to Luis for his guidance to deliver a good thesis.

On a personal level, thanks first to my family and loved ones, for how lucky I feel about having them and for their constant support. Thanks for a great year of incredible experiences, the ones that can be enjoyed and the ones to learn from. Thanks to all my friends, the ones that will always be there and the ones that come and go but leave great memories to enjoy.

Madrid,

September

2018

Oscar Blanco Fernández.

Table of contents

Abstract	i
Keywords.....	i
Acknowledgments.....	ii
Table of contents	iii
List of Figures	vi
List of Tables	viii
List of acronyms and abbreviations	ix
1 Introduction	11
1.1 Background.....	11
1.2 Problem definition	12
1.3 Purpose	12
1.4 Goals	12
1.5 Structure of the thesis	13
2 Background	14
2.1 Cooking Fuels.....	14
2.1.1 Global scenario	14
2.1.2 Cooking in SSA.....	14
2.1.3 Repercussions from current cooking methods	16
2.1.4 Defining Clean, Efficient, and Sustainable Cooking	20
2.1.5 Cooking fuels and technologies	21
2.2 Sustainable cooking market.....	24
2.2.1 Customer study	24
2.2.2 Market Segments.....	25
2.3 Institutional Solar Cooking	26
2.4 Proposed technology	29
2.4.1 General system.....	31
2.4.2 Solar collector	31
2.4.3 Heat storage	32
2.4.4 Cooking unit.....	32
2.4.5 Thermosiphon	33
3 Methodology	35
3.1 System modelling.....	35
3.1.1 Purpose and scope of the model	35
3.1.2 Election of modelling software	35
3.1.3 Modelling workflow.....	36
3.2 Data Collection	38
3.3 Assessing reliability and validity of the results.....	38
3.3.1 Reliability	39
3.3.2 Validity	39
4 Model and Simulations.....	40

4.1	Model design.....	40
4.2	Data inputs.....	41
4.3	Control.....	41
4.4	Physical components.....	42
4.4.1	Pot heater	43
4.4.2	Oil tank heat storage.....	43
4.4.3	Solar collector	44
4.4.4	Solar irradiance.....	44
4.4.5	Thermosiphon.....	45
4.5	Limitations	45
4.5.1	Non-thermal effects.....	45
4.5.2	Unconsidered effect of geometries	46
4.5.3	Undeveloped design of thermosiphon.....	46
4.5.4	Solar tracking simplification	47
4.5.5	Solar irradiance conditions.....	47
4.5.6	Boiling temperature control	47
4.5.7	User behaviour modelling	47
5	Analysis.....	49
5.1	Simulation setup.....	49
5.1.1	Cooking unit insulation.....	49
5.1.2	Thermosiphon to cooking unit.....	49
5.1.3	Oil heat storage.....	49
5.1.4	Thermosiphon from solar collector.....	50
5.1.5	Solar collector	50
5.2	Main Results	51
5.2.1	Cooking unit insulation.....	51
5.2.2	Thermosiphon to cooking unit.....	52
5.2.3	Oil heat storage.....	53
5.2.4	Thermosiphon from solar collector.....	54
5.2.5	Solar collector	55
5.2.6	Solar irradiance.....	56
5.3	Reliability and Validity of the results	57
5.4	Discussion	58
6	Additional observations.....	60
6.1	Thermosiphon technology.....	60
6.2	Oil oxidation.....	61
6.3	Installation process.....	61
6.4	Height difference	63
6.5	Solar tracking.....	64
	65
6.6	Thermal resistance.....	65
6.7	User behaviour	66
7	Concluding remarks.....	67
7.1	Conclusions.....	67
7.2	Future work.....	68
7.3	Reflections	68

References.....	69
Appendix A: Absolicon T160 performance test data	73
Appendix B: Study case School.....	77
Appendix C: MATLAB initialization and inputs script	81

List of Figures

Figure 1 Access to clean fuels and technologies for cooking, 2014 (Global Alliance for Clean Cookstoves; Energy Sector Management Assistance Program, 2015)	15
Figure 2 Current data and future projections on shares of cooking technologies (Bram Smeets, 2017)	15
Figure 3 Primary fuel used for cooking by urban and rural households by sub-region, 2015 (International Energy Agency, 2017)	16
Figure 4 Increase of energy efficiency with modern cooking technologies ..	19
Figure 5 Residential Energy Consumption in Africa is dominated by cooking (Bram Smeets, 2017).....	19
Figure 6 IWA tiers of performance for cooking (Gobal Alliance for Clean Cookstoves, s.f.)	20
Figure 7 a) Charcoal Stove. b) Three stone fire. c) Basic improved stove. c) Rocket stove	22
Figure 8 Technology based classification of existing institutional solar cookers. Adapted from (Sunil Indora, 2018)	28
Figure 9 Simplified sketch of the studied technology	30
Figure 10 Absolicon T160. Glass cover and collector tube. Photo by the author	31
Figure 11 Working principle, solar trough collector	31
Figure 12 Absolicon solar collector	32
Figure 13 Loop and counter flow thermosiphons.....	34
Figure 14 Spiral modelling. Original from (Boehm, 1988)	37
Figure 15 Reliability and validity	38
Figure 16 Structure of the Simulink model	40
Figure 17 Simscape example for instructive purposes	41
Figure 18 Physical Simulink model overview	42
Figure 19 Pot heater Simulink subsystem	43
Figure 20 Oil tank Simulink subsystem	44
Figure 21 Solar collector Simulink subsystem.....	44
Figure 22 Heat loss variation with insulation	51
Figure 23 Surface heat loss variation with lid	51
Figure 24 Heat losses variation with varying lid and insulation	51
Figure 25 Heat input variation with varying lid and insulation	51
Figure 26 Temperature profile with varying resistance	52
Figure 27 Oil tank heat loss variation with insulation thickness	53
Figure 28 Temperature variation with oil tank volume	54
Figure 29 Heat loss variation with oil tank volume	54
Figure 30 Oil temperature connected to solar collector	54
Figure 31 Oil tank heat loss variation with insulation thickness	54
Figure 32 Oil tank and solar collector temperatures with varying thermosiphon.....	55
Figure 33 Heat storage temperature for varying solar collector dimensions	56
Figure 34 Seasonal solar irradiance	56
Figure 35 Thermosiphon arrangement in prototype	61
Figure 36 Solar collector and oil tank in prototype.....	62
Figure 37 Copper tube connexion	63

Figure 38 Solar collector and oil tank 2.....	63
Figure 39 Solar path at location in a) March 20 th ; b) June 21 st ; c) September 23 rd ; d) December 21 st . Taken from (SunCalc, 2018).....	65

List of Tables

Table 1 Factors on adoption of institutional solar cookers. Adapted from (Otte, 2013)	27
Table 2 Boiling time vs thermal resistance for each cooking unit	53

List of acronyms and abbreviations

BoP	Bottom of the Pyramid
HAP	Household Air Pollution
ICS	Improved Cook Stove
SSA	Sub-Saharan Africa
WHO	World Health Organization
LPG	Liquified Petroleum Gas

1 Introduction

1.1 Background

The lack of access to clean, sustainable cooking and its repercussions on the members of affected households, global climate, and deforestation, is a serious challenge. A maximum limit for indoor emissions of hazardous gases and particles, as well as global emissions defines clean cooking in relation to its health and environmental risk. Far from the reality present in developed countries, around 2.8 billion people (38% of the global population) lack access to clean cooking. Moreover, while access to clean cooking is improving, it is outstripped by population growth, so that 400 million additional individuals lack access from year 2000.

The negative impacts from lack of access to an appropriate and sustainable cooking method are not limited to health risks. On the environmental side it increases local forest degradation as well as GHG and black carbon emissions and the forest degradation in the area. In economic terms, it creates a dependency on what is usually a non-renewable resource. This represents a significant cost and leads to the loss of opportunities for income generation due to the time spent on fuel collection. Finally, from a gender perspective, being women the responsible for gathering the fuel and cooking, it fosters a gender difference in which women are the ones mostly affected by these negative externalities. Other social effects such as education, or nutrition are often related as well.

The potential to introduce a sustainable heat source or technology that alleviates the problems described has led to a considerable range of alternative cooking solutions. Improved cook stoves, which increase the efficiency and reduce emissions; alternative fuels such as LPG, ethanol, or locally produced biogas, use of briquettes and pellets, and solar cooking are some examples of solutions. Each of them present different drawbacks and advantages and could be suitable depending on application and location.

Solar cooking understood as supplying the heat for cooking using solar radiation, has the potential to deliver a sustainable solution. Its operation produces no emissions which negatively affect health or the environment, consumes no fuel and thus relieves the user from fuel dependency. However, available systems often have drawbacks in affordability, cooking time, and usability/fit with the user requirements. This is mainly due to higher complexity of the system, variability of the solar resource, and low power output and temperatures reached.

This thesis assists on the development and deployment of an solar cooking solution under development by analyzing the solution and developing a model and tool for sizing and dimensioning of the components and the system's operational capacity. The system is under development in a collaboration between the Swedish companies Joto Solutions AB and Renetech AB. This solution addresses the described drawbacks for solar cookers, providing a heat storage through repurposed oil, and efficiently transferring the stored heat to the pots without other external inputs e.g. electricity. With heat storage included, the challenge from variability of the solar resource may be overcome, and higher power for faster heating, and available energy for "slow

cooking” can be made available. In addition, the design, components and materials needed may permit an affordable solution and wide deployment.

1.2 Problem definition

The world is far from being on track to achieving universal access to clean and modern cooking fuels and technologies by 2030 as established in target 7.1 of the Sustainable Development Goals (SDGs) (UN, 2016). Projections estimate that 2.3 billion people will remain without access to clean cooking facilities in 2030 under current policy and population trends, 2 billion of whom will remain reliant on solid, mostly unsustainable biomass and waste as source of energy for cooking (WHO; IEA; GACC; UNDP; World Bank, 2018). Solar cooking devices have the potential to help mitigate this problem and deliver a sustainable cooking solution but need additional progress to overcome certain weaknesses. Further efforts are required in the design and research of solar cooking devices. A solution must be obtained that can explore its full potential while addressing the drawbacks that are hindering the dissemination of these devices

1.3 Purpose

The objective of this thesis is to analyse and dimension a novel solar cooking system that has been proposed. A model will be used as the main tool for the development of this work. The model will be based on a broad study of each component of the solution and their integration. It will analyse the behaviour of the system and its capacity to fulfil the requirements established by the user. Moreover, the model will serve as the core of a tool for assessment and dimensioning of future cases.

1.4 Goals

The main goal of this thesis is to make a complete analysis on the proposed technology and dimension it to cover the user requirements in an optimal way. The following targets were set to achieve the overall goal.

- Describe the clean cooking solutions market.
- Examine the physics that define the technology of the proposed system.
- Develop a model on the proposed system.
- Implement the model on a specific case study.
- Dimension the technology.
- Make a critical analysis of the system.

1.5 Structure of the thesis

This thesis can be divided into three main parts. An investigation of the context of the solution, including a description of the field of clean cooking, previous research in this area, and a description of the proposed system. A presentation on the work that has been carried out in this thesis, with an argumentation on the decisions made. Finally, the results of the analysis made through the model and critical observations are presented.

The Background chapter contains all the information relevant to the context of the thesis. The clean cooking fuels market is described, with a final focus on the market segment of institutional solar cooking. Moreover, the proposed technology is described in detail, with an individual explanation for each of the components.

The Methodology chapter explains the steps that have been taken to build the model and analyse its results. This includes how the results have been analysed from a critical perspective to ensure the quality of the work.

Model and Simulations include a description of the model that has been created. Each of the components are reviewed in detail. Moreover, identified weak elements of the model are described in the “Limitations” section.

The Analysis section shows the major results that have been obtained through the model together with a discussion on the deductions from these results and an analysis of their reliability and validity.

In Additional observations, several comments are made on different aspects of the solution. These are notes from observations throughout the thesis period and have been considered important for the continued development of the technology.

Finally, the Concluding remarks chapter summarize the findings and outcomes of the thesis and gives a more concise vision on the development of the technology.

2 Background

2.1 Cooking Fuels

Cooking is one of the most common activities in human life, yet the use of cooking fuels differ largely worldwide. In more developed countries, and in more developed households in developing countries, cooking is carried out using an electric or gas stove. However, many developing countries face the opposite situation, in which these fuels are rarely used, and most households are forced into using fuels and stoves with highly negative impacts for the user and for the environment.

2.1.1 Global scenario

At present 43% of the global population, or approximately 3 billion people, do not have access to clean and modern fuels and technologies for cooking. Instead, one third of the global population uses solid biomass as its primary cooking fuel, around 120 million people use kerosene, and 170 million people use coal (WHO; IEA; GACC; UNDP; World Bank, 2018). The use of such traditional cooking practices has been pointed out as a major problem for human development. Access to clean fuels and technologies for cooking is one of the main targets of the Sustainable Development Goal number 7: “Ensure access to affordable, reliable, sustainable and modern energy for all” (UN, 2016). The World Health Organization has been focused on the problem for over a decade (WHO, 2014), and numerous organizations such as the “Global Alliance for Clean Cookstoves” have been founded by the UN and other public entities to fight this precarious situation.

With current projections, the targets set by the institutions are unlikely to be met. The annual rate of increase in access to clean cooking* needs to accelerate from 0.5 percentage points to 3 percentage points to reach universal access to clean cooking by 2030, as established in the SDGs. In the current trajectory, 2.3 billion of the global population will remain without access to clean cooking by 2030 (International Energy Agency, 2017).

2.1.2 Cooking in SSA

Although lack of access to modern and clean cooking technologies is a problem common to most developing countries in Asia and Africa, the situation is most challenging in Sub-Saharan Africa. Here, not only the share of population without access to clean cooking is higher than in the rest of the world, as can be seen in Figure 1, but the growth rate of access to clean cooking is also the lowest, with 0.3 percentage points increase annually.

Population growth is outpacing the progress in clean cooking access in SSA. The region’s overall population has been growing four times as fast as the population with access to clean cooking

* “Clean” is defined by the outdoor and indoor emissions of a certain cooking system. The term is defined in depth in (Global Alliance for Clean Cookstoves, 2018)

(IRENA, 2018). As a result, the absolute number of people without access to clean cooking in SSA increases each year despite the slight increase in the share of access.

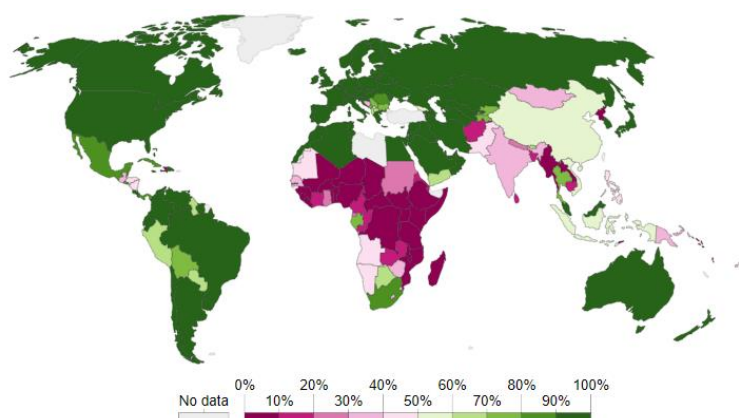


Figure 1 Access to clean fuels and technologies for cooking, 2014 (Global Alliance for Clean Cookstoves; Energy Sector Management Assistance Program, 2015)

Solid fuels clearly sustain most of the cooking demand in Africa. An estimated 82% (700 million Africans) cook primarily with solid fuels. Between the other 18%, 7% cook with kerosene, 5% with LPG, and 6% with electricity (Africa Clean Cooking Energy Solutions Initiative, 2014). Among solid fuels, wood takes the largest share, with charcoal in second place. The wood fuel is for the most part not sustainably sourced and thus contributes to climate change. Future projections do not see the necessary improvement in the use of solid fuels in SSA. As reflected in , biomass fuel sources are expected to cover most of the demand under the current trajectory. Moreover, it can be seen the effect of population growth with more people consuming solid fuels than at the current date.

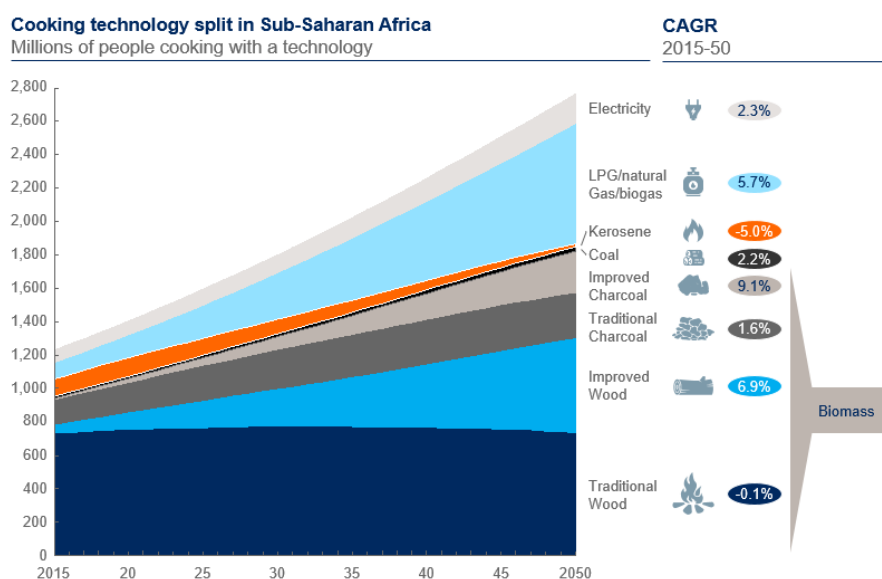


Figure 2 Current data and future projections on shares of cooking technologies (Bram Smeets, 2017)

The situation is particularly critical in rural areas, where modern technologies do not seem to enter. In rural SSA, the penetration of electricity and LPG for cooking is almost negligible, with future projections also much lower than in urban areas. The infrastructure required for LPG and reliable electricity for cooking is far from being economically and technically feasible in the context of rural SSA. The cooking situation has wide-ranging detrimental effects, with much work being required to alleviate the situation. Innovative approaches for enabling access to sustainable cooking practices is highly needed.

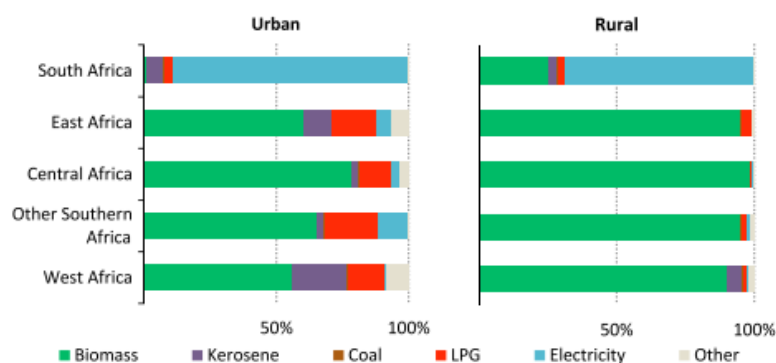


Figure 3 Primary fuel used for cooking by urban and rural households by sub-region, 2015 (International Energy Agency, 2017)

2.1.3 Repercussions from current cooking methods

The core of the cooking challenge is related to the health and environmental risks associated with the combustion of solid fuels. Nonetheless, its implications are much wider and extend to social, economic, and gender problems. The midrange economic value of the problems caused by cooking with solid fuels has been estimated at \$ 123 billion annually (\$ 22–224 billion), with multiple underlying effects (Global Alliance for Clean Cookstoves; Energy Sector Management Assistance Program, 2015).

2.1.3.1 Health Impact

Cooking with polluting fuels and stoves has been called a major public health crisis. The WHO estimates that 3.8 million people die each year from diseases attributable to household air pollution (HAP), caused by the inefficient use of solid fuels and kerosene for cooking (approximately 7% of global mortality) (WHO, 2018). HAP related diseases include pneumonia, stroke, ischemic heart disease, chronic obstructive pulmonary disease, and lung cancer. Figure 13 illustrates the proportion of deaths due to HAP worldwide, indicating a larger concern in Sub-Saharan Africa and South Asia.

In addition to the pollution, firewood collection injuries and cooking burns are other underappreciated health consequences. Transport of heavy firewood bundles results in chronic pains and spinal injuries, and a large share of the global burn deaths are caused by cooking with solid fuels and kerosene (Global Alliance for Clean Cookstoves; Energy Sector Management Assistance Program, 2015).

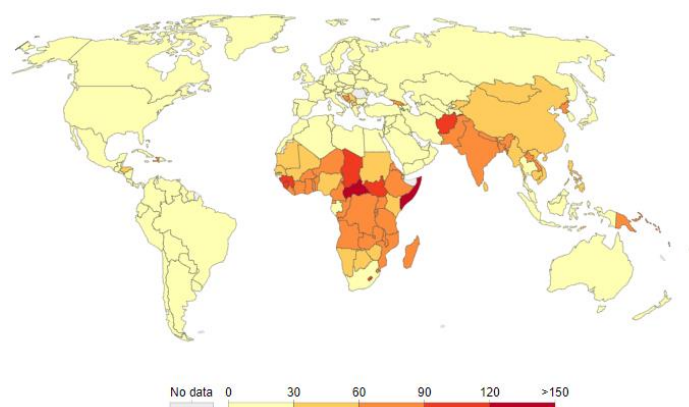


Figure 13: Death rate from indoor air pollution per 100.000, 2015 (Rose & Ritchie, 2018)

2.1.3.2 Environmental Impact

Cooking with solid fuels has negative environmental effects both at a global and at a local level. Wood and charcoal for cooking are the most problematic fuels in this field, although kerosene is also a concern. Recent studies have estimated the total use of biomass for cooking at over 1 billion MT per year (Bailis, et al., 2015). While this quantity is hard to imagine, it is obvious that there is a direct impact in the environment.

The generated greenhouse gas emissions from cooking with unsustainable solid fuels (mainly wood and charcoal) represents between 1.5-3% of global CO₂ equivalent emissions. Moreover, emissions of black carbon and other particles of incomplete combustion, that also play an important role in anthropogenic global warming, are even more excessive, with 20% of the global black carbon emissions attributable to cooking with solid fuels. Accounting for black carbon emissions doubles the equivalent carbon footprint of solid fuel cooking. The shorter lifetime of such particles also suggests that its reduction would lead to relatively rapid global cooling benefits (Global Alliance for Clean Cookstoves; Energy Sector Management Assistance Program, 2015).

Locally, the main environmental concerns are the emissions with a regional effect and the impact of fuel collection in the forests surrounding human settlements. Black carbon emissions can influence regional precipitation and temperature patterns through albedo cooling effects and glacial melting (Cho, s.f.). These effects are likely to be substantial in some areas, affecting water catchments for central Africa and plantations of mountain cash crops. The effect on the forests is mainly due to fuelwood collection, which leads to forest degradation, but not necessarily to deforestation. Deforestation effects vary greatly on a country context, as each region has a different policy towards wood plantations and deforestation.

2.1.3.3 Economic Impact

Alongside environmental and health effects, there are significant economic costs associated with solid fuels for cooking. Surveys on the BoP population estimated that 7% of the household expenditures are dedicated to the purchase of cooking fuels (World Bank Group; World Resources

Institute, 2007). The share is expected to increase due to raising cost of cooking fuels relative to household incomes.

In addition to its high cost, dry firewood and charcoal have a highly fluctuant price, which can be dependent on externalities such as seasonal rains. If the firewood is not purchased but collected, it must be considered the opportunity cost for the time invested during collection. This opportunity cost has been estimated as three times lower than fuel cost, but it is still significant, and collection also attains many other health and gender burdens (Nerini, et al., 2017).

2.1.3.4 Gender Impact

The afflictions that have been stated from traditional cooking in developing countries falls mainly on women, creating a gender difference. The woman is generally in charge of the cooking, which results in higher exposure to emissions. Men's exposure levels to emissions already exceed the safe minimums, but female cooks are exposed to up to four times their levels. Women are also the ones in charge of collecting the firewood leading to further health, economic, and violence risks. Along with water collection, firewood collection is among the most physically arduous activities endured by rural poor women. The opportunity cost from the time spent collecting the firewood and cooking is also more pressing among women. Finally, there is a gender-based violence due to the exposure to risk of rape and sexual harassment during firewood collection, particularly in the case of refugee camps.

At the same time, women also hold the responsibility for the cooking, which means that their decision on fuel preference and cooking method is often more significant than the men's. This clearly depends on the context and environment, but there are many regions where women have more decision power on fuel choice than men.

2.1.3.5 Energy Impact

In the regions that suffer from lack of access to modern cooking technologies, the energy for cooking represents the largest share of the energy demand. As can be seen in ,this is mostly noted in the case of SSA, where cooking covers 80% of the final energy demand. For these regions, changing the energy source and amount used for cooking can be the key for the introduction of more sustainable energy systems. Improving the energy supply for cooking in developing countries holds a great potential for accelerating the transit upwards in the energy ladder*, towards modern energies more sustainable for the user and the environment.

* The Energy Ladder is a representation of the relationship between the access to different types of energies and the social and income status. Moving up the energy ladder means moving towards more sophisticated energy systems.

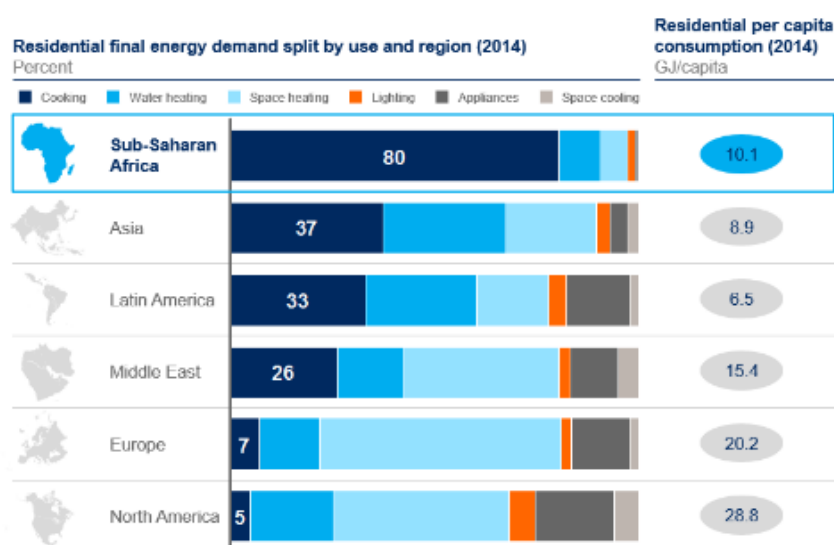


Figure 5 Residential Energy Consumption in Africa is dominated by cooking (Bram Smeets, 2017)

The energy efficiency of different cooking fuel and technology combinations varies greatly. Traditional sources based on biomass are in general much less efficient than more modern sources, requiring more energy for the same purpose. It can be seen in how stepping out of biomass technologies would lead to a significant increase in energy efficiency, with technologies that have a lower energy intensity for cooking. Switching to a landscape with modern energy technologies would mean an increase in energy efficiency for the region. A total lower demand of energy for providing the same service.

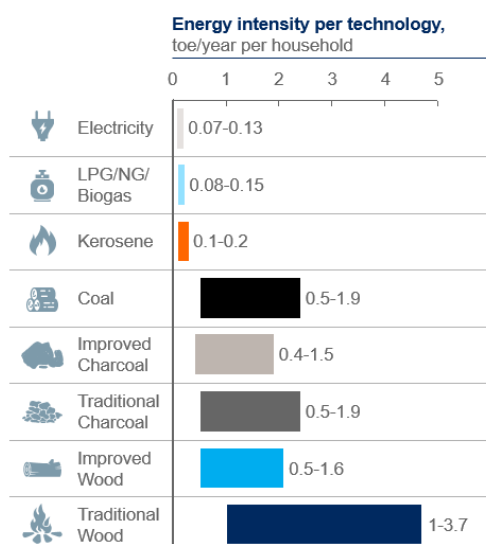


Figure 4 Increase of energy efficiency with modern cooking technologies

2.1.4 Defining Clean, Efficient, and Sustainable Cooking

The different dimensions in which cooking is seen to have an impact allow for a classification of the cooking methods. The term “clean cooking” has already been mentioned as describing the state of the cooking landscape, presumably with a focus on the emissions from cooking. However, a definition of what “clean” entails has not been given in this text so far. The term “efficient” may also be also subject to such a classification. Here we also introduce the concept of sustainable cooking, in all taking several dimensions of impact into account.

Precise and coherent definitions of “clean cooking” and “efficient cooking” have been proposed by the Global Alliance for Clean Cookstoves (Global Alliance for Clean Cookstoves, s.f.). The Alliance uses the tiered performance guidelines in the ISO International Workshop Agreement (IWA) for setting the range for “clean” and “efficient (ISO, 2012).

There are four indicators considered in the IWA classification for cooking, as shown in . Efficiency or fuel use, total emissions, indoor emissions, and safety. Tiers of performance define a rating for each of these indicators. There are 5 tiers of performance, from 0 to 4, being tier 0 the lowest and tier 4 the highest performance for each of the indicators. The tiers are limited quantitatively, enabling a precise classification of a given cooking system by each indicator.

Each of the indicators have different metrics. Efficiency is measured through thermal efficiency and specific power consumption. Emissions, both indoor and outdoor, are measured in terms of particulate matter per unit of energy and carbon monoxide emissions. Safety is assessed from by a point system with ten weighted safety parameters.

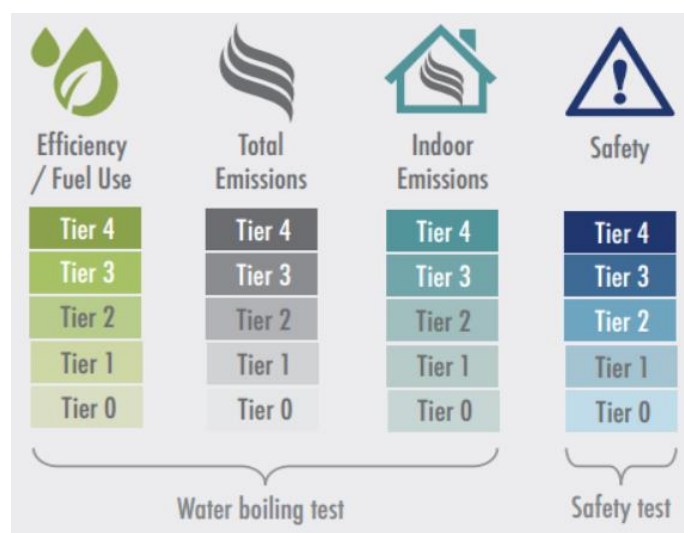


Figure 6 IWA tiers of performance for cooking (Global Alliance for Clean Cookstoves, s.f.)

A cooking system is defined as “clean” when it reaches tier 3 or above, either in indoor emissions or in overall emissions. This way, both potential health impacts and environmental impacts are considered.

A cooking system is defined as “efficient” when it reaches tier 2 or above in “Efficiency/Fuel Use”. This implies a power thermal efficiency above 25% and a power specific consumption lower than 0.039 MJ/min/L. It should be noted that thermal efficiencies are commonly low in the cooking process and far from 100% efficiency. Tier 4, representing the highest thermal efficiency, starts at 45% efficiency.

For the work presented in this thesis, this classification based on “clean” and “efficient” has limitations. When considering the different dimensions of impact of cooking technologies explained in the previous point, this classification falls short. The classification, to some extent, includes the health, environment, and energy aspects, but does not consider the economic impact of the technology. Moreover, it is more suitable for fuel-based systems, especially those using wood, charcoal, or kerosene.

It has been considered appropriate to introduce the concept of sustainable cooking. This term intends to include the main aspects that make a cooking solution sustainable and suitable both in the long and short term. The concept considers the environmental, health, and economic aspects of the solution.

A cooking solution is here defined as sustainable when it fulfils the requirements for clean cooking, both for indoor and outdoor emissions, and is at the same time economically viable for the targeted market. Thus, the term focuses not only on the technology but also on the potential end user. As an example, electric stoves working on clean energy are both clean and efficient, but they are not sustainable for rural areas in SSA since the access to power is not reliable and the electricity and infrastructure cost cannot be afforded by most users.

2.1.5 Cooking fuels and technologies

The cooking methods are characterized both by the fuel that is used, and the technology employed for this fuel. This is particularly important for understanding the use of charcoal and wood, which represents the bulk of the supply in SSA as shown in . Different cooking systems for the same type of fuel may have different levels of energy efficiency, environmental impact, health risks, and more. Moreover, there are alternative technologies such as solar cooking technologies, which are not dependent on any type of fuel.

2.1.5.1 Dominant cooking methods

The most basic energy source for cooking is the “three stone fire”, which constitutes the most common cooking method in SSA. It requires only three suitable stones of similar height on which a cooking pot is placed over the fire. Therefore, it is also the cheapest option available in terms of upfront costs. The cooking vessel is placed very close to the fire, reducing the excess of waste heat. The stones serve as windbreaks and increase the thermal properties of the fire. It is the solution with the lowest thermal efficiency.

The use of charcoal for cooking cannot be performed in an open fire as with wood, but requires a basic stove. The stove consists of a recipient in which the charcoal is burnt, with the pot placed

above it. A basic charcoal stove has a high level of carbon monoxide emissions. Since carbon monoxide is an unburnt fuel, this also represents a high level of fuel waste (GIZ HERA, s.f.).

Improved cookstoves are solutions with increased efficiency and reduced emissions compared to traditional combustion methods as already described. There is a range of improved cookstove types designed to work with firewood, charcoal, animal or crop waste, or even several of these options combined. Although the smoke is still vented inside the house, improved cookstoves can lead to reduced amounts of smoke due to better combustion and higher efficiencies.

Basic improved cookstove solutions present small functional improvements in fuel efficiency, which in turn may influence the amount of emissions. These cookstoves are normally between tiers 0 and 2 for efficiency and tiers 0 and 1 for emissions. Thus, they are still far from being considered “clean” and can rarely be considered “efficient”. This type of cookstoves have 10% of the market (Africa Clean Cooking Energy Solutions Initiative, 2014).

Intermediate improved cookstoves present different designs for a higher improved fuel efficiency and emission reduction. This includes rocket stoves and highly improved charcoal stoves. These cookstoves can be defined as “efficient” since they achieve tiers 2 and 3 on efficiency, but still have poor performance in emissions, not reaching the tier 3 (required to be defined as “clean”). The market penetration of this cookstoves (3.5%) is lower than for the basic stoves (Africa Clean Cooking Energy Solutions Initiative, 2014).



Figure 7 a) Charcoal Stove. b) Three stone fire. c) Basic improved stove. d) Rocket stove

Kerosene, LPG and electric stoves, are technologies that hold significant shares of the cooking landscape in SSA (7%, 5%, and 6% respectively) (Africa Clean Cooking Energy Solutions Initiative, 2014). However, their presence in rural areas is almost negligible.

Kerosene is more expensive than biomass-based fuels and has a lower penetration in rural areas, which are more price sensitive. Moreover, it is still a hazardous fuel with risks of poisoning, fires, and explosions (Nicholas L. Lam, 2012). LPG is a more advanced technology that achieves the requirements for being clean and efficient. However, the infrastructure for LPG supply, the cost of an LPG stove, and the cost of the fuel, make this solution not suitable for lower income (which often coincides with rural) areas (Michael Toman; Randall Bluffstone, 2017). The cost of cooking

with LPG can be 4 to 10 times higher than with purchased firewood (Global Alliance for Clean Cookstoves; Energy Sector Management Assistance Program, 2015) . Electricity cookstoves connected to the grid holds the same disadvantages as LPG stoves, with the added difficulty of a non-reliable grid. Even in areas with access to the grid and a user willing to pay for an electric stove and the electricity required, frequent unexpected power cuts discourage the use of this technology for cooking.

2.1.5.2 Alternative cooking methods

The strong focus that has been made on achieving clean and efficient cooking by diverse institutions has led to a wide range of inventions trying to solve the problem in diverse ways. There has been extensive work on developing the design of current cookstoves and fuels, and on delivering new ways of cooking. As an example, in regions such as South Asia, cooking with biogas from domestic anaerobic digesters have played an important role.

Advanced improved cookstoves define solutions like regular cookstoves but with technological improvements in the combustion. This type of solution is available for all kind of fuels, charcoal, wood, kerosene, animal dung, crop waste, etc. There is a wide range in terms of performance and, consequently, in cost, for these solutions. The best cookstoves, although being powered by solid fuels, can reach great reductions in emissions, with some solutions reaching tier 4 for indoor or outdoor emissions. These solutions are produced by companies worldwide and targeting mainly household cooking. The drawback of this solutions for the user is typically the higher upfront cost and, sometimes, the dependence on a specific fuel.

Innovations in fuel choices have also been made regardless of the cookstove technology. The aim has been to produce fuels that can lead to lower emissions and higher efficiency. Pellets, as a substitution for charcoal and fuelwood, plays an important role. Pellets are often produced from biomass waste, such as crop waste, and may have a high energy content and pellets stoves may be relatively efficient.

Anaerobic digesters supply biogas that can be used as fuel. The digesters take in organic matter such as food waste, animal manure and agricultural waste, and produce digestate that can be used as a fertilizer and biogas that can serve several purposes as a source of energy. This solution however, is highly dependent on the availability of the feedstocks and requires medium to high upfront costs for the infrastructure and a continuous maintenance and operation.

Solar PV and wind energy, coupled with batteries for storage, are often considered when trying to enable energy access in rural areas. These technologies provide electricity without requiring an access to the grid and are at the forefront of the so called “microgrids” which may enable electricity access in isolated areas. The infrastructure requirements for the implementation of these technologies are high and, although they can provide energy with low marginal cost to the owner, this kind of systems would only be used for cooking purposes if they are designed to have the capacity for heating in the kW range per household and if reliability is assured, in terms of no sudden energy shortages while cooking.

Solar thermal heating delivers energy directly in the form of heat, which is needed for cooking, not having the efficiency losses in transforming from sunlight to electricity to heat, as in solar PV. There are different designs and features of this technology that drastically may change the user experience: The availability of heat storage determines the possibility of cooking outside daylight hours. Direct systems require cooking outside by the solar collector, while indirect cooking can connect the collector to the indoors stove. Hybrid systems enables the use of traditional or other fuels together with the solar solution. However, most of them have in common a high upfront cost due to the infrastructure, which creates a barrier depending on the market segment and calls for a business model which compensates for this barrier.

2.2 Sustainable cooking market

The market for sustainable cooking solutions includes almost three billion people that lack access to this service. In SSA alone, there is almost one billion people in this market, a number which is growing each year due to population growth. The IEA projects that a total investment of \$95 billion will be needed to achieve clean cooking by 2030 (Global Alliance for Clean Cookstoves; Energy Sector Management Assistance Program, 2015). Access to sustainable cooking represents both a major humanitarian concern, and a market with a great potential for investment.

The market mainly serves the Bottom of the Pyramid (BoP) market, representing the largest but poorest socio-economic group. This is, the more than 4 billion people that live on less than \$1500 per year. This market has proven challenging to penetrate and stands out due to its strong dissimilarities with the common markets approached in the developed world (C.K. Prahalad, 2002).

Most of the people in the BoP market live in rural villages, or urban slums and shantytowns, and they usually do not hold legal title or deed to their assets. They have little or no formal education and are hard to reach via conventional distribution, credit, and communications. Selling to the BoP requires a rigorous understanding of consumer behavior and the way products are made and delivered (Simanis & Duke, 2014).

2.2.1 Customer study

Global numbers and data on the cooking landscape have too low resolution to understand the individual users, and therefore, the market. Especially in the BoP market, with an end user in an environment drastically different to what is experienced in a developed country, it is essential to get to know the user and the environment she/he lives in.

A study on the key aspects affecting the purchase decision for a clean cookstove in Kenya (Global Alliance for Clean Cookstoves, 2013), revealed the following points as the main barriers to the adoption of clean cookstoves:

- Liquidity constraints: Consumers find it difficult to come up with the entire purchase price in one lump sum depending on the type of stove.

- Quality assurance: Consumers are not able to verify the claimed characteristics of the product or have unrealistic expectations
- Durability concerns: Consumers fear the stove will not work or will break quickly, especially with new technologies.
- General lack of awareness: Many consumers do not know about the problems associated with traditional cook stoves, that were explained in this thesis in 2.1.3, nor are they aware of alternatives.

Another study on consumer choices for households highlighted the importance of higher utility in the purchase decision (Johnson & Takama, 2012). The consumer will be prone to buy a more efficient and cleaner cookstove only if the utility level of this second one is higher. Due to the lack of awareness on the health impact from unclean cooking, other levels of utility must be implemented. The addition of a regulating valve for cooking or a technology for providing light as well with the cooking solution are examples of added utilities that can benefit the purchase decision.

Solutions that resemble the traditional stoves have shown to be preferred by the users, according to a study assessing the user acceptance on an innovative (the “firepipe”, fueled with pellets) cookstove (Johnels & Murray, 2013). The cooking culture must be considered during the designing process and this might lead to different localized solutions. For example, in Ethiopia the “injera” is the base for most of the meals. This dish consists on a large bread or “pancake” that requires a flat, large sized stove for cooking. A solution that does not allow for this would have little chance of success in Ethiopia. Similarly, different users have different needs such as frying at high temperatures or maintaining a stable heat. These variables need to be studied for designing a solution that agrees with the needs of the targeted user.

Cooking time is another major factor in the purchasing decision for a better cookstove as reflected in a study from Kenya and Zambia (Jürisoo, 2016). Saving money or fuel, reducing the cooking time, and the aesthetic, modern appeal relating to the buyer’s aspirations, were concluded to be the main three purchasing factors.

2.2.2 Market Segments

The cooking method market can be divided in three main segments: Household cooking solutions; community cooking solutions; and institutional cooking solutions.

The household market is the largest and most focused market. It represents the daily cooking that is performed by individuals and families. It is characterized by being highly sensitive to upfront costs, due to lack of income and low liquidity, and at the same time not reliable for alternative financing methods due to the lack of a well-structured financing system on many national and regional markets. For natural reasons, most of the efforts on improving cooking methods in SSA have been focused in the household market, and it is thus a market with a high level of competition.

Community cooking exists where the collective benefits and gathers around a common cooking solution. This can be the case of villages, where a large population is allocated in the same area and investing in shared solutions has a potential for cost reduction. This market has been explored as an alternative for solutions that present upfront costs too high for the household market. Many times, the idea of communal cooking is proposed to implement the solution, rather than communal cooking being an already existing practice.

Institutional cooking here refers to the cooking that is developed in institutions such as schools, that offer food on a regular basis to a large amount of people. This market is characterized by a large scale which, for most of the cooking solutions, indicates reduced costs for infrastructure. Thus, solutions that have disadvantages on the upfront costs but prove beneficial on the continuous costs (mainly the fuel), have a great potential in this market. Moreover, the market enables alternative financing methods with a stronger reliability on payments, and the possibility for tailored solutions to the specific case, instead of mass production of the same solution.

2.3 Institutional Solar Cooking

Institutional solar cooking refers to cooking at a larger scale. The general definition for institutional solar cooking is adopted by (Otte, 2015), who considered solar cooking as institutional when cooking for 30 people or more per day. This definition takes a wide range, with cases of institutional solar cooking that target thousands of meals per day.

Despite the many benefits given by solar energy as a source for cooking, and the efforts made by different organizations to promote it, the method remains underutilized. This is even more pronounced in the case of institutional solar cookers, a field that has received a much lower focus than the household solution.

Work on institutional solar cooking is still at an early stage. Most of the work has a side purpose for research and development, rather than a purely commercial approach. Solar cookers haven't reached commercial success within the BoP with exception of Tibet and the Andean Altiplano, places with limited access to fuel wood (Kilman, 2015). Best practices are still under study and the success rate of implementation is low. Moreover, many of the challenges facing institutional solar cookers are different from the problems faced in household cases.

The reasons for low acceptance of solar cookers in the literature, are more focused on households and less applicable for the case of institutional solar cooking. Institutional cooking presents a different framework with differences in the infrastructure, operations, and functional purposes. (Sunil Indora, 2018) identified the favorable characteristics of institutional solar cooking. His findings remark the fixed settings in an institutional case, with schedule, food choices, and amount of food to be cooked as constant variables. This allows for a design and dimensioning well adapted to the user needs. Besides, there is generally more physical space available for this infrastructure, and institutions and community groups may in some cases have better affordability for the system.

The benefits of such a system that offers low or negligible operational cost on fuel but has a high upfront cost are also improved with scale. When increasing the scale of the system, the infrastructure costs see a lower relative increase than the fuel costs, which become more significant. Therefore, the system has a stronger potential for being economically competitive, or even advantageous, to traditional cooking means.

Solar thermal cooking as a sustainable cooking solution may be compared with solar PV. The latter has had a much larger spread in developing countries. It can produce electricity for other means as well. However, for cooking in areas with scarcity of resources, the solar thermal cooking presents a more simple, direct, and efficient method of harnessing solar energy. What is requested of solar thermal cooking is reliability.

A comparative study on the motivations for adoption of institutional solar cooking was done by (Otte, 2013). The study identified 19 variables for the adoption of solar cooking shown in Table 1. These variables serve as a recommendation on the points to be analyzed when developing a solution for institutional solar cooking.

Table 1 Factors on adoption of institutional solar cookers. Adapted from (Otte, 2013)

Economic	Cultural	Social	Political	Technical	Environmental
Affordability	Food Characteristics	Motivation	Financial schemes	Satisfying performance	Availability and price of alternatives
Local employment opportunities	Traditional cooking habits	Power / gender relations	Dissemination strategies	Easiness of use	Availability of suitable location
	Schedule of daily routine	Use of solar cookers by disseminators		User-friendliness	Levels of solar radiation
		Supplier characteristic		Repair possibility	Level of infrastructure

Among the factors presented, some of them were said by the same author to be of significance. Motivational factors and the three cultural factors were vital for the adoption of the technology. Moreover, the presence of an economic and environmental incentive was relevant for the continuous use of solar cookers.

A further study on the cultural factors for adoption of institutional solar cookers was done by (Otte, 2014). The study turns previous claims of solar cooking technologies being unfeasible due to social disruption to a critic stating the need of implementing solutions integrated in the existing socio-cultural framework. The author proposes moving away from an image of a foreign technology to a solution that is an integrated part of the society. Moreover, examples of diverse cultural factors are explained to give a better view. With cultures such as Brahma Kumaris in India,

which highly value the environmental benefits of the solution as they believe cooking with a positive energy yields better food, or the Tswana culture in Botswana, where the fire plays a significant social role in their life.

The most updated review on institutional solar cooking solutions that have been implemented was done by (Sunil Indora, 2018). The study presents a technology-based classification of the existing systems shown in Figure 8. The classification makes a distinction according to the presence of a heat storage, the link between the solar collector and the cooking unit (direct and indirect), and the type of collector used. Moreover, it mentions the three most common types of system for institutional means: Scheffler dish, Fresnel reflector, and paraboloid dish.

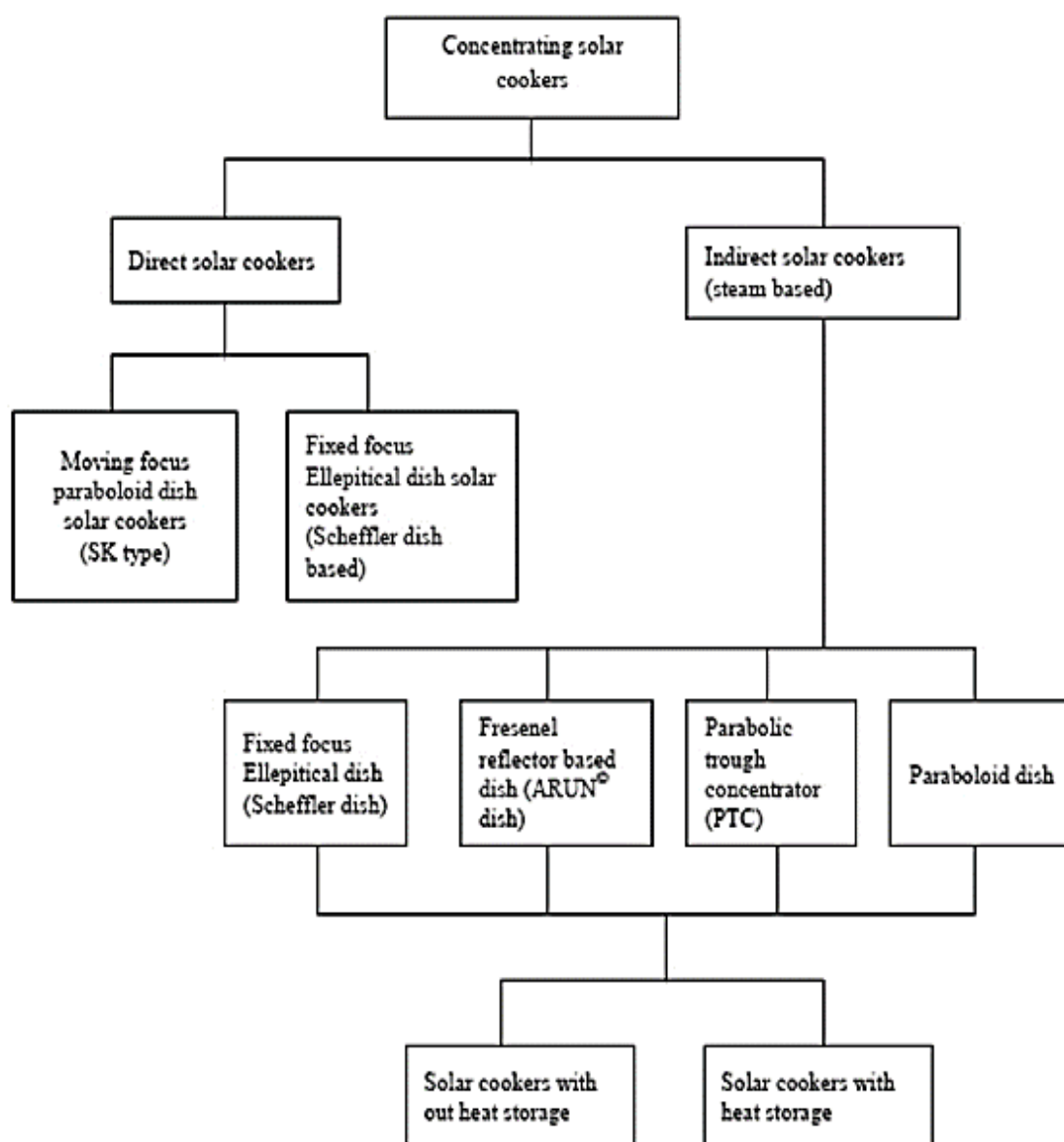


Figure 8 Technology based classification of existing institutional solar cookers. Adapted from (Sunil Indora, 2018)

The presence of a heat storage device has a great influence in the characteristics of the solution. Unavailability of cooking power when the sun goes away is the most challenging point of solar cookers according to (Erdem Cuce, 2012). This challenge is overcome with thermal energy storage techniques, usually based on sensible heat or phase change materials that transfer the heat to the cooking devices. Oils and organic phase change materials are the predominant choice for heat storage (Lameck Nkhonjeraa, 2017). Oils provide an affordable material with good heat transfer characteristics.

Implementation of a heat storage is most of the times necessary to provide a complete solution for the user. It acts as a backup for a power resource that is highly unpredictable. This is particularly important in the case of institutional solar cooking, where cooking must follow a fixed schedule and the risks are higher by affecting more users. However, it also poses several problems. First, the addition of heat storage adds more infrastructure to the system. Moreover, it leads to a significant amount of heat loss when transferring the energy from the storage to the cooking section, as was studied by (Craig, 2015).

Advantages of direct or indirect cooking methods, respectively are often related to the user culture for cooking. In direct solar cookers, the radiation is focused directly on the cooking device. While this may lead to lower heat losses e.g. with a simpler system, it also imposes restraints on the user. Most of the direct systems require the cooking to be done outside, under the sun. Therefore, acceptance of this system is more related to the user's (traditional) way of cooking and resistance to a change in their practice. Indirect systems implement a middle step for transmission of the heat to the desired cooking (s)pot, rendering a more flexible solution for the user. The indirect system may be more complex and costly and entail energy losses.

The type of solar collector has a strong influence in the efficiency but also the cost of the technology. First, the higher the concentration ratio, the higher the temperature that can be achieved. Thus, parabolic solar collectors generally achieve higher temperatures than trough collectors, and the same with the later and flat plate collectors. This has a direct influence in managing the minimum temperature requirements, which will vary depending on the type of cooking (boiling, frying, baking...). Moreover, there are other differences like the type of solar tracking required, the amount of area required, or the suitability for the type of solar radiation at the location.

Apart from the main characteristics that define a solar cooking solution, there are other considerations in the system. Solar solutions can consider also the use of traditional cooking fuels as a backup, achieving a hybrid solution that might increase the reliability of the system. Moreover, there can be a distinction between the need of an electrical appliance for the system (such as a pump or a set of sensors) or a completely mechanical solution, that might be more appropriate for the BoP market, providing an easier maintenance and repair.

2.4 Proposed technology

The analysis made in this thesis has been focused towards the technology proposed by the company Joto Solutions AB for a solar cooking device called the Joto Jiko. The original idea of

the company has been developed further throughout the analysis but maintained the same working principles as its base. The aim of the company has been to use their knowledge and innovations in heat technology to provide a suitable cooking solution for developing areas.

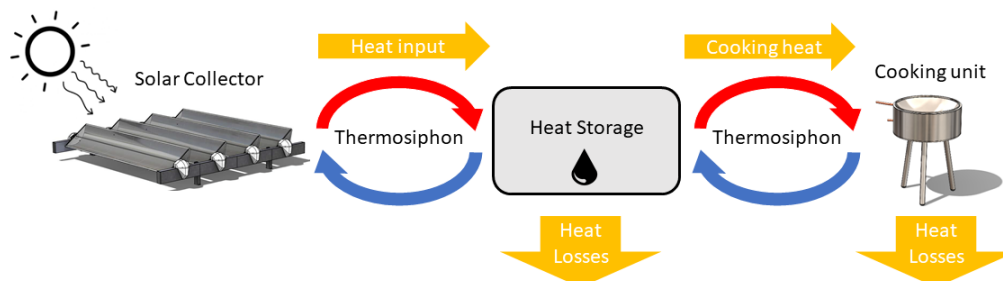


Figure 9 Simplified sketch of the studied technology

A solution without need for electricity or other external energy than the sun has been one of the main arguments of the system. Due to the increased complexity and decrease in robustness and difficulty of repair that electric devices may imply, a system with no electric components was sought. Instead, the system aims towards simplicity and ease of installation, operation and repair through a purely mechanical system.

In difference to some other indirect solar cooking devices, the heat transfer mechanism does not use a powered device. Heat transfer through a working fluid is commonly done by active displacement of the working fluid between the different parts of the system (collector, storage, cooking unit). This requires the use of a pump, powered by electricity or other motive power, for the circulation of the fluid. The proposed technology instead uses a passive heat exchange mechanism that is thermally driven.

The solar collector in the design, represents a tradeoff between simplicity of use and heating requirements. It has been mentioned that parabolic solar collectors reach higher temperatures than trough or flat plate collectors. Given the range of temperatures needed, this often makes parabolic collectors the preferred choice for solar cookers. However, these are highly dependent on a solar tracking system, which is often complex and requires external power. The system modelled in this thesis presents a trough collector less dependent on a solar tracking system, and with the appropriate thermal output.

Presence of a heat storage is also a key point of the solution, with an idea that is low cost and environmentally friendly. Engine oil is recycled for its use as a heat storage medium. This provides good heat transfer properties, an affordable price, and a way for reusing a polluting substance.

The technology prioritizes user experience, cost, and suitability for the working environment, through simplicity and robustness. New ideas and innovations that have been mentioned enable this compromise between features. These will be explained in detail in the following sections.

2.4.1 General system

The studied system receives power from solar radiation and transforms it into heat for cooking with an intermediate step with heat storage. It thus has three main parts; a solar collector, heat storage, and cooking unit. The heat flow from the solar collector to the cooking unit is facilitated by two thermosiphons that connect the system. The inclusion of thermosiphons permits heat storage without circulating the heat storage medium. A simple sketch of this system with the energy flow can be seen in Figure 9.

2.4.2 Solar collector

An industrially sized parabolic trough collector is used as the power source. Trough collectors consist of a parabolic reflector with a tube on its focal point as in Figure 11. Thus, the parallel rays received from the sunlight are concentrated on the tube, which contains the heat transfer fluid. The parabolic reflector is optimized for concentrating the rays with a smooth and reflective surface. The collector tube is designed for maximum absorption of irradiance, commonly with a black surface, and a high heat conductivity to the fluid inside.

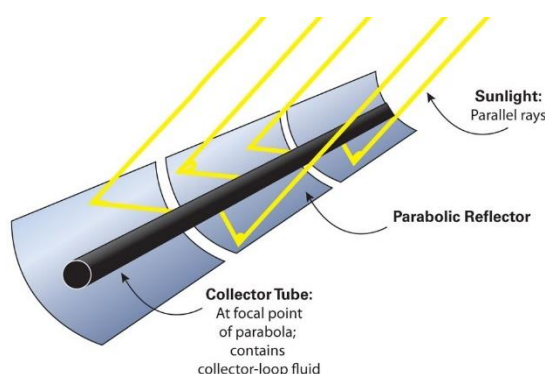


Figure 11 Working principle, solar trough collector



Figure 10 Absolicon T160. Glass cover and collector tube. Photo by the author

The model of solar collector for the prototype installation is the Absolicon T160, Figure 12. Absolicon is a company specialized in solar collectors, with this model being their product designed to achieve the highest temperatures. The T160 includes a glass cover for decreasing heat losses to the ambient as shown in Figure 10. The trough rotates around the collector tube, which is in a fixed position, for tracking the solar radiation. The tube extends across the limit of the trough structure and allows for a simple integration with the rest of the system. Tests on the product have shown the highest optical efficiency recorded for a trough solar collector, with an efficiency of 76.6% (Absolicon, 2018).

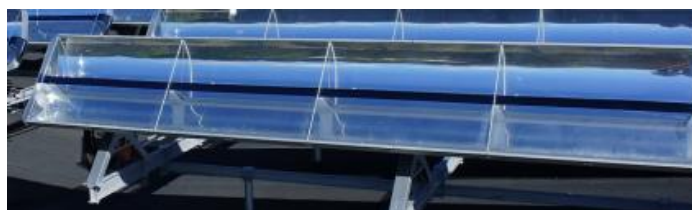


Figure 12 Absolicon solar collector

Absolicon's T160 solar collector is manufactured in units with specific dimensions. Each unit has a length of 5.49m, width of 1.056m, and a total weight of 148kg. Power per unit at peak irradiance conditions (1100W/m^2) is approximately 4000W depending on the temperature in the collector tube. All the relevant data for this study on the solar collector has been extracted from the results of performance tests on the technology carried out by SP Technical Research Institute of Sweden (now part of RISE). More detailed information on the solar collector modeled in this thesis is presented in Appendix A.

2.4.3 Heat storage

The heat storage is based on sensible heat storage with engine oil. A liquid, and specifically oil has been selected for several reasons: It is largely available, engine oil is present in most vehicles and has to be dispatched when changed for new oil; It has a low cost, taking used oil from the responsible entity can even be beneficial by assuming the disposal task of a pollutant substance; Reusing the oil has a beneficial environmental impact, by extending its life and avoiding bad disposal techniques, especially important in developing countries. The stored oil in practice also serves as a carbon sink; And ultimately, engine oil presents good properties for heat storage and heat transfer.

Storing the oil in a tank connected to the other two components allows for a simple technique of heat storage. The oil absorbs and releases heat through natural convection with the thermosiphons. Rockwool insulation (or similar) covering the tank prevents significant heat losses. The system does not require any external action to function properly.

Heat storage capacity is determined by the oil properties and conditions. Temperature, specific heat, and volume of oil are the three main factors that determine the amount of energy stored. Specific heat of engine oil ranges between 2 and 3 J/gK, depending on type of oil and temperature (Wrenick, 2005). This study has considered engine oil with a specific heat of 2.5 J/gK. The temperature at which the oil is kept sets a tradeoff between energy density (which increases with temperature), temperature gradient (which increases heat transfer for cooking), and power supply by the solar collector (which decreases in efficiency with temperature).

2.4.4 Cooking unit

The cooking unit is the component of the system with most user interaction. Thus, a user centered design is most relevant for this component. The aim is to provide an efficient solution that does not disrupt traditional cooking practices. It is crucial that the user can manipulate the food in a similar way to cooking with a conventional stove. The system replaces the heating method from

firewood combustion to a heat exchanger. Moreover, it does so with a minimal impact in the used tools for cooking.

The condenser side of the thermosiphon provides the heat for cooking. The vapor from the thermosiphon is condensed when circulating through a copper tube below the pot or cooking container. This condensation releases the heat that is needed for cooking. Heat transfer between the copper tube and cooking device can be done through direct contact of both surfaces. Moreover, the possibility of immersing both surfaces in a fluid with a higher heat transfer coefficient than air, such as oil, is well considered.

The full cooking unit is enclosed in a structure that integrates the components and provides insulation. The structure is crafted according to the dimensions of the cooking device. Since the focus is large scale cooking, the cooking devices are not easily replaceable, and it is more practical to tailor the surrounding structure. Cooking commonly has high heat transfer losses, thus, the insulation provided by the structure has a high influence on the total system performance. A layer of rockwool surrounding the walls minimizes these heat losses.

User experience is improved by allowing control on the power input. A valve in the copper tube adjusts the mass flow of vapor that pass in the tube. The energy flux, proportional to the mass flow, may thus be controlled with a valve. This allows for control of the cooking temperature.

2.4.5 Thermosiphon

The thermosiphon transfers the heat between the different components in an efficient way, while not requiring external power. The passive heat exchange acts through gravity displacement due to the density difference between water vapor and liquid water. With an appropriate temperature difference, the fluid flows between the two ends of the thermosiphon, transferring heat to the cold side, and cooling the warm side.

Optimal functioning of the thermosiphon depends on several factors. Water is at a two-phase state to reach the required density difference. Cold side of the thermosiphon is higher than the hot side. Given that there is enough temperature difference at each end, the water condenses on the cold side and evaporates on the hot side. Correct dimensions and properties of the thermosiphon are also needed for enhancing the fluid flow.

Two alternatives are considered for the thermosiphon technology, closed loop and counter flow thermosiphons. Figure 13 shows a sketch of the heat exchange mechanism by both technologies.

In a closed loop thermosiphon, the fluid flows in a preferential direction by the coupled effect of vapor pressure and gravitational force. In the evaporator, expanding vapor phase pushes batches of fluid towards the condenser, where the water condenses releasing heat and filling the tube with liquid phase.

In the counterflow thermosiphon, as the evaporator section is heated up, the liquid starts boiling and vapor rises and condenses on the walls in the heat-rejecting zone. The liquid film flows down the walls by gravity to the evaporator zone, counter current to the vapor.

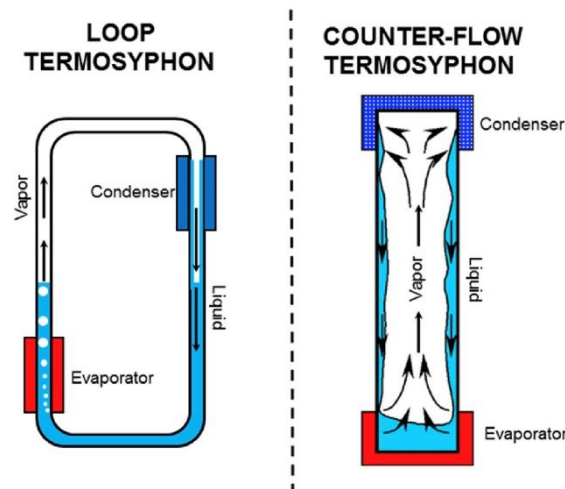


Figure 13 Loop and counter flow thermosiphons

The choice between closed loop and counterflow thermosiphon has an influence on the simplicity and performance of the system. A loop thermosiphon has a better performance than a counter flow thermosiphon (M.Mameli, et al., 2016). However, closed loop technology requires two connections with the oil storage per thermosiphon (input and output), and it was judged by the technology owners and the author as more complicated to install for this reason. Both alternatives are considered but in the first attempt to build a prototype simplicity has been preferred, and counter flow thermosiphons are used .

Heat transfer is enhanced with the addition of fins to the surface of the thermosiphon. Fins improve the heat transfer between the oil in the storage tank and the thermosiphon by increasing the area for heat exchange. Annular fins, which form rings perpendicular to the tube, are set on the tube increasing the heat transfer surface. Since there is no induced flow of oil, heat transfer occurs through natural convection, with a low heat transfer coefficient. Thus, presence of fins to enhance the heat transfer becomes necessary to optimize the magnitude of heat flow.

3 Methodology

Based on the proposed technology and a specific case, the system was analyzed and dimensioned. Dimensioning was performed with a wide scope, integrating the system and needs. The model, which was the main tool for dimensioning and analysis, links the process from solar radiation input to user requirements. Through this integration, all the components could be analyzed and dimensioned by their influence on the user side.

The specific case that was implemented in the model is based on a school in Kenya where over 700 meals are cooked each day with firewood. The company Ecobora provided the information on the infrastructure, schedule and quantities for cooking, and current situation of the school.

3.1 System modelling

The model was developed to provide a flexible and complete tool for analyzing the behavior of the solution and sizing its components accordingly. The aim was to enable a tool capable of making a close-up study of the dynamic performance and results of the system. Physical mechanisms (heat transfer, storage, radiation) were implemented and coupled with the control by the user. Results from the model under different settings allowed the output of numerical recommendations for satisfying user needs.

3.1.1 Purpose and scope of the model

The purpose was the use of a model with simulations enabling a detailed behavioral study of a global system. Simulations provided a time dependent analysis of the results, allowing a close examination. Results obtained led to specific numerical recommendations on dimensioning. The flexibility of the model enabled iterative simulations under different system setting and environment conditions. Moreover, the flexibility aimed at building a generic tool, useful for other future case studies.

Boundary conditions for the depth and extension of the model were set aiming for a broad study with enough detail and accuracy for the targeted results. Boundary conditions prioritized the extension range to be studied, which comprehended the physical system from the solar radiation to the user needs with a quantification of the cooking needs. Physical system was modelled incorporating the main heat transfer processes occurring.

3.1.2 Selection of modelling software

Modelling software was selected by defining the required characteristics to achieve the purpose and scope of the model. It was stated that the selected software should be able to:

- Integrate processes in the physical domain with user requirements.
- Provide time dependent simulations showing the dynamic behavior.

- Enable flexibility for changes in the environment, studying different conditions.
- Enable flexibility for changes in the setup, with iterations for optimal setting.
- Have a simple user interface, enabling the use of the model by non-experts.

Three softwares were considered for the model and selected according to these requirements:

COMSOL Multiphysics is a finite element software widely used for heat transfer modelling. It's potential for detail on the physical domain is high. However, flexibility for different settings is low, since changing the physical dimensions require redesigning the geometries and mesh.

LabView is a platform and development environment for the design of systems with a graphical programming language. Although it is more intended for its integration with hardware systems, it also enables modelling of physical systems through its graphical programming. It is not specialized on building a model for simulations and does not focus on heat transfer in physical systems. However, programming of these effects can be done through transfer function blocks with their respective equations.

Simulink is an environment of graphical programming that operates based on MATLAB. The software focuses on dynamic simulations of the implemented models. Although Simulink operates mainly with signal operations and transfer function blocks, it also contains a physical system toolkit. Simscape allows for simulation of a physical system with domains and blocks on different physical environments (mechanical, thermal, hydraulically).

Among the three options, Simulink was the selected software. Although COMSOL Multiphysics allows for a more detailed study of the physical domain, it is less flexible and presents a more complex user interface. Moreover, the level of physical detail that can be achieved with the use of Simscape, is enough for the scope of this work. When comparing with LabVIEW, it had similar possibilities to Simulink's basic toolkit. Yet, the ability to use Simscape simplifies the work, since it contains most of the required blocks for modelling heat transfer, without requiring the implementation of the respective transfer functions to simulate these physical effects.

3.1.3 Modelling workflow

The workflow approach to build the model followed guidelines like the Spiral Model for software development proposed by (Boehm, 1988). This modelling approach combines features from waterfall and rapid prototyping modelling. The result is a spiral in which the model evolves by successive iterations. For each iteration objectives are determined, approach is analyzed, work is developed, and the next phase is planned, in that order. A graphical representation of this approach can be seen in Figure 14.

Spiral modelling allowed for a planned and structured work with iterative trial and error exercises. The modelling objectives, which were set from the beginning, were always present throughout the work. Simultaneously, the work tasks and methods for achieving these objectives, were constantly altered through trial and error. This was highly beneficial as the software environment and the task

were new to the author, providing rapid learning through iterations without significant risks for the model. Moreover, MATLAB & Simulink allow for results visualization at any stage of the model, providing a proper environment for this work approach.

The spiral model was followed by developing each component individually and integrating it to the rest of the system. The model was divided into its main elements: Control, pot heater, oil storage, solar collector, irradiance. The center of the spiral, and start of the work, was the control side of the model, which models the user's control of the system. The different elements were developed once the previous had been finished and integrated into the model. This was done in an orderly manner starting at with the control and finishing with the solar radiation.

Elements were developed through iterations with an increasing complexity. Work on each element was first performed with the element isolated from the model until it presented the required features for integration with the rest of the system. When integrated with the system, iterations continued from a wider perspective until achieving the desired result and moving on to the next element.

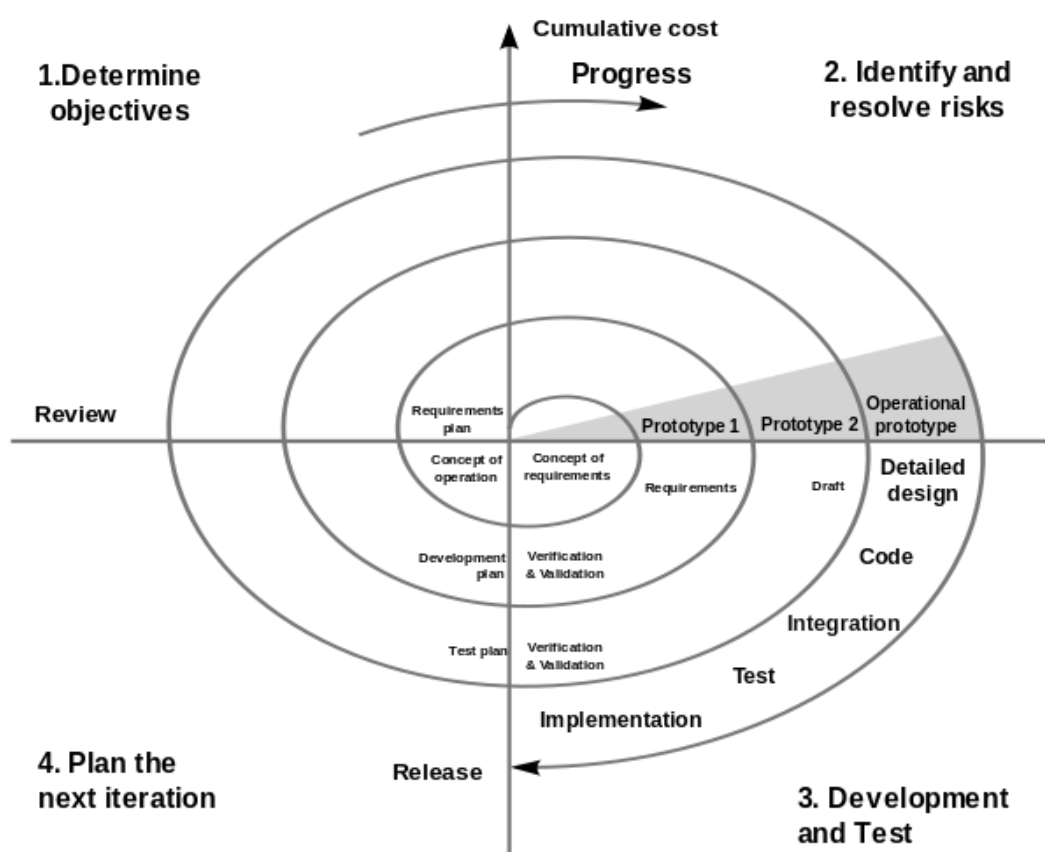


Figure 14 Spiral modelling. Original from (Boehm, 1988)

3.2 Data Collection

The model was built based on the defined characteristics of the technology and information from the study case. Renetech, Joto Solutions, Absolicon and the Kenyan company Ecobora provided the necessary information on the data necessary for the conduction of this work.

As this work is the basis for recommendations on dimensioning the technology, the bulk of information was qualitative on the system setup, rather than quantified data. Joto Solutions provided their knowledge on the working principles of the technology with a permanent assistance for its correct implementation in the model.

There were certain features that contained specific quantified data for the work. The dimensions of the solar collector units were a fixed constrain in this study, with the information being provided by the manufacturer, Absolicon. The relevant material on the solar collector that has been of use in this study can be seen in Appendix A.

The relevant information on the case study in Kenya was collected by the company Ecobora. Ecobora is a Kenyan company that has partnered in this project as the local partner for the implementation of the solution. Through a field visit to the studied school, they provided the necessary information for the implementation of this case into the model. Moreover, their constant assistance was vital to truly understand such a different environment. Information collected from Ecobora on the school has been attached in Appendix B.

Other data that was found necessary for the development of the model, such as properties of the materials in use (specific heat, conductivity, etc.). Was mostly collected through online sources properly identified and referenced in the model for possible verification.

3.3 Assessing reliability and validity of the results

Simplifications or assumptions on more detailed characteristics were sometimes made, due to absence of data or increase in depth and complexity over the scope of the work. In these cases,

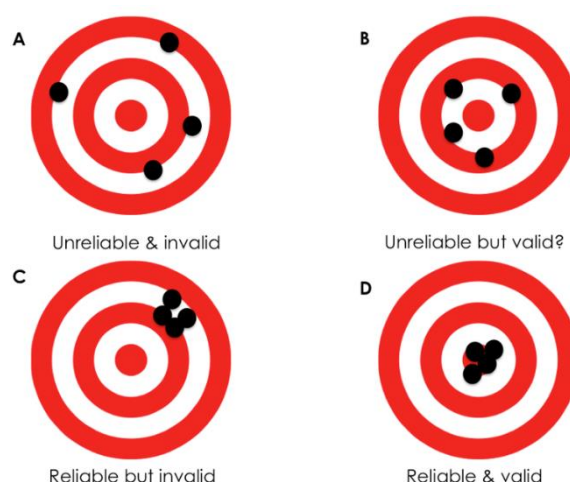


Figure 15 Reliability and validity

the influence of these assumptions or simplifications in the results were considered. A nice analogy with what reliability and validity means can be seen in Figure 15, where reliable results are those that can be repeated with the same outcome and valid results are those which achieve their objective.

3.3.1 Reliability

The idea behind reliability is that any significant result must be repeatable with a similar outcome (Shuttleworth, 2008). Other research must show same results under the same set of conditions to prove that the results are reliable. When reliability is discussed in this section, it refers to the reliability of the model and the results that can be obtained with it.

To assess reliability of the results, two means were considered. First, when there were available results from another research, those were compared to the obtained results to spot any major differences. Second, a form of sensitivity analysis was carried out as the model was executed under different parameters, observing if any feature provoked a sudden change in the tendency of the results.

3.3.2 Validity

Validity refers to how well the results obtained meet all the requirements of the scientific research method. This means if the structure of the work is consistent and the outcome puts together the objectives and conclusions with sound arguments.

To ensure the validity in this work, the settings for the simulation were specifically selected for the desired set of results. This way, influence from other elements were minimized, making the relation between objective and results isolated from external effects. This helps ensure that the model itself is valid, however, it also must be ensured the validity of the model on imitating reality.

A model has the objective to be as realistic as possible, making it more valid for its purpose of simulating reality. It has been already mentioned that this model is broad in scope, without great depth in the detail. Thus, many simplifications have been made that had to be assessed valid for the real case. Moreover, whenever a fault was seen in the model, it was recorded and stated among its limitations in section 4.5. This not only allowed to see the defects of the model, but to consider its weaknesses when obtaining the results. Therefore, allowing results that have been approached to ensure validity or that, at least, are given together with a note considering their validity.

4 Model and Simulations

4.1 Model design

The construction of the model shows a clear division in different elements. First separation has been between the control side of the system and the physical side of the system. The control side, consisting on the signals that regulate the functioning of the physical side, was built separate to the physical side instead of embedded in it. Moreover, the physical side also presents a division in the different elements that compose the system, which were also built separately and then integrated together.

The structure can be seen in Figure 16, which presents a shot of the model in Simulink. The blocks that can be seen in this image are subsystems which contain each of the elements.

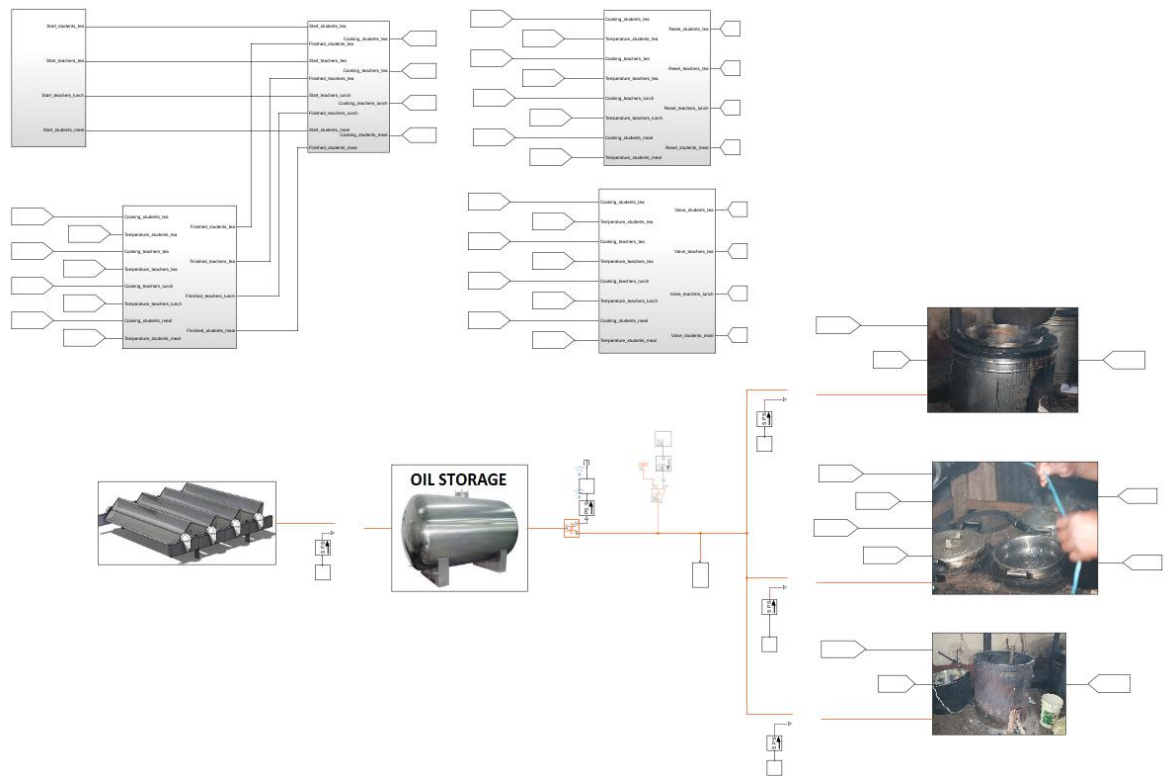


Figure 16 Structure of the Simulink model

The control elements are set in the upper left side. This part does not contain any component from the Simscape toolkit and all the signals are basic Simulink signals, which are colored black. Simulink signals transfer information between blocks in a one-directional way. The information, coming from the input data or the physical side, is processed to deliver different actions accordingly.

The physical model is set in the lower side. It can be distinguished by the orange lines that connect this part of the system. These lines are inherent to the Simscape Thermal toolkit. Instead of transferring information from one processing block to another, the links in Simscape contain the state and properties associated to the blocks it connects. The blocks are not for processing a signal, but for representing the physical phenomena between two areas.

An example of the Simscape Thermal toolkit for instructive purposes is given through Figure 17. A conductive heat transfer block is connected to a heat flow source and a thermal mass. The lines, which connect the blocks, contain the properties of the nodes connected. The heat flow source forces an amount of power to flow from one of its connections to the other. The conductive heat transfer block imposes a relation between the transferred power and the temperature at each of its nodes. Finally, the thermal mass, changes its temperature from the original state as power flows in through the node.



Figure 17 Simscape example for instructive purposes

The versatility of this software has allowed for the integration of different modelling tools. Apart from Simulink and Simscape, MATLAB has also been used to complement the solution and even to model certain features when this was considered more convenient. Introduction of data for the model was preferred through a MATLAB script uploading all the necessary inputs into the workspace. This provides with a simpler interface for a non-expert user and the possibility of accessing all the data through the same tool.

4.2 Data inputs

The MATLAB Script for initialization of the system uploads all the necessary data for the model. The data contains inputs to be specified by the user, such as the number of days to run the simulation or number of solar collectors, parameters for the dimensions of the system, and fixed parameters on the properties of materials and conditions for the setup. Execution of the script loads all the variables in the model. The script can be seen in Appendix C.

4.3 Control

The control side models the user interaction with the technology. It works together with the pot heater elements, as they are the only components manipulated by the user. The modelled behavior relates to when the user wants to cook, quantity of food being cooked, and amount of cooking time needed.

There are two inputs of information processed in the control subsystems and two outputs that act on the physical system as a result. The control takes in information on the periodical times at which to start cooking each type of food, and the temperature logging from the pots as an indication of the state of cooking. By processing this information, the control side acts on the valve that allows heat to flow into the pot from the oil storage, and the reset valve that returns the pot to its original state once the cooking has finished.

The control process can be better explained through the different steps that take place. When cooking must start, the control receives the respective signal and declares the start of cooking in one of the cooking units. This results in the valve being opened and heat flowing into the pot which starts increasing its temperature. The temperature is monitored and, once it reaches a boiling point, information on boiling time will order to stay in boiling conditions for a certain amount of time or stop if not needed. Staying at boiling conditions will activate the regulation of the valve to keep the heat flow at the necessary point for boiling. Once the process is completed, the cooking is declared finished and the state of the pot is reset to ambient conditions. This process is performed for each of the cooking devices at the different cooking times.

4.4 Physical components

The physical system is connected from the solar collector to the cooking units through the same Simscape Thermal network. Therefore, each of the components have an influence on each other through this network. In the setting shown in Figure 18, there are three pot heating elements being fed by one oil storage and an array of solar collectors. The heat flow direction under normal functioning goes from solar collector to pot heaters. The connection between the elements implement the behavior of the thermosiphon with a thermal resistance.

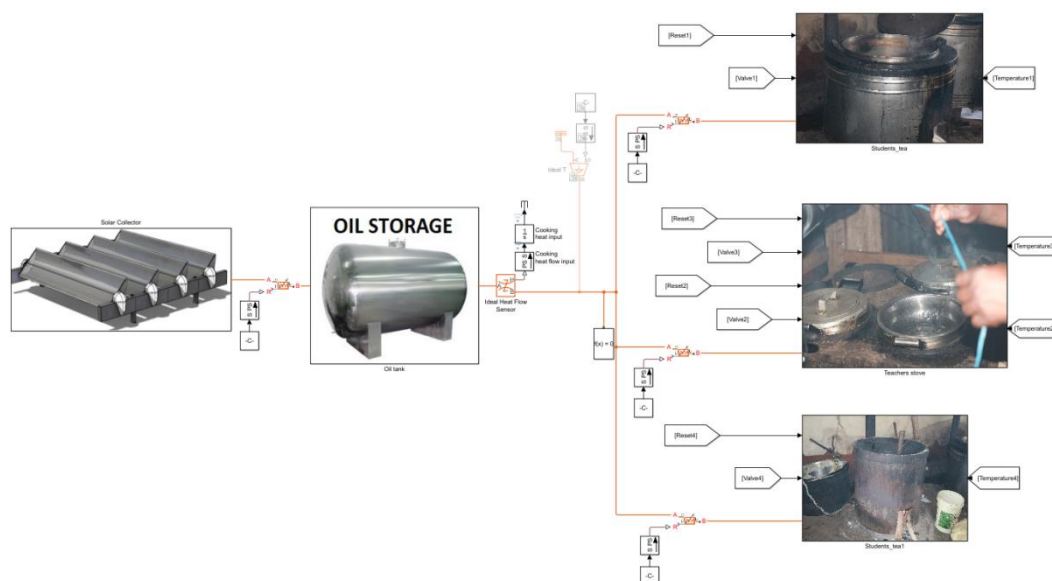


Figure 18 Physical Simulink model overview

There is no resistance to heat transfer inside the oil heat storage in the model. The oil is modelled as if the temperature was homogeneous throughout the oil tank. Therefore, there is no modelling of the temperature difference between the oil at the connection with the thermosiphon from the solar collector and the oil at the connection with the thermosiphon to the pot heaters. Moreover, the effect of stratification of temperatures is disregarded due to the same simplification.

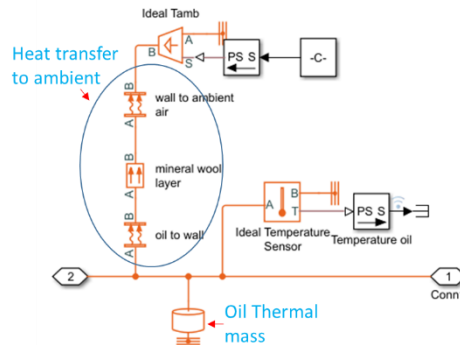


Figure 20 Oil tank Simulink subsystem

4.4.3 Solar collector

The solar collector subsystem supplies a specific heat power to the system depending on its temperature and the level of radiation. The results from the solar collector's performance test in Appendix A, are used to calculate the power supply. The MATLAB script initialization, Appendix C, loads this table relating radiation, temperature, and power supply into the workspace. The power lookup table in the solar collector subsystem, extrapolates the irradiance and temperature values to output the corresponding power supply. It uses the temperature between the solar collector and thermosiphon, which models the temperature of the collector tube, and the irradiance data from a timeseries object "Irradiation_ts".

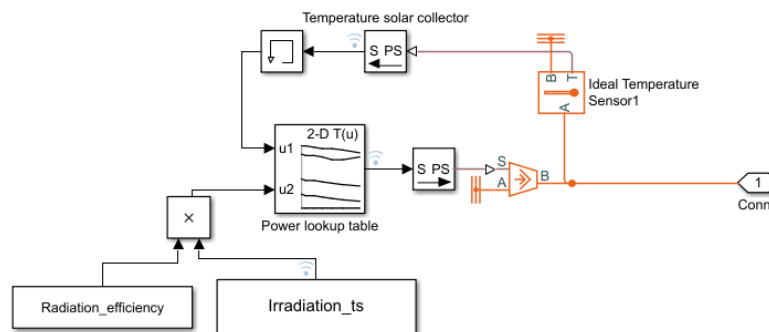


Figure 21 Solar collector Simulink subsystem

4.4.4 Solar irradiance

Solar radiation is calculated for a specific location and set of days with the Bird Clear Sky model provided by NREL (NREL, u.d.). The algorithm implemented in this software estimates the clear sky direct beam, hemispherical diffuse, and total hemispherical solar radiation on a horizontal surface, based on the theoretical approach in (Bird, 1981).

Introducing the case study settings in the Bird Clear Sky Model outputs the irradiance data during the entire year. Through the MATLAB initialization script, Appendix C, the user can select the starting day and amount of days to be used for the simulation. The radiation data is collected in the timeseries object "Irradiation_ts" for its use in the Simulink model.

4.4.5 Thermosiphon

Thermosiphons between the main components were modelled through a thermal resistance. This reduces the functioning of the thermosiphon to its ability to transfer heat. The thermal resistance, which can be defined as $TR = \Delta T / \dot{Q}$, defines the relation between the temperature difference between two points and the power that flows through them. The lower the thermal resistance, the higher the heat transfer, and the closer the thermosiphon is to an ideal behavior.

4.5 Limitations

While being extensive in the range of elements that the model considers, it has stronger limitations in the depth of the study. It was mentioned in section 3.1.1 how this approach is according to the purpose and scope originally designed. However, the limitations must be regarded for a correct employment of the model. Knowing its weak points is a prerequisite for proper use of the model and it is the first step towards planning for future improvements.

4.5.1 Non-thermal effects

Different physical effects take place in the system that have not been modelled. The Simscape Thermal network only considers thermal effects such as heat transfer, storage, temperatures etc. Although the thermal aspects are the focus of the model, there are other processes that occur in the system and have not been considered. Fluid flow is important for the functioning of several of the components, such as the thermosiphon. Effects of pressure, density, and volume changes are also important for the design of the solution. Ultimately, phase change in the used fluids occurs, changing the properties of the substances

Consideration of further physical effects than thermal would have produced results for a wider range of applications and even give a higher accuracy to the obtained results. Results on the relation of the pipe length and the fluid flow in the thermosiphon, or the pressure increase with temperature in the oil tank, would yield a more complete study. Moreover, these effects are not isolated from each other, and the relations between them are lost by not considering them, affecting the quality of the results.

Simscape toolkits allow for the implementation of other physical processes using different domains. Like Simscape Thermal, other domains include fluids, two-phase, liquid, and additional effects. Different domains can be used together in the same Simulink model.

The integration of domains increases the complexity of the work. First attempts on the model tried to incorporate the thermal liquid domain to account for pressure loss in the pipes and relation between pressure and temperature. However, the increased complexity showed in this approach

made it unfeasible to cover the targeted extension for the model under the scope of this master thesis.

4.5.2 Unconsidered effect of geometries

The model does not consider the geometries and dimensions. Opposite to other softwares such as finite element tools, Simulink does not work with geometries and three-dimensional models. Dimensions of the system are considered when needed, such as the area of a surface for the convective heat transfer block, or the volume of oil for the thermal mass in the oil tank.

Considering the geometry aspects of the system would have improved the modelling of some of the components. It was mentioned earlier in section 4.4.2 how the behavior of the oil tank is not accurately modelled due to disregard of the effects inside the tank. The movement of the oil inside the tank and the stratification of temperatures is not considered in this model, while these processes have a significant effect on the heat transfer properties of the oil tank.

Accounting for a homogeneous temperature of the oil tank makes a more optimistic model. The temperature drops from the oil next to the solar collector to the oil next to the cooking unit is not considered. This improves the heat transfer in the model in comparison to reality. Moreover, the stratification of oil is a feature that should be studied as it can be beneficial if used correctly. This means, implementing the thermosiphons at the points where they would have highest temperature differences for enhancing the heat transfer.

4.5.3 Undeveloped design of thermosiphon

The thermosiphon is the most complex element in the technology, however it has been roughly modelled through a thermal resistance. The working principle of a thermosiphon was explained in section 2.4.5, showing its dependence on multiple physical effects such as change of fluid state, displacement due to density difference, and fluid flow through a tube. In the model, this complex technology has been reduced to its potential for heat transfer between the two points it connects.

Reducing the thermosiphon to a thermal resistance neglects the influence of many of the processes taking place in this component. First, it considers that the relation between heat transfer and temperature difference on each side is constant, which is far from reality and might only happen in between a certain working range for the thermosiphon. Moreover, the model does not consider any heat losses in the thermosiphon, which might be accurate depending on the insulation that is used on this component.

This lack of accuracy in modelling the thermosiphon has been fostered by software limitations, and an uncomplete picture of the technology. There is no toolkit in Simscape that can model the fluid displacement due to density difference caused by change of state. This can be done by creating a new domain that takes this effect into account, requiring a complete expertise in Simscape, or by integrating a finite element software such as COMSOL in the model. Moreover, two alternatives for thermosiphons were proposed, with not enough specifications on either to model them accurately.

4.5.4 Solar tracking simplification

The orientation of the solar collector towards the solar irradiance is not modelling the reality accurately. The model does not consider the incidence angle deviating from the perpendicular plane to the solar collector, while representing the solar collector surface as constantly horizontal.

The technology does not have yet a defined method for tracking the solar irradiance throughout the daily and seasonal variations. Two alternatives are taken into consideration; however, none of them are accurately represented in the model. The model is optimistic when compared to the first alternative with a solar tracking and pessimistic when compared with the alternative with solar tracking. The last one, apart from achieving the sun to be in the perpendicular plane to the solar collector as assumed in the model, also takes in more irradiance per square meter by orienting the surface. Considering the solar incidence angle and tracking with the surface would be the next step in accuracy for this model.

4.5.5 Solar irradiance conditions

The solar irradiance was modelled for clear sky conditions. However, this is not representative of the conditions throughout the year. Meteorological effects should be taken into consideration for a more realistic approach. The results cannot be properly extrapolated to real conditions if this is not considered.

4.5.6 Boiling temperature control

When boiling is reached and must be maintained, the temperature controller that regulates the heat flow does not achieve the appropriate temperature profile. The content of the pot is modelled as a thermal mass, which does not include a change of phase. Therefore, there is no physical limitation imposed by the system restricting the temperature to surpass 100°C. Instead, modelling this feature is done through a temperature controller on the control side that regulates the opening valve. This approach has showed several flaws.

First, if working properly, and the temperature is kept at 100°C, it assumes that there is no energy being spent in sensible heat for the phase change. This would be equivalent to assuming that the user does an ideal control on the heat flow for minimizing the heat input during boiling. Moreover, the heat that the opening valve allows through depends on the setting of the surrounding elements, not only on the valve's value, which leads to an inaccurate control.

4.5.7 User behaviour modelling

Modelling of the user behavior has been simplified to certain characteristics. The information obtained from the case study has allowed to implement the schedule for cooking and amount of food to be cooked; however, this does not cover all the user behavior characteristics that influence the result.

It is unknown how the user will operate the system at all time, e.g. when a lid will be used on the cooking unit, or if the heat flow will be manually reduced when boiling starts. These kinds of actions on the system largely influence the result but cannot be modelled with the available information.

5 Analysis

5.1 Simulation setup

Simulations were performed for the study of several aspects of the system. The setup was done individually for each feature to be analyzed. Through this approach, the optimal setup was targeted in each analysis.

The relations between the different elements and their influence in the results were considered. Settings specified downstream in the physical system affected the results when analyzing other elements upstream. To solve this, an individual setting was specified for most simulations. The values for these individual settings were calculated considering the normal functioning of the technology.

In the following paragraphs, the setup implemented for each set of results is explained. This will enable a better comprehension of the results and the argumentation of each approach. Furthermore, it gives guidelines to replicate the conducted simulations.

5.1.1 Cooking unit insulation

The relation between the insulation on the cooking unit and the heating was analyzed. This included the influence of the thickness of the insulation and the use of a cover on the cooking unit. The system was modified accordingly to these situations, changing the setup of the heat transfer blocks from the pots to the ambient.

The cooking unit was isolated from the other elements upstream for this analysis. The solar collector and oil storage elements were replaced by an ideal temperature source. The source maintains a constant temperature at its node. The set temperature of 175°C simulates the temperature of the oil storage in a normal working range.

5.1.2 Thermosiphon to cooking unit

The relation between the thermal resistance of the thermosiphon and the speed of cooking was evaluated. This exercise had the aim to aid in the dimensioning of the thermosiphon. Ideal conditions from the oil storage of 175°C were kept. The setting on the cooking units was set to 2cm of insulation and use of a simple lid.

5.1.3 Oil heat storage

The effect of insulation and the size of the oil storage were studied. Different settings were used for analyzing each feature. Assumptions on the geometry of the oil tank were the first step for these simulations, since a specific shape for the device had not been defined. Calculations related to the geometry of the oil tank, such as area or volume, were done simplifying to the shape of a cube, with equal length on each side.

Insulation was studied by tracking heat losses under a constant temperature. 175°C was considered the normal operating temperature of the oil in the system. The oil tank was isolated from the rest of components for studying its insulation.

Size of the oil storage was analyzed first by comparing the relation between the size of the tank and the available power for cooking. The available power for cooking was measured in terms of the amount of time that cooking could be performed until the useful heat for cooking was depleted. The model was set with the oil storage and cooking units disconnected from the solar collector. Moreover, an initial temperature was given to the oil tank of 175°C .

The settings downstream of the oil storage were the same as in the previous section, with the addition of defining the thermal resistance for the thermosiphon. Thermal resistances were set to 0.006K/W for the students' tea and meal and 0.05K/W for the teacher's cooking units, respectively. The insulation of the oil storage was set to 15cm thick, seen preliminarily as the most adequate value.

A final test on the oil heat storage evaluated the threshold on its thermal inertia as a buffer for the solar collector heat supply variations. For this test, 5 solar collector units were connected to the storage.

5.1.4 Thermosiphon from solar collector

Influence of the thermosiphon from the solar collector was studied. Although there are no heat losses in this thermosiphon model, the thermal resistance has an influence on the heat input. Thermal resistance determines the temperature difference at each side of the thermosiphon. Since the power of the solar collector depends on its temperature, the resistance of the thermosiphon indirectly affects the delivered power.

Performance of the thermosiphon was studied through the temperatures at each of its connections. The settings having an influence in this result are the ones in the solar collector. By seeing preliminary results on the solar collector, it was assumed that 5 solar collectors were operating. The initial temperature for the oil was set at 175°C , as a reasonable value for oil temperature at the start of the day.

5.1.5 Solar collector

The number of solar collectors of the selected size and capacity needed to deliver the required power was studied. This set of simulations involved the operation of the entire model. The settings downstream were the same as for the oil tank simulations in section 5.1.3, with the addition of a 3m^3 oil tank covered by a 15cm layer of insulation. Also, the thermosiphon from the solar collector was set to 0.002K/W .

The solar irradiance conditions were taken from the "Bird Clear Sky Model". Therefore, the results are only representative under clear sky conditions. The set dates for the simulations were on the spring equinox.

5.2 Main Results

Key results are presented in this section according to their relevance for the research objectives. Individualized results for each component are given on what is considered important for its analysis and dimensioning.

5.2.1 Cooking unit insulation

The first set of the results is on the effect of the insulation thickness on heat losses. Figure 22 shows the heat loss variation between the start and finish of cooking from having no insulation to 4cm thick insulation of mineral wool on the walls of the recipient. The heat losses are reduced by approximately 60% with the addition of insulation. This incremental influence fades when increasing the insulation thickness over 2cm. At this level of insulation, the heat loss through the upper surface covers the bulk of the total heat loss.

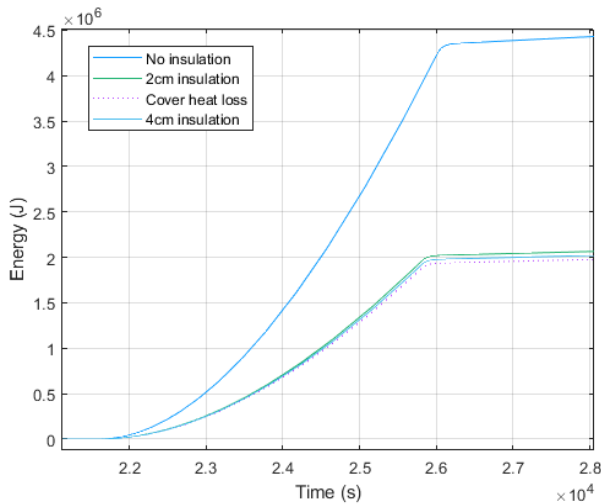


Figure 22 Heat loss variation with insulation

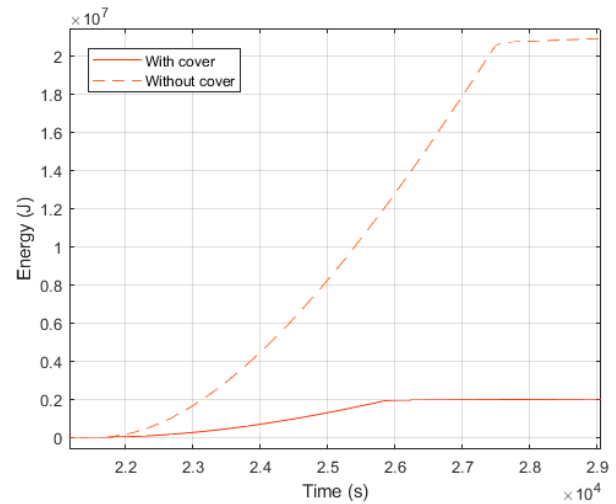


Figure 23 Surface heat loss variation with lid

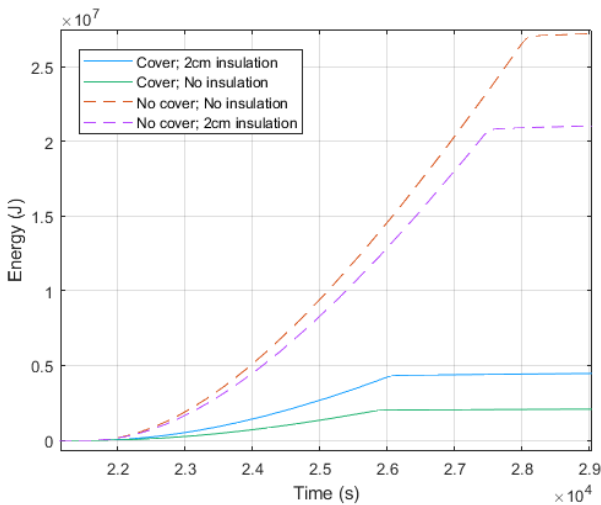


Figure 24 Heat losses variation with varying lid and insulation

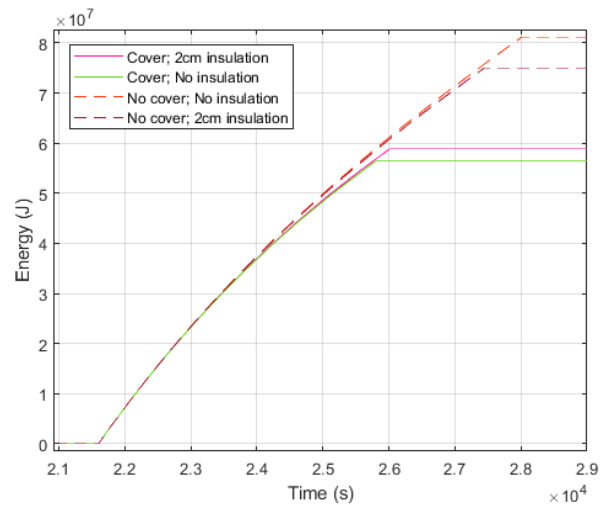


Figure 25 Heat input variation with varying lid and insulation

Results on the presence of a cover on the pot were also gathered. Figure 23 shows the heat losses through the upper surface of the recipient, with and without a cover, with 2cm thick insulation the case without a cover shows the surface heat losses being 10 times larger.

Figure 24 and Figure 25 show the combined influence of the presence of insulation and cover on the total heat losses and heat input, providing a wider perspective. The profiles show the increase in heat until the cooking ends. The presence of a cover has the largest influence in the heat losses, with heat losses being on the range of 90% lower. Providing an insulation reduces the heat losses around 55%. On its influence in required heat, from no insulation and cover to the opposite case, insulation and cover, the heat input decreases in a 31%, presence of a cover accounts for a 25% decrease.

Similar results are obtained when analyzing the other cooking units. Although there are slight differences, the tendencies show similar improvements in heat losses through the addition of insulation and a cover. Total heat required for cooking with a 2cm insulation and the use of a cover is 112kWh.

5.2.2 Thermosiphon to cooking unit

The time required to reach the boiling temperature was considered as the best variable to study the heat transfer potential of the thermosiphon. During heating to reach boiling temperature, the highest power is requested from the thermosiphon. Therefore, if the thermosiphon has an adequate thermal resistance when boiling is the goal, it will also be enough for maintaining the boiling temperature, which requires less power.

Figure 26 shows the variation of the temperature profile with different values for the thermal resistance of the thermosiphon for the student's tea cooking unit. The temperature increases as the cooking takes place until it reaches the boiling point and then is reset to ambient temperature. It can be seen how boiling occurred earlier for lower thermal resistance. This occurred in a similar

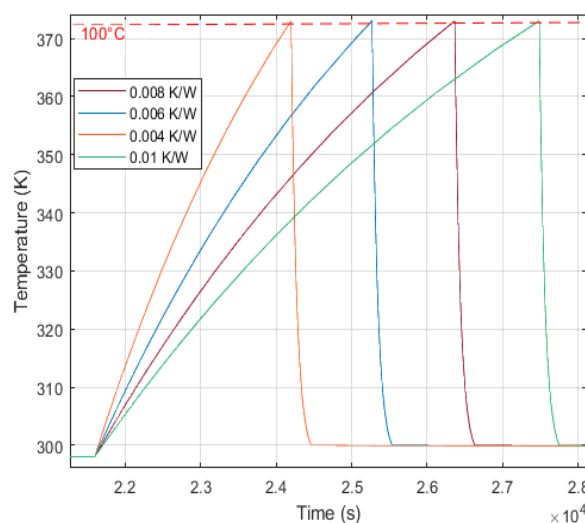


Figure 26 Temperature profile with varying resistance

fashion for the other two cooking units, which were also analyzed. The variation in boiling time with thermal resistance is recorded in Table 2.

Table 2 Boiling time vs thermal resistance for each cooking unit

Students tea unit		Students meal unit		Teachers unit	
Resistance (K/W)	Boiling time	Resistance (K/W)	Boiling time	Resistance (K/W)	Boiling
0,01	01:38	0,008	02:16	0,05	01:35
0,008	01:19	0,006	01:36	0,04	01:14
0,006	01:01	0,004	01:03	0,03	00:56
0,004	00:43	0,002	00:31	0,02	00:42

5.2.3 Oil heat storage

The first results on the influence of the insulation on the heat loss are shown in Figure 31. It can be seen how the heat loss exponentially decreases with the addition of insulation. To have a reference, 3000W (heat loss with 2.5cm of insulation) is approximately the same as the power supplied by each solar collector unit under good irradiance conditions (1000W/m^2). With such a weak insulation, the total heat loss in the oil tank is in the range of 25% to 45% of the total heat input by the solar collectors.

The size of the oil tank was first studied from 2m^3 to 4.5m^3 . Figure 28 shows the different temperature profiles for each oil tank size for several days. It can be seen how the temperature drops as the heat storage is depleted. Considering 110°C (383°K) as the minimum temperature needed for the oil tank to boil the content in the cooking units, the oil tank only lasted a day for volumes larger than 3m^3 .

Figure 29 shows the variation of the heat losses with the volume of the oil tank for a day. The sudden decreases in energy | It shows how there is a proportional increase in heat losses for larger tanks. This is due to the increase in surface as the volume increases.

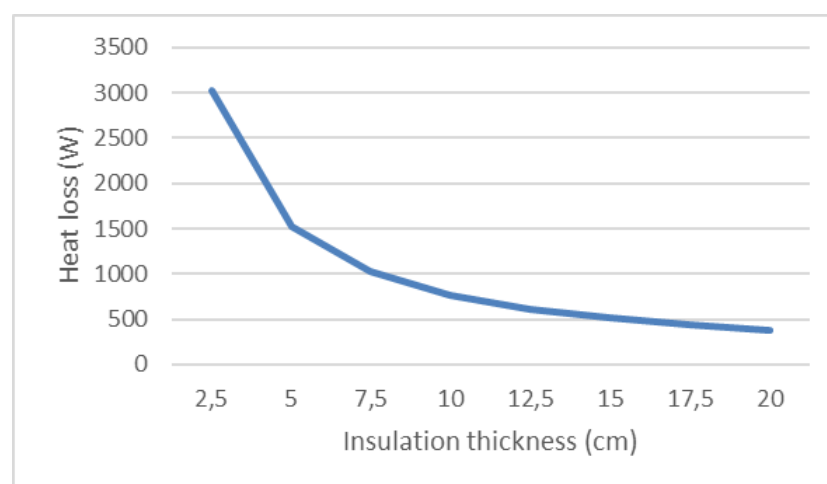


Figure 27 Oil tank heat loss variation with insulation thickness

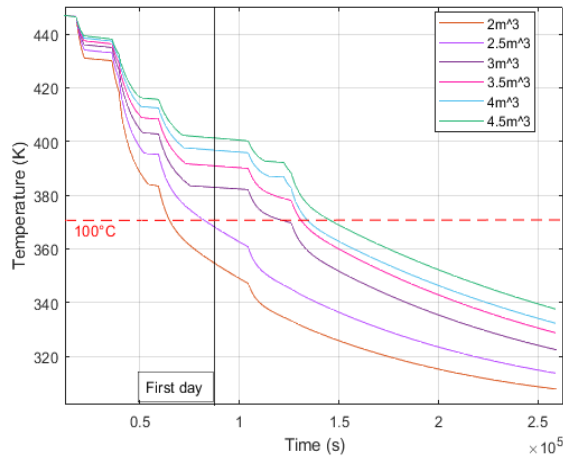


Figure 28 Temperature variation with oil tank volume

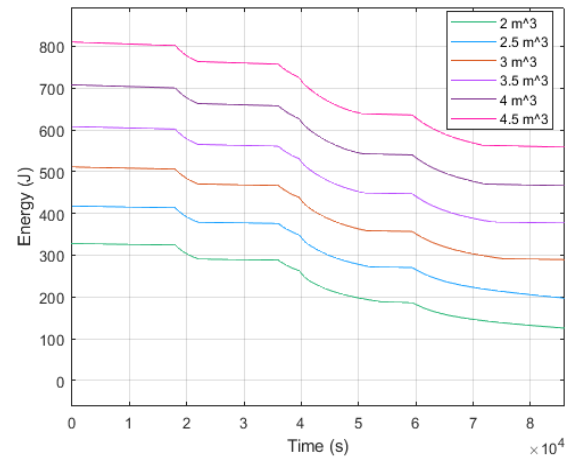


Figure 29 Heat loss variation with oil tank volume

The last results concerning the oil storage were performed for observing the behaviour of smaller tanks when connected to the solar collector. This allowed to set a lower limit in the dimensions of the tank. Figure 30 shows the temperature variation for a day for volumes between 0.5 m^3 and 1.5 m^3 . It can be seen how the smaller the tank, the smaller its thermal inertia, suffering higher temperature variations along the day. In the smaller tank, the temperature drops to values close to boiling temperature at its lowest, while also reaching the maximum temperature at its peak.

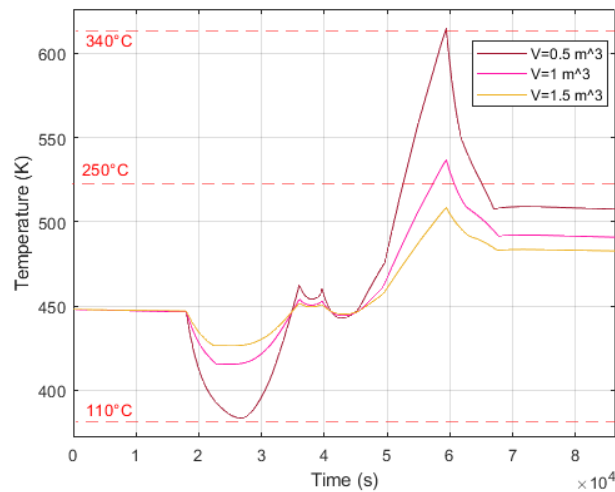


Figure 30 Oil temperature connected to solar collector

5.2.4 Thermosiphon from solar collector

Changes on the thermal resistance of the thermosiphon influence the temperature in the solar collector and oil storage. The temperature profile in each of the components for different thermal resistance of the thermosiphon can be seen in Figure 32.

The temperature of the solar collector increases as the day passes, reaching its maximum before the solar irradiance and input power, starts to decrease. The same occurs with the oil storage temperature, as it is also affected by the power supply. The discontinuities in the temperature profile for both elements in the figure can be explained by the influence of the elements downstream. Those sudden decreases in the oil storage and solar collector temperatures are due to heat being drawn for cooking purposes during cooking sessions.

The 250°C mark in Figure 32, indicates a limit for the temperature of the solar collector. Although the solar collector can operate above this temperature, it has been observed by the manufacturer that overheating starts to occur between 250-300°C. At this range, the selective surface coating of the pipe is damaged and loses its properties. This occurs, according to the model, for a thermosiphon with a thermal resistance of 0.006 K/W.

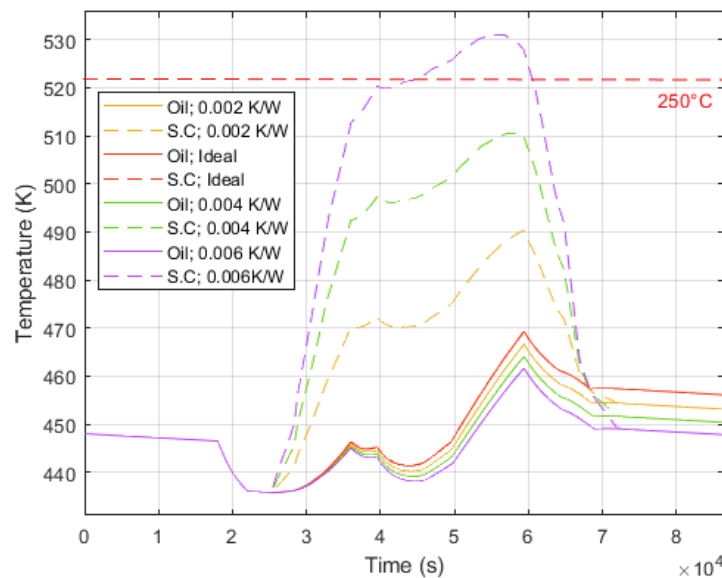


Figure 32 Oil tank and solar collector temperatures with varying thermosiphon

The temperature of the oil storage shows a decrease with the thermal resistance. The higher the thermal resistance, the higher the temperature at the solar collector. This results in a lower power output according to the specifications of the manufacturer. Simulations showed a 10% decrease in the total energy delivered by the solar collector during a day, when comparing ideal conditions with perfect heat transfer to a thermal resistance of 0.006 K/W.

5.2.5 Solar collector

The temperature profile of the oil tank during 15 consecutive days of operation can be seen in Figure 33. The repetitive oscillations in the figure show the daily variation in the temperature. The initial setpoint for the oil temperature is at 175°. From this point the different arrangements tend to different temperatures. Since the power of the solar collector is inversely proportional to the temperature, the temperature stabilizes at a certain point for each case.

It can be seen how 4 solar collectors show stability at 175°C, while with 5 solar collectors the temperature rises until stabilizing around 230°C, and with 3 solar collectors around 117°C.

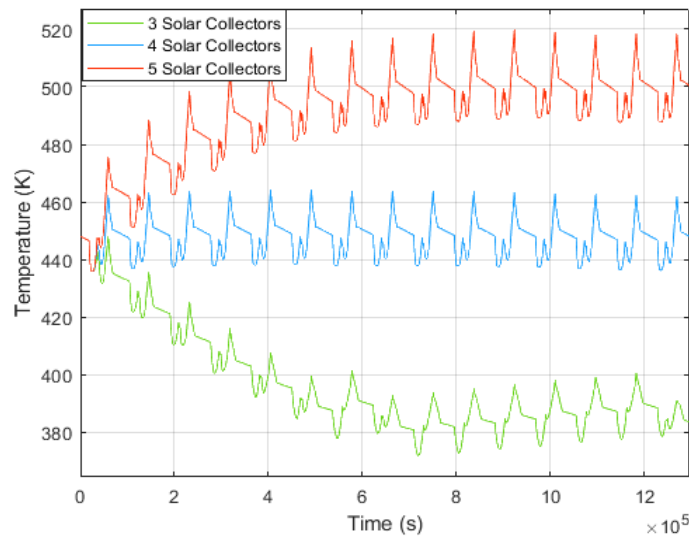


Figure 33 Heat storage temperature for varying solar collector dimensions

5.2.6 Solar irradiance

The solar irradiance at solstices and equinox was calculated for the location of the case study. The aim is to evaluate the seasonal difference in performance of the system. Figure 34 shows the results which indicate a decrease of approximately 6% from the highest irradiance, in the winter solstice, to the lowest, in the summer solstice. This is due to the close location to the equator for the study case.

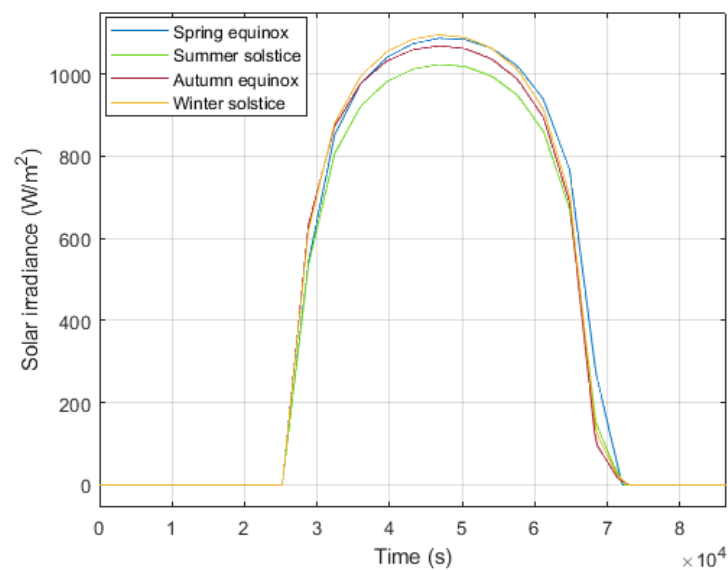


Figure 34 Seasonal solar irradiance

5.3 Reliability and Validity of the results

The most critical influence on the reliability of the model was observed on the cooking unit side. The temperature control implemented in the model to maintain the cooking unit at a boiling temperature was a source of unreliability. This problem was briefly mentioned in section 4.5.6.

Heat flow control is executed through manipulation of a variable resistance that separates the cooking unit from the heat supply. A good control depends on setting the right parameters. However, the correct value for these parameters does not only depend on the characteristics of the valve, but on the characteristics of the surrounding elements too, as the power supply or heat losses. Changes on the surroundings produced a different control and, thus, a different temperature curve for the cooking unit.

This problem was considered through the execution of the simulations and obtention of results. Simulations not relying directly in this part of the model were preferred. However, it still hinders the reliability of the model.

Comparisons of the results with other research were also performed to assess the reliability. (Berick, 2006) calculated the heat loss in pots when cooking and concluded that a placing a cover on the pot contributes to 90% energy savings when boiling. In the same order of what was found in this study, where heat losses were reduced 90% with a cover. Moreover, heat input for cooking was compared with theoretical calculations that were initially performed, with results in the same range.

Heat input from the solar collector was also compared to theoretical calculations considering the irradiance and temperature at certain moments. The comparison was positive on the reliability of this side of the model.

Validity of the model to simulate the reality was seen compromised in several aspects. Most of these have also been mentioned as limitations in section 4.5, as features where the model deviates from reality. The two most important deviations are related to the solar irradiance and the user behavior.

It has been mentioned how the results involving the solar irradiance are only valid under clear sky conditions. This presents an ideal condition that is not often identical to the real situation. Thus, the solar irradiance used as an input in this model yields idealistic results and should be considered.

The presence of a cover in the cooking unit cannot be ensured in the real operation of the system. It has been seen how this feature has an influence of a 25% decrease in the heat requirements. This has a great influence for dimensioning all the components present in the system. Many of the results have been obtained based on having a cover and, consequently, lower heat requirements. However, this might not be representative of the real case, in which case, the results tend again to reflect an ideal scenario.

In general, the results of the model are likely to be optimistic when compared to the real case. Having elaborated the model from a purely theoretical basis has probably led to disregard many potential imperfections in the system. Moreover, most of the assumptions have been optimistic. Therefore, the results should be taken with caution, knowing that the real case will likely require larger dimensions. This can to some extent be addressed by validating the model and its results against the prototype characteristics.

5.4 Discussion

The presented results have showed several levels of performance for the modelled system under different conditions. Analysis of this results, considering their validity and reliability, can lead to an initial dimensioning of the technology. Many of the dimensions were already discussed for the necessary assumptions in the simulation setup of each components. Here, they will be discussed in depth, trying to integrate the results obtained for each element.

Analysis on heat losses in the cooking unit showed the importance of insulation and the use of a cover. Although simple measures, their influence on the heat requirements is critical. A 2cm layer of rockwool surrounding the cooking unit was enough insulation to minimize the heat losses through the walls to a negligible amount. Simultaneously, it is a reasonable value for an object with the given dimensions.

Placing a cover on the cooking unit was a feature of great importance. Moreover, it was characterized in the validity analysis as an uncertainty, since it cannot be ensured. This uncertainty can mean a 33% increase (25% decrease) in the heating requirements. This shows the necessity of ensuring the use of a cover and a possible error in the validity of the model that affects upstream of the cooking unit.

Preliminary thermal resistance values for the thermosiphon were assumed in the result section. These values accomplished a cooking time of one hour for boiling the tea and one hour and a half for boiling the meal under the assumption of using a cover for the cooking units. Without a cover, cooking time would be increased in approximately a 33%. This means around one hour and 20 minutes for boiling tea and 2 hours for boiling the meal.

It must be assessed if these values are acceptable and what is the margin for error. This can be done by comparing to what is currently acceptable for the user. From the information given on the user, Appendix B, it currently takes two hours to boil the food and five hours to cook the meal (including the time after boiling starts. Even without a cover, cooking times would still be lower than the current solution. Therefore, the values of 0.006K/W for the students' units and 0.05K/W for the teachers' unit, assumed throughout the model, are a good recommendation for the dimensions of the thermosiphons.

The capacity of the oil heat storage to supply heat under not sunny conditions was related to its volume. This showed that, to last for a day of cooking, a minimum of 3m³ of oil was needed. This is, under the optimistic assumptions downstream of no heat losses in the thermosiphon and use of a cover for the cooking unit. Therefore, the volume would be even larger from a more realistic

perspective. This represents a large size for an oil tank, and the need for such a system must be reevaluated.

The presence of an intermediate oil storage has three main benefits. First, it buffers the large temperature variations from the solar collector with its thermal inertia. Second, it distributes the heat provided by the solar collector throughout the day, acting as a short-term storage. Third, it acts as a long-term storage through the night for the next day.

A storage smaller than 3m^3 can still provide the first two benefits, and the long-term storage for the next day depending on its size. If the target for long term storage is to cover cooking even during a day without any solar irradiance, then a 3m^3 oil tank is needed. However, if the requirements are minimized to enabling continuous cooking under average meteorological conditions, the size of the storage can be reduced, although, there is also a limit.

The results with smaller tanks when connected to solar collector showed a limit on the minimum size for the oil storage. A certain amount of thermal inertia is needed to avoid low temperatures, that do not enable useful heat for cooking, and high temperatures, which surpass safety values. Figure 30 showed that the volume should be larger than 1m^3 to avoid these problems. An acceptable behavior is achieved with a 1.5m^3 tank, which is enough to store the energy needed for cooking the next day.

Results on the thermosiphon from the solar collector showed 0.002K/W as a reasonable thermal resistance, with enough margin until the overheating limit at 250°C . This value of thermal resistance does not have to be achieved with a unique thermosiphon. This thermal resistance is three times lower than the recommended for the larger cooking units. Instead of using a unique thermosiphon with this thermal resistance, three thermosiphons with 0.006K/W can be arranged in parallel for the same outcome. Using the same unit repeatedly will simplify the manufacturing task.

Dimensioning of the solar collectors presents the highest uncertainty among the given recommendations. It has the uncertainty related to any feature downstream of the solar collector being wrongly dimensioned, and the uncertainty of the meteorological effects not being implemented in the model.

Under the optimistic conditions represented in the model, 4 solar collectors produce 114 kWh each day, which proves enough to supply heat for the system. However, it is likely that 5 units, which represents a 25% increase in the power, will be needed if a more realistic perspective is taken. This will have to be assessed in future work by implementing the necessary changes to the solar collector and irradiation elements of the model. Knowing that the outcome will probably be optimistic still, since the model is built from a theoretical basis, without flaws that occur, and with disregard of some effects in the simplifications made.

6 Additional observations

Close contact with a developing technology by modelling its performance, has inevitably led to additional observations on the system. Along this work the solution was reviewed in detail, revealing aspects not present on the model but still critical for its success. A field trip to the site where the prototype was being arranged was a fundamental part of this additional analysis.

The next sections will describe observations on aspects that were seen to exhibit a risk for the solution, or that were important pieces to consider.

6.1 Thermosiphon technology

The chosen alternative for implementing the thermosiphon between the solar collector and the oil storage represents a modification to the common arrangement of a thermosiphon. The alternative is based on the counter current flow thermosiphon explained in Figure 13. However, the approached design shows an almost horizontal structure. Figure 35 shows this design in which the entire length of the solar collector tube acts as the evaporator, and the section of the tube going into the oil tank as the condenser. The level of the water is cautiously measured to enable coexistence of liquid and vapor phase in such a way that the solar collector tube always has a layer of liquid.

The working principle of this thermosiphon is the same as the standard counter flow one. As the evaporator heats the liquid water, it becomes vapor. Due to the density difference and higher height on the opposite side, this vapor flows to the condenser side in the oil tank. Here, the vapor condenses, releasing heat to the oil tank, and becoming liquid that flows back to the evaporator side.

Having a thermosiphon uncommonly large for its thickness and in an almost horizontal setting, presents doubts on its correct functioning. On one hand, the small diameter of 22mm for a length of approximately 7 m, might impose a high-pressure loss for the fluid flow along the tube. Moreover, the angle of the slope, being close to horizontal, might not displace the fluid with the same force as in a vertical arrangement.

This design will have to be tested in the prototype for validation. It enables a simpler setting than a closed loop thermosiphon, which would need two entry points into the oil storage and the connection of both ends in the solar collector. However, if it does not prove to achieve the required specifications, it may have to be substituted for a closed loop thermosiphon, which is the second alternative.

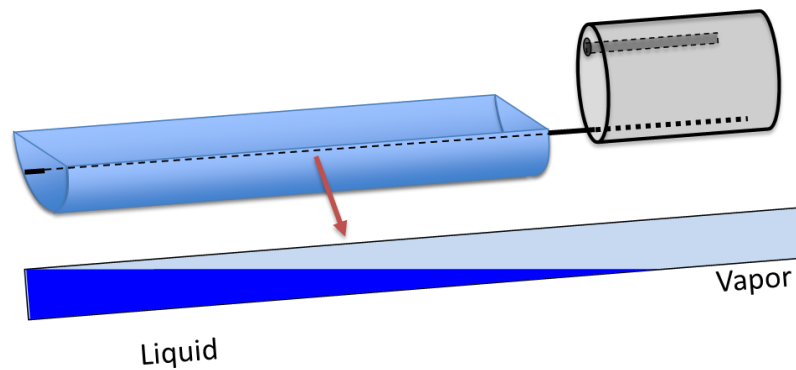


Figure 35 Thermosiphon arrangement in prototype

6.2 Oil oxidation

Oil has been chosen as the appropriate fluid for the heat storage due to its good heat transfer properties. However, oil can lose its properties if not correctly maintained. Oxidation of oil is a common problem. Higher temperatures and mixing with air nurtures this problem. As the oil oxidizes, it produces smoke, becomes more viscous, and loses its ability to carry and transfer heat (Paratherm, 2016).

Oxidation of the oil inside the tank would lead to a decrease in its energy storage capacity and heat transfer with the adjacent components. This would affect the functioning of the system when there is absence of the solar resource with a lower storage, and the time needed for cooking with a decrease in the power being delivered to the cooking unit.

This difficulty can be solved by ensuring an isolation of the oil from air. Correct sealing of the oil tank is the solution to this. However, the oil dilates with temperature. With a volumetric coefficient of expansion of 0.0007 for engine oil (The engineering toolbox, s.f.), 3 cubic meters of oil would dilate 409.5L when going from 25°C to 220°C. Adding an inert gas inside the tank to be compressed as oil dilates. An expansion chamber that increases the available volume is another possibility that is currently being studied for the prototype. However, the feasibility of this options should be assessed for the oil tank once the dimensions have been specified.

6.3 Installation process

A field trip to the site where the prototype was being built, allowed for additional observations on the manipulation of the system. During this field trip, the solar collector was arranged with a small oil tank storage for the first trials. Challenges were seen in the installation process, particularly with connecting the solar collector to the oil storage. Figure 38, Figure 37, and Figure 36, were pictures taken during the fieldtrip to illustrate the work on the prototype.

Solar collector and oil tank are connected through the thermosiphon, which consists of a copper tube extending from each part, Figure 37. This copper tube allows only for a small flexibility

proving quite rigid. At the same time, it must be implemented in a certain angle, restricting the height and position of each of the components to which it connects.

The copper tube is first introduced in the oil storage, fixed to its correct position, and then the loose end must be connected to the solar collector. Due to the restrictions posed by the angle that must be obeyed, and the rigidity of the structure, this meant installing the oil tank at the correct height and distance from the solar collector to connect the thermosiphon. Since the oil storage is a fixed structure with a weight over 100kg, this proved a complex maneuver.

Installing the small oil storage, used for the prototype, in the correct position, required the use of heavy machinery and more time than was expected. A tractor was used to lift the oil tank up while the ground was levelled to the appropriate height.

This complexity in the installation must be considered for the implementation of the solution and, maybe, for the pursue of other alternatives that might solve this challenge. More flexible tubes are the most direct solution. After this first challenge, a “pigtail” was installed to add flexibility. However, this modification will likely affect the fluid flow inside the tube.

The size and weight of the components were also analyzed for considering the simplicity of installation. Although it has a large size, the weight of the solar collector is of 148kg, allowing for manual manipulation of the device. About the oil storage, the current prototype is not representative of the 3m³ (or in that range) oil tank that will be used. However, the weight will have to be considered when selecting the appropriate oil storage.



Figure 36 Solar collector and oil tank in prototype



Figure 38 Solar collector and oil tank 2



Figure 37 Copper tube connexion

6.4 Height difference

For the thermosiphons connecting the components to work properly, there must be a height difference between them. The heater for the cooking unit must be higher than the oil storage and this one higher than the solar collector. This height difference might imply challenges for the correct installation of the system.

If the terrain is not, by coincidence, levelled in a way that allows for this height difference in the installation, two actions will have to be evaluated. Either lowering the ground level on the solar collector side or raising the cooking unit inside the kitchen, or a combination of both. The first one would imply changing the terrain, with the respective work and challenges that this entails. The second one might have a limit in the user acceptance of the solution when changing the setting of the cooking space.

Prior to any installation of this system, it will be imperative to revise the ground level, and the possibilities for modifications that render it adequate for this system. For this and other reasons, the success of this system is dependent on the layout of the kitchen and its surroundings. First, the kitchen must be next to an exterior without shading for the solar collector. Second, this open space must be large enough to contain all the equipment (solar collector and oil tank). And third, as mentioned, the level of this surrounding space must allow for a negative height difference from the cooking space.

6.5 Solar tracking

Two alternatives were given for the solar tracking system of the solar collector. Here the topic is briefly analyzed for the possible advantages and disadvantages of each of them for the case study. The results were not quantified, to do so, there needs to be at least a study on the variation of the solar collector's power output as a function of the angle of the solar radiation, and a cost study on the implementation of a solar tracking device. It should be noted that concentrating solar collectors, are more sensible to the angle with the sun than other solar power sources such as PV or flat plate collectors.

The location of the case study is close to the equator. In Figure 39 the sun's path t can be seen during the solstices and equinox, which are the most characteristic days. The sun's movement oscillates around the perpendicular plane to the ground going from East to West. In the equinox, the movement of the sun is contained in this plane. During the summer and winter solstice, the maximum altitude of the sun reaches 66° and 67° respectively.

The first alternative is to set the solar collector without a solar tracking device. The solar collector is oriented with its axis going from East to West. The second alternative is to set the solar collector with a solar tracking device. For this set up the solar collector is oriented with its axis going from North to South, what is defined as an EW tracking.

For the first alternative, it is imperative to assess the variation of power output when the radiation comes from a different plane than the perpendicular to the solar collector through its axis. Apart from during the equinox, the path of the sun along the day does not conform to a plane containing the solar collector. This means that the radiation will not reach perpendicularly to the solar collector during most of the day, but rather oscillate around this perpendicular plane if the setting is correct. Moreover, if this set up is implemented, it will be necessary to arrange the solar collector with a specific orientation at certain days. This will reduce the error in the angle with the sun by doing a "seasonal solar tracking".

The second alternative is more complex and with a higher cost due to the implementation of a mechanism to track the sun. However, it solves the problem of daily solar tracking, with the incidence of the solar radiation always in the plane perpendicular to the solar collector through its axis. The efficiency will be lower as the sun's path deviates North or South with the seasons, with a lower irradiance per square meter.

The EW tracking is the correct arrangement for a tracking system in this location. At latitudes closer to the equator EW tracking outperforms other orientation arrangements (ArianBahrami, et al., 2016). During the equinox, this system would achieve a perfect tracking of the sun, during the solstices, the efficiency would be at its lowest.

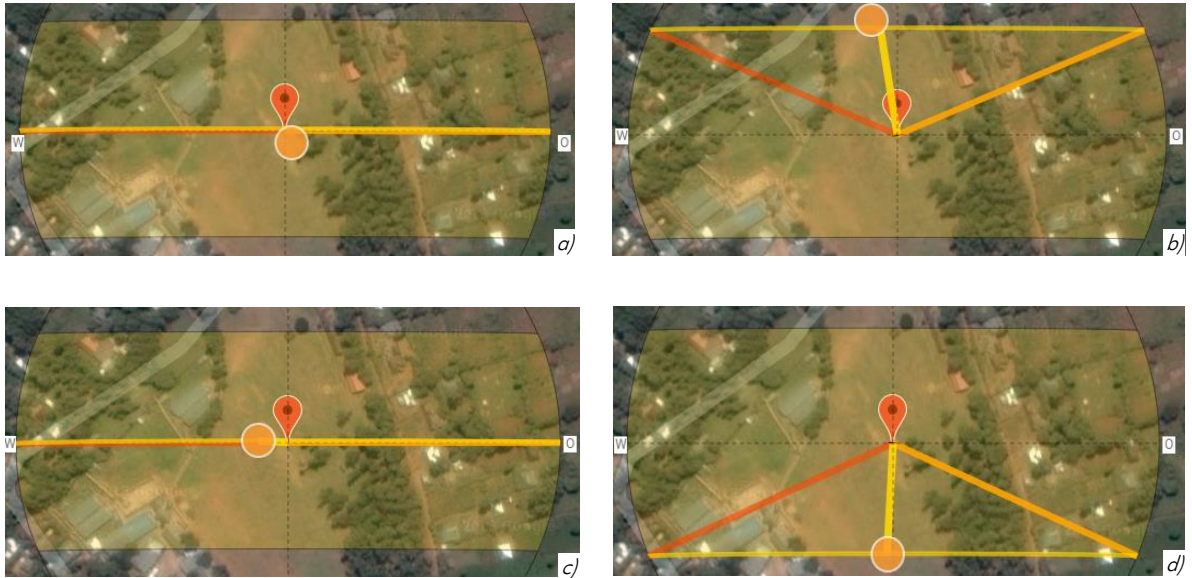


Figure 39 Solar path at location in a) March 20th; b) June 21st; c) September 23rd; d) December 21st. Taken from (SunCalc, 2018)

6.6 Thermal resistance

Thermosiphons were modelled and dimensioned through a thermal resistance. This value does not have a specified relation with the actual dimensions of the thermosiphon being used for the prototype. This relation must be established to translate the given recommendations on thermal resistance to the design of the thermosiphon.

The prototype provides the experimental facility needed to study the thermosiphon. With the correct measurements, the performance of the thermosiphon can be analyzed in terms of its overall thermal resistance.

Measurements to be taken for this task aim to track the heat flow and the temperature difference. From these two variables, the thermal resistance can be extracted as $TR = \Delta T / \dot{Q}$.

Temperature can be obtained in the oil side with a temperature sensor adjacent to the thermosiphon. For the water side, which is in a two-phase state, both a temperature sensor and a pressure sensor would output the temperature on this end.

Heat flow can be obtained by measuring the increase of heat with time. Under perfect insulation conditions, the temperature rise in the oil tank can yield the total heat transferred to the tank through $C_p \Delta T = Q$. By tracking the heat increase with time, the heat flow is also obtained since it is represented by the slope of the heat profile. This can be combined with the temperature logging in time and output the thermal resistance through the first formula.

For this experimental analysis to be accurate, heat losses must be minimized. The thermosiphon and the oil storage must have the necessary insulation to neglect the heat losses.

6.7 User behaviour

Throughout this study, the importance of the user behavior for dimensioning the solution has been made clear. The use of a cover, or the adequate regulation of heat flow for cooking are simple measures with a great influence on the total heat required for cooking.

Similarly, to the efforts made to develop an energy efficient technology, there needs to be efforts to achieve an energy efficient user. Educating the user on a correct operation of the system should be considered as part of the solution. An educational process that raises awareness and teaches how to cook in an energy efficient way, needs to be implemented with the solution for a correct performance.

7 Concluding remarks

7.1 Conclusions

A broad analysis was made on the proposed technology for institutional solar cooking. A model was built on the technology to study its performance. Additional observations on the system were also given. Required dimensions were given together with other recommendations and insights for the development of the Joto Jiko project to enable a solution for solar cooking in developing areas.

The model was created through Matlab and Simulink, using the Simscape thermal toolkit provided by Simulink. It serves as a tool for dimensioning and evaluating the technology for each proposed case. Moreover, a case was implemented in the model and recommendations were given on the required dimensions. Recommendations for the school estimated five solar collectors and a 1.5m³ oil tank for the heat storage. Values to dimension the required heat transfer through the thermosiphon were also given.

Other general recommendations were also obtained through the modelling tool. The effect of the required insulation was studied, with specific recommendations on the thickness of the insulation layer. Other features were also important for the performance of the system. The placement of a cover for cooking was identified as one of the main measures for reducing heat losses.

Risks were identified on the feasibility of the technology. The proposed design of the thermosiphon still needs to be verified. Given the high heat transfer that is intended, the authors opinion is sceptic on this technology. Closed loop thermosiphons have proven to perform better than counter flow thermosiphons, and the proposed technology does not obey the recommended set up for a counter flow thermosiphon. Nonetheless a recommendation was given for measuring the thermal resistance of the used thermosiphon.

Other challenges as preventing the oxidation of oil or ensuring the height difference between the different components were also pointed out.

Installation of the technology is also seen as a challenge. The connection of the system imposes restrictions for the arrangement of the different components. Requiring heavy equipment to be accurately positioned.

The analysis on solar tracking leaves only two recommended options. An East West orientation without solar tracking, or a North South orientation with solar tracking. The second has the highest performance, but also adds complexity to the system.

Finally, user behavior needs to be considered as part of the solution. Education of the user for ensuring a correct operation of the system is crucial. The behavior of the user is decisive in the energy efficiency of the system.

7.2 Future work

Limitations and additional observations have made the basis of recommendations on future work. Soon, the work should lead to a validation of the technology and a more precise model for dimensioning the system accurately.

Results obtained through the experiments on the prototype will be decisive on the feasibility of the technology. This is particularly important for the thermosiphon, since it is the only complex element of the technology that has not been previously tested. The tests in the prototype should lead to a design according to the specifications for the given thermal resistance.

Further improvements to the model shall be performed for a more accurate and reliable estimation on the dimensions for the system. This includes implementing practical effects observed in the model, a higher detail on certain features, and particularly a more realistic model for the solar collector's incidence angle and solar irradiance accounting for meteorological effects.

Finally, the work on the proposed system enters another stage with the implementation of the pilot project. It is crucial to keep analyzing the performance of the solution during the pilot project. Even if the technology has been previously analyzed, the pilot project enables results on the integration of the technology with the user, which is the final test on the feasibility of the system.

7.3 Reflections

Many challenges still lay ahead for the success of this project. The proposed system is at an early stage, with the first steps into the realization of the technology. Other fields such as the business model, or financial planning have not been mentioned but are also being developed, facing their respective challenges.

For the solution to work, it is of supreme importance that the targeted environment is always considered. Making a solution for the BoP market requires deep interaction and collaboration with the user. This contact, that has so far been done through Ecobora, must be strengthened as the project develops to build a suitable solution. In any business, the client's opinion will be key to success. In the BoP this is even more important, as understanding a client living in such different conditions requires much more effort.

Scalability of the solution can lead to a great social impact. Institutional cooking represents a niche in the clean cooking market. Having targeted this segment of the market is itself one of the key innovations of the project. Moreover, the market is vast, with thousands of institutions still cooking with traditional fuels. If the solution proves successful, it can lead to a great improvement in the clean cooking scenario.

References

- Absolicon, 2018. Världens bästa koncentrerande sulfångare. *Absolicon solar collectors magasinet*, p. 4.
- Africa Clean Cooking Energy Solutions Initiative, 2014. *Clean and Improved Cooking in Sub-Saharan Africa*, s.l.: s.n.
- ArianBahrami, OnyekaOkoye, C. & UgurAtikol, 2016. The effect of latitude on the performance of different solar trackers in Europe and Africa. *Applied Energy*.
- Bailis, R., Drigo, R., Ghilardi, A. & Maserà, O., 2015. The carbon footprint of traditional woodfuels. *nature climate change*.
- Berick, A., 2006. [En línea]
Available at: <http://stoves.bioenergylists.org/berickheatloss>
[Último acceso: 2018].
- Bird, R., 1981. *Simplified Clear Sky Model for Direct and Diffuse Insolation on Horizontal Surfaces*. s.l.:s.n.
- Boehm, B. W., 1988. *A Spiral Model of Software Development and Enhancement*, s.l.: s.n.
- Bram Smeets, C. T. H. C. & M. H., 2017. *Sub-Saharan Africa continues to depend on inefficient cooking technologies-McKinsey Energy Insights*. [En línea]
Available at: <https://www.mckinseyenergyinsights.com/insights/sub-saharan-africa-continues-to-depend-on-inefficient-cooking-technologies/>
[Último acceso: June 2018].
- C.K. Prahalad, S. L. H., 2002. The Fortune at the Bottom of the Pyramid. *strategy+business*.
- Cho, R., s.f. The Damaging Effects of Black Carbon. *State of the Planet*.
- Craig, T. O., 2015. Parabolic solar cooker cooking with heat pipe vs direct spiral copper tubes.
- Erdem Cuce, P. M. C., 2012. A comprehensive review on solar cookers. *Applied Energy*.
- GIZ HERA, s.f. *Cooking Energy Compendium*. [En línea]
Available at: https://energypedia.info/wiki/Cooking_with_Charcoal
[Último acceso: July 2018].
- Global Alliance for Clean Cookstoves; Africare; McCANN, 2016. *The Truth About Cooking Landscape Analysis*, s.l.: s.n.
- Global Alliance for Clean Cookstoves; Energy Sector Management Assistance Program, 2015. *The state of the global clean and improved cooking sector*, s.l.: s.n.
- Global Alliance for Clean Cookstoves, 2013. *Kenya Country Action Plan*, s.l.: s.n.
- Global Alliance for Clean Cookstoves, 2018. *How does the Alliance define "clean" and "efficient"?*. [En línea]
Available at: <http://cleancookstoves.org/technology-and-fuels/standards/defining-clean-and-efficient.html>
[Último acceso: 2018].
- Global Alliance for Clean Cookstoves, s.f. *How does the Alliance define "clean" and "efficient"?*. [En línea]
Available at: <http://cleancookstoves.org/technology-and-fuels/standards/defining-clean-and-efficient.html>
[Último acceso: July 2018].
- Global Alliance for Clean Cookstoves, s.f. *IWA Tiers of Performance*. [En línea]
Available at: <http://cleancookstoves.org/about/news/01-01-1990-iwa-tiers-of-performance.html>
[Último acceso: July 2018].

- International Energy Agency, 2017. *Energy Access Outlook*, s.l.: s.n.
- IRENA, 2018. Chapter 3 - Access to clean fuels and technologies for cooking. En: *Tracking SDG7: The Energy Progress Report*. s.l.:s.n.
- ISO, 2012. *Guidelines for evaluating cookstove performance*, s.l.: s.n.
- Johnels, E. & Murray, S., 2013. *Performance Evaluation of the FirePipe Cookstove with focus of its Product Development*, s.l.: KTH Bachellor Thesis.
- Johnson, F. X. & Takama, T., 2012. Consumer Choices for Cook Stoves. En: *Economics of Modern and Traditional Bioenergy in African Households*. s.l.:s.n.
- Jürisoo, M. a. F. L., 2016. *The journey to clean cooking: Insights from Kenya and Zambia*, s.l.: Stockholm Environment Institute.
- Kilman, K. T. & P., 2015. *Business model innovation and new product development For a solar cooker in a BoP-market*, s.l.: s.n.
- Lameck Nkhonjeraa, T. B.-O. G. J. C. K. K., 2017. A review of thermal energy storage designs, heat storage materials and cooking performance of solar cookers with heat storage. *Renewable and Sustainable Energy Reviews*.
- M.Mameli, y otros, 2016. Advanced multi-evaporator loop thermosyphon. *Energy*.
- Michael Toman; Randall Bluffstone, 2017. *Challenges in Assessing the Costs of Household Cooking Energy in Lower-Income Countries*, s.l.: World Bank Group.
- Nerini, F. F., Ray, C. & Boulkaid, Y., 2017. *The cost of cooking a meal. The case of Nyeri County, Kenya*, s.l.: s.n.
- Nicholas L. Lam, K. R. S. A. G. a. M. N. B., 2012. KEROSENE: A REVIEW OF HOUSEHOLD USES AND THEIR HAZARDS IN LOW- AND MIDDLE-INCOME COUNTRIES. *National Institutes of Health*.
- NREL, s.f. *Bird Clear Sky Model*. [En línea]
Available at: <https://www.nrel.gov/grid/solar-resource/clear-sky.html>
- Otte, P., 2013. *Warming Up to Solar Cooking – A Comparative Study on Motivations and the Adoption of Institutional Solar Cookers in Developing Countries*, s.l.: s.n.
- Otte, P., 2015. *Mapping global impact data for solar cooking: A case study*, s.l.: s.n.
- Otte, P. P., 2014. 21. A (new) cultural turn toward solar cooking—Evidence from six case studies across India and Burkina Faso. *Energy Research & Social Science*.
- Paratherm, 2016. *Oxidation in heat transfer fluids*, s.l.: s.n.
- pwc, 2017. *Worldwide tax summaries*. [En línea]
Available at: <http://taxsummaries.pwc.com/ID/Sweden-Individual-Other-taxes>
- Rose, M. & Ritchie, H., 2018. *Indoor Air Pollution; Our World in Data*. [En línea]
Available at: <https://ourworldindata.org/indoor-air-pollution>
- Shuttleworth, M., 2008. *Explorable*. [En línea]
Available at: <https://explorable.com/validity-and-reliability>
[Último acceso: 2018].
- Simanis, E. & Duke, D., 2014. Profits at the Bottom of the Pyramid. *Harvard Business Review*.
- SunCalc, 2018. *SunCalc*. [En línea]
Available at: <https://www.suncalc.org/>
- Sunil Indora, T. C. K., 2018. Institutional cooking with solar energy: A Review. *Renewable and Sustainable Energy Reviews*.
- The engineering toolbox, s.f. *Volumetric or cubical expansion coefficient of liquids*. [En línea]
Available at: https://www.engineeringtoolbox.com/cubical-expansion-coefficients-d_1262.html
- Toole, R., 2015. *The Energy Ladder: A Valid Model for Household Fuel Transitions in Sub-Saharan Africa?*, s.l.: s.n.

- UN, 2016. *Sustainable Development Knowledge Platform; Sustainable Development Goal 7*. [En línea]
Available at: <https://sustainabledevelopment.un.org/sdg7>
- WHO; IEA; GACC; UNDP; World Bank, 2018. *Policy Brief 2: Achieving Universal Access to Clean and Modern Cooking and Technologies*, s.l.: s.n.
- WHO, 2014. *Clean household energy can save people's lives*. [En línea]
Available at: <http://www.who.int/features/2014/clean-household-energy/en/>
[Último acceso: 2018].
- WHO, 2018. *Household air pollution and health*. [En línea]
Available at: <http://www.who.int/news-room/fact-sheets/detail/household-air-pollution-and-health>
[Último acceso: June 2018].
- World Bank Group; World Resources Institute, 2007. *The Next 4 Billion*, s.l.: s.n.
- Wrenick, S. S. P. P., 2005. HEAT TRANSFER PROPERTIES OF ENGINE OILS. *Proceedings of WTC2005*.

Appendix A: Absolicon T160 performance test data

Description of the collector

Based on data from the manufacturer

Manufacturer:	Absolicon Solar Collector AB
Address:	Absolicon Solar Collector AB Fiskaregatan 11 SE-871 33 Härnösand SWEDEN
Tel./Fax:	+46 (0) 611-55 70 00
Brand name:	T160
Drawing number:	-
Collector type:	Parabolic trough collector with one-axis tracking device ¹
Year of production:	2016
Serial number:	-



Figure 1 Collector model during thermal performance test (single row)



Figure 2 Principle sketch of collector mounting in field with four rows

Dimensions of collector unit

Length:	5490 mm	Absorber area:	0.44 m ² (From manufacturer)
Width:	1056 mm	Gross area:	5.8 m ² (Measured by SP)
Height:	-		

Technical specifications

Weight (excl. tracking mechanism):	148 kg
Fluid content:	0.64 dm ³
Heat transfer fluid, recommended:	Tyfocor
Number of covers:	1
Cover material:	Hardened low iron glass
Cover thickness:	4 mm
Cover transmittance after treatment:	0.92
Cover structure/treatment:	-
Number of tubes or channels:	1
Tube diameter (outer dimension):	25.4 mm
Tube diameter (inner dimension):	22.4 mm

Test results for glazed liquid heating collectors under outdoor quasi dynamic conditions

Peak power ($G = 1\,000\text{ W/m}^2$) per collector unit:

3 600 W_{peak}

Table 1 Collector output record (W) for glazed liquid heating collectors with ambient temperature, ϑ_{a} , fixed at 25°C ³

ϑ_{a} [K]	Irradiance [W/m^2]			
	400 W/m^2 ($G_{\text{b}} = 200\text{ W/m}^2$, $G_{\text{d}} = 200\text{ W/m}^2$)	700 W/m^2 ($G_{\text{b}} = 440\text{ W/m}^2$, $G_{\text{d}} = 260\text{ W/m}^2$)	1000 W/m^2 ($G_{\text{b}} = 850\text{ W/m}^2$, $G_{\text{d}} = 150\text{ W/m}^2$)	1100 W/m^2 ($G_{\text{b}} = 1000\text{ W/m}^2$, $G_{\text{d}} = 100\text{ W/m}^2$)
25	910	1 940	3 600	4 200
35	880	1 900	3 560	4 170
55	810	1 830	3 490	4 090
75	730	1 760	3 420	4 020
95	660	1 690	3 350	3 950
123 ⁴	560	1 580	3 250	3 850
160 ⁵	430	1 450	3 110	3 720
NOTE The reported values are for normal incidence				

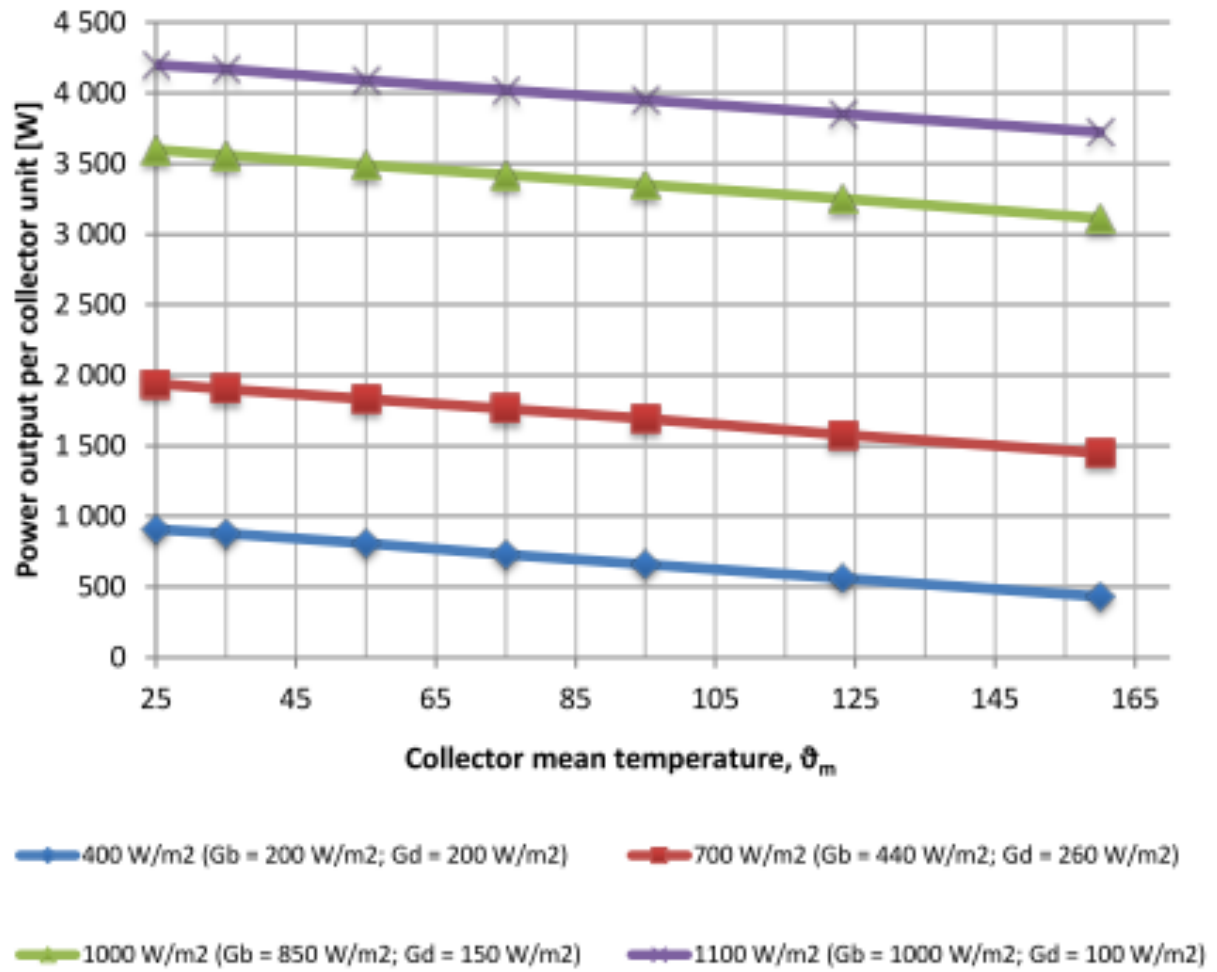


Figure 3 Power output per collector unit

Multi linear fit to data:

$$Q/A = \eta_{0,b} * K_b(\theta_L, \theta_T) * G_b + \eta_{0,d} * K_{0d} * G_d - c_6 * u * G - c_1(\vartheta_m - \vartheta_a) - c_2(\vartheta_m - \vartheta_a)^2 - c_3 * u(\vartheta_m - \vartheta_a) + c_4(E_L - \sigma T_a^4) - c_5 dt_m / dt$$

Appendix B: Study case School

1 Introduction

The school is located in rural Kenya. It has almost 700 students and in addition almost 50 teachers and other staff. It is a boarding school, open three semesters per year of three months each , starting January, May and September. Between each semester there is a one month break.

Students have food breaks in the course of each day. Cooking is done indoors, using firewood as a heat source. Cooking is done separately for two groups, teachers (and other staff) and students.

1.1 COOKING FOR TEACHERS



Cooking for teachers in action, showing the high levels of smoke in the kitchen

There are 48 teachers, inclusive of non-teaching staff.

Teachers are served 3 meals a day, i.e. 2 tea breaks (06:00 and 1:00 approximately), and one lunch meal

The cooking for teachers is done using different cooking pots (called *sufuria* in swahili) and in a different cooking area than cooking for the students though under the same structure.

Cooking is carried out on a firewood stove with the following measures:

Width:	ca 98 cm	(3.2 feet)
Length:	ca 95 cm	(3.1 feet)
Height:	ca 40 cm	(16 inches)

The stove has four spaces for pots. Each pot has a volume of approximately 20 litres, with a diameter of 40 cm (1.3 feet) and a height of 70 cm (2.3 feet).



20 liters sufuria size (used for cooking for teachers).

1.2 COOKING FOR STUDENTS

The school has 695 students, both male and female. Food for all students is served as cooked from the same points.

The students receive take 4 meals a day i.e 2 tea breaks , lunch and supper, described in the table below.

Meal	Served at	Content	Energy need/cooking time
Breakfast	6:00Am	Tea	To cook tea using dry firewood is estimated at 2 hours.
Tea break	11:00Am	Tea	
Lunch time	12:30pm	either "ugali", made from maize meal, or boiled maize kernels, vegetables, beef and rice	To cook food i.e maize/ugali it estimated at 5 hours.
Supper time	6:00pm	Same as lunch	

The cooks use the big sufurias as on the pictures below to cook for students. Student sufuria measurements are

Diameter: ca 85 cm (2.8 feet)
Height: ca 50 cm (1.6 feet)



Cooking pot for students



Students' cooking boiler

This is where the largest sufuria is inserted.

Measurements are

Diameter: ca 89 cm (35 inches)
Height: ca 91 cm (3.0 feet)

of which 2.7 feet is above the ground and 0.3 feet buried in the ground for stability.

SUFURIAS FOR COOKING TEA

These sufurias are different from the ones of cooking meals.

The measurements are

Diameter: ca 56 cm (22 inches)

Height: ca 24 cm (9.4 inches)

1.3 Note on costs

Cost for Firewood

Per 3 months, cooking in the school consumes 4 to 6 Lorries of firewood.

The price for one lorry is approximately USD 600-USD800.

Per year the firewood budget is approximately USD 10,000.

1.4 Location of heat storage and solar collector



Proposed location for solar collector and heat storage tank

The picture above shows possible location of the heat storage tank and of the Solar Collector. There are physical restrictions as to the location of the three main units of the system which will be discussed further in the detailed design phase.

1.5 Other

In the kitchen, the cooks have a problem with working light, especially at night in combination with electricity blackouts.

Appendix C: MATLAB initialization and inputs script

```
%INITIALIZATION FOR THE SOLAR RADIATION AND SOLAR COLLECTOR

%USER INPUT: Set the start day for the simulation, the amount of days
%to last and the number of collectors
Collector_units = 6; %Number of solar collector units of 5.8m^2
Start_day = 2;
Amount_days = 6;
Radiation_efficiency = 1; %A number from 0 to 1, proportion of radiation that reaches
the solar collector.
%Load the data from the excell sheet
Direct_Beam_year = [0; xlsread('Bird_clear_sky_model_2018_08_07', 'BIRD Model', 'W3:W87
61')]; %added a row of 0 to the vector at the beginning to start at hour 0 (since in the d
ata day one starts at hour 1)
Difuse_Horizontal_year = [0; xlsread('Bird_clear_sky_model_2018_08_07', 'BIRD Model', '
Z3:Z8761')];

%starting hour and end hour to take the data from the xls
Start_hour = (Start_day*24)-23;
End_hour = Start_hour+(24*Amount_days)-1;

%Calculate the irradiation for the set range of hours
Direct_Beam_hours = Direct_Beam_year(Start_hour:End_hour+1);
Difuse_Horizontal_hours = Difuse_Horizontal_year ( Start_hour:End_hour+1);
Irradiation_hours = Direct_Beam_hours + Difuse_Horizontal_hours;
Number_hours = 0:3600:Amount_days*24*3600;

%Convert the data to a timeseries object for its use in Simulink
Irradiation_ts = timeseries(interp1(Number_hours, Irradiation_hours, 0:1:Amount_days*2
4*3600));

Simulation_time = 3600*24*Amount_days;

%Power table logging adding irradiation boundary
P_table = Collector_units * [910 1940 3600 4200; 880 1900 3560 4170; 810 1830 3490 409
0; 730 1760 3420 4020; 660 1690 3250 3950; 560 1580 3250 3850; 430 1450 3440 3720];
P_table = [zeros(7,1) P_table]; %Adding the boundary condition so at 0W irradiance the
re is no power
T_table = [25 35 55 75 95 123 160 ] + 273;
Irradiance_table = [ 0 400 700 1000 1100];

%GENERAL COOKING DATA
Boiling_temperature=273+100;
Ambient_temperature=273+25;

%Users
Number_staff = 48;
Number_students = 695;

%Cooking schedule. Time is in seconds
Time_teachers_tea_morning = 6*60*60;
Time_teachers_tea_afternoon = 13*60*60;
Mass_teachers_tea = Number_staff*0.250;

Time_students_tea_breakfast = 6*60*60;
Time_students_tea_break = 11*60*60;
Mass_students_tea = Number_students * 0.250;
```

```

Cookingtime_firewood_students_tea = 2*60*60;

Time_teachers_lunch = 12.5*60*60; %Lunch time for teachers is not in the data, I assumed it to be the same as for students
Mass_teachers_lunch = 0.4*Number_staff;

Time_students_lunch = 12.5*60*60;
Time_students_supper = 18*60*60;
Mass_students_meal = 0.4* Number_students;
Cookingtime_firewood_students_meal = 5*60*60;%The time that they currently spent cooking with firewood

%Cooking time requirements.

% "Max" times. Including from the start of heating to the end after boiling for a while if it is the case
Max_tea_time = 1.6*60*60; %Assumption: one hour and 20 minutes as the maximum time they want to take for cooking tea
Max_students_meal_time = Cookingtime_firewood_students_meal ;

%Boiling times. The time required for cooking once boiling has started
Tea_boiling_time = 120; %one minute waitin after it has boiled, just to put something

Meal_boiling_time = 1.5*60*60;

%Cooking devices

Width_firewood_stove_teachers = 0.98;
Length_firewood_stove_teachers = 0.95;
Height_firewood_stove_teachers = 0.40;

Number_teachers_pot = 4;
Diameter_teachers_pot = 0.3;
Height_teachers_pot = 0.3;
Volume_teachers_pot = 0.02; %These values might be wrong since the diameter and height yield another volume

Diameter_students_sufuria_tea = 0.56;
Height_students_sufuria_tea = 0.24;

Diameter_students_sufuria_meal = 0.85;
Height_students_sufuria_meal = 0.50;

%Heat transfer coefficients

Oil_free_convection = 200; %(50-350) https://www.engineersedge.com/heat\_transfer/convective\_heat\_transfer\_coefficients\_13378.htm
Air_free_convection= 50; %(10-100) https://www.engineersedge.com/heat\_transfer/convective\_heat\_transfer\_coefficients\_13378.htm
Steam_forced_convection = 300; %Estimated from values for steam under free convection and air under forced convection
Conductivity_mineral_wool = 0.04; %Taken from https://www.engineeringtoolbox.com/thermal-conductivity-d\_429.html
Copper_thermal_conductivity=385; % Assuming copper pots http://hyperphysics.phy-astr.gsu.edu/hbase/Tables/thrcn.html
Copper_pot_thickness = 0.0025; %Thickness for copper commercial pots https://en.wikipedia.org/wiki/Cookware\_and\_bakeware#Cookware\_materials

%Current recipients: These refers to final version 1, where the recipients holding the pots are the current ones that they have.

```

```

Material_outer_pot_layer_conductivity = 100; %Assumed conductivity of the layer th
at surrounds the pots for tea and food for students
Material_outer_pot_layer_thickness = 0.03; %Assumed thickness of the layer that su
rrounds the pots for tea and food for students

Specific_heat_water = 4187; %J/Kg*K
Specific_heat_air = 1000;
Density_air = 1.225;
%Designed recipients for pots. All the insulation is done through mineral wool
Thicknes_insulation_tea_students = 0.04;
Thicknes_insulation_meal_students = 0.05;
Thickness_insulation_stove_teachers = 0.04;

%THERMOSIPHON HEAT EXCHANGER

Inner_diameter_thermosiphon = 0.021;
Outside_diameter_thermosiphon = 0.022;
Fin_diameter = 0.043;
Fin_thickness = 0.0006 ;
Fin_separation = 0.01;
Heat_exchanger_length = 0.82;
Fin_number = Heat_exchanger_length / (Fin_thickness+Fin_separation);

Fined_area = (pi*(Fin_diameter-Outside_diameter_thermosiphon)^2)/4)*Fin_number;
Fined_estructure_area = Fined_area + pi*Outside_diameter_thermosiphon*(Heat_exchanger_
length-Fin_number*Fin_thickness);

Resistance_1_2 = log ( Outside_diameter_thermosiphon/Inner_diameter_thermosiphon)/(2*p
i*Copper_thermal_conductivity*Heat_exchanger_length);
Fin_efficiency = 0.87; % calculated by use of the tables for fin efficiency(one availa
ble in the document fin cooling). Data entered for oil convection = 200 and copper conduct
ivity = 385
Resistance_2_f = 1/ ((1-((Fined_area/Fined_estructure_area)*(1-Fin_efficiency)))*Fined
_estructure_area*Oil_free_convection);
Resistance_total_heat_exchanger = Resistance_1_2 + Resistance_2_f;

%Without finns
R_without_fins = Resistance_1_2 + 1/(Oil_free_convection*pi*Outside_diameter_thermosip
hon*Heat_exchanger_length);

% OIL TANK
%For a tank as a 1x2x1.5 container (3 cubic meters)

Initial_oil_temperature= 273+200; %Used as assumed temperature when initializing the t
ank to feed the pots for a few days without external power
Oil_temperature=273+175;
Density_oil_tank = 800; %Estimation based on values seen for different engine oils, it
also varies with the temperature and between different engine oils
Volume_oil_tank = 3;
Area_oil_tank = 2*(1*2+1*1.5+2*1.5); % we are suposing that the tank has losses to amb
ient temperature all around, including the floor
Mass_oil_tank = Density_oil_tank * Volume_oil_tank ;
Specific_heat_oil = 2500; % Taken as an average mesure for 150 degrees from http://www
2.eng.cam.ac.uk/~mpfs/papers/articles/WTC2005/pdfs/t-3/WTC2005-64316.pdf
Thickness_mineral_wool_oiltank = 0.04 ;

```

