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Assessing the feasibility of a Solar Water Heating System in rural Uganda

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Renewable Energy

Preface

This master thesis is a result of five years as a student, with the two last years at the Norwegian University of Life Sciences in Ås. An engineering degree in Energy Technology made me want to save the world but I understood that this would be an overwhelming task. However, after my master's degree in Renewable energy I am a little closer to my mission. I have gained knowledge of the whole specter of the renewable energy sector, which I am thankful for.

I am grateful for the opportunity of writing a "Master med Mening" through Engineers without borders and for making my field trip to Uganda possible. I would like to thank Anne Grete Kjørrefjord and Nyenga Foundation for believing in me and for a warm welcome at the Foundation. Further, thank you to my mentor, Hans Eilif Bjerkvig for interesting inputs and ideas and for being a great traveling companion.

I want to thank my supervisor Muyiwa Samuel Adaramola for valuable help and guidance, and for always being available. Finally, I want to thank Kosegruppa for fun moments and support through the process. Especially thanks to Håkon Kjersem and Alexander Dybvad for constructive discussion and help.

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Abstract

Energy in rural Uganda is often a limited and expensive commodity where as much as 80% of the population lives in rural areas. Biomass is the traditional source of energy and accounts for more than 80% of the energy used for cooking purposes in these rural areas. Using clean energy sources for cooking can provide several benefits such as improved health, reduced pressure on local natural resources and emissions of greenhouse gasses. Solar water heating is one of these alternative sources that can be used to replace conventional cooking fuels, such as wood and kerosene, for heating water.

The aim of this study was to design and select an optimal Solar Water Heating System (SWHS) for a Learning Centre (LC) in rural Uganda, in order to reduce the amount of firewood used to boil water and for cooking. Based on quantity and temperature of required warm water for cooking purpose in the LC and designed SWHS, performance of three different Solar Water Heating Systems with different water storage capacity and collector surface area, which are available in the Ugandan market, were assessed and compared.

It was found that daily warm/hot water requirement is 200 liters with a temperature range from 60°C to 100°C. Furthermore, the results showed that the optimal SWHS would be a direct system with flat plate collectors with storage capacity of 300 liters. The system will reduce the wood consumption with 54% and a yearly reduction of CO_2 emissions of 6,6 ton. The economic analysis indicated that this system was, however, not economically viable in this location. Notwithstanding, implementation of a SWHS within the facility would create positive effects for the staff at the kitchen such as improved working environment with less pollution. In addition to this, the SWHS could be used as a teaching and demo facility for the students and people within the neighborhood of the Foundation, as possible water heating options for small, medium- and large-scale applications.

Sammendrag

Energi i landlige Uganda er ofte begrenset og kostbar vare der mer enn 80% av befolkningen bor i landlige områder. Biomasse er den tradisjonelle energikilden og står for over 80% av energien som brukes til matlaging. Bruk av rene energikilder til matlaging kan gi flere fordeler, for eksempel bedre helse, redusert press på lokale naturressurser og utslipp av klimagasser. Solvarmeanlegg er en av disse alternative kildene som kan brukes til å erstatte konvensjonelle matlagingsbrensler, for eksempel ved og petroleum, for oppvarming av vann.

Målet med denne studien var å designe og velge et optimalt solvarmeanlegg for et læringssenter på landsbygda i Uganda, slik at mengden brensel som brukes til kokende vann og matlaging, kan reduseres. Basert på mengde og temperatur på nødvendig varmtvann til matlagingsformål ble ytelsen av tre forskjellige solvarmeanlegg med forskjellig lagringskapasitet og innstrålingsareal, som er tilgjengelig på det ugandiske markedet, vurdert og sammenlignet.

Det har blitt funnet at det daglige behovet for varmtvann er 200 liter med temperaturområde fra 60°C til 100°C. Videre viste resultatene at det optimale solvarmeanlegget ville være et direkte system med plane solfangere med lagringskapasitet på 300 liter. Systemet vil redusere bruken av tre med 54% og en årlig reduksjon av CO2-utslipp på 6,6 tonn. Den økonomiske analysen indikerte at dette systemet imidlertid ikke var økonomisk levedyktig på denne plasseringen. Til tross for at implementering av et solvarmeanlegg vil skape positive effekter for de ansatte på kjøkkenet, for eksempel ved forbedret arbeidsmiljø med mindre forurensning. I tillegg kan solvarmeanlegget brukes som undervisnings- og demonstrasjonsanlegg for studentene og innbyggerne i Stiftelsens nabolag, som mulig vannoppvarmingsalternativer for små, mellomstore og store applikasjoner.

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Abbreviations

ETC	Evacuated Tube Collector
FPC	Flat Plate Collector
GHG	Greenhouse Gases
ICS	Integral Collector System
LC	Learning Centre
MCDA	Multi-Criteria Decision Analysis
NOK	Norwegian Kroner
NPV	Net Present Value
O&M	Operation & Maintenance
SF	Solar Fraction
SPP	Simple Payback Period
SWH	Solar Water Heating
SWHS	Solar Water Heating Systems
UGX	Ugandan Shilling

1 Introduction

1.1 Background

As a result of the increasing demand for energy resources for improving living standards and economic development, the environment and the climate are being intensely changed and damaged by continuous extraction and use of these energy resources, especially, fossil fuels (Sampaio & González, 2017). With a growing population and a forecasted increase in energy demand, the world is facing environmental problems such as greenhouse gas emissions and its effect on climate change (Conti et al., 2016). In 2015, the United Nations set 17 Sustainable development goals to ensure a sustainable world for the current and future generations. Goal 7, "Affordable and clean energy" aims for universal access to affordable, reliable and modern energy services by 2030 (UN, 2019).

Africa is one of the continents with maximum vulnerability to the consequences of climate change because of the vast population growth and the human activities, which are associated with the growth (Aliyu et al., 2018). Despite its abundant energy resources, the poor state of infrastructure and appropriate technology to harness the resources, are slowing down the development of the continent. Access to modern clean energy (for cooking) and electricity is generally low ƒali Africa, especially in sub-Saharan Africa countries. Uganda, which has one of the fastest growing populations in Africa with a yearly population growth of 3,1 %, suffers from energy deficit even though it is a country with great amount of energy resources (The World Bank, 2019). Approximately 80% of the population is living in rural areas and primarily lives out of small-scale agriculture and animal husbandry (FN-Sambandet, 2018).

Uganda is a country located in East Africa, surrounded by Kenya in the East, South Sudan in the North, Tanzania in the South, Democratic republic of Congo in the West and Rwanda in the South West as shown in Figure 1.1. Most of the country is approximately 900 meters above sea level and a fifth of the country consists of open water or swampland. The climate is tropical with stable temperatures of 20-25 degrees all year. Uganda is gifted with rich energy resources, such as hydropower, fossil fuels, biomass and solar energy but has a poor national electricity grid which only covers 18% of the population (Avellino et al., 2018).

Figure 1.1 Map of Uganda showing the major cities and the neighboring countries (Alamy Stock Photo, 2014)

The energy sector of Uganda is mainly based on wood fuel extraction and wood charcoal consumption. The reliance on bioenergy consumption is due to limited access to modern energy. A great share of wood and charcoal, which can be associated with effects on both human health and environment, is used for cooking. As shown in Figure 1.2, 69% of the fuel used for cooking in 2009 was wood (Mohammed et al., 2015). In 2010, diseases related to pollution were reported to be the second highest health issue after malaria (Nabulo & Cole, 2011). Furthermore, high rate of deforestation is an environmental issue affecting Uganda, which is expected to grow as the human population and energy demand rises (Mohammed et al., 2015).

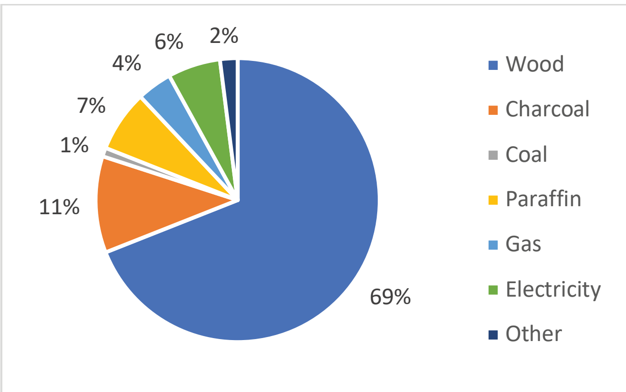

Figure 1.2 Percentage of different types of fuels used for cooking in Uganda (Mohammed et al., 2015)

The need for clean and accessible energy is making utilization of renewable energy technologies (especially, solar energy conversion systems) now commonly used for small-scale lighting and battery charging purposes in Uganda. Hence, harnessing the sun´s energy is an essential component of a sustainable energy future that can contribute to reach UNs sustainable development goals. Solar thermal is one of the most profitable technologies within renewable energy and has an immense market globally. Solar water heating (SWH) accounts for over 80% of the solar thermal market in the world and has therefore become the most popular solar thermal system. SWH is broadly used in many countries in the world because of its safe and cheap way to collect hot water by solar radiations (Wang et al., 2015).

1.2 Background on solar water heating systems

Solar water heating systems are used to heat water that can be used for domestic and commercial purposes. Depending on the location as well as quantity and quality (temperature) of required hot water, SWH systems may not eliminate the need for other heating resources such as wood or electricity however, SWHS could reduce the proportion of the auxiliary energy resources. Generally, there are two types of SWHS, passive and active systems (Gautam et al., 2017). Active system uses an electric pump to circulate the heat transfer fluid, while the passive system does not use a pump. Active systems can be classified as direct and indirect. In a direct circulation system, the water that is taken out from the hot water tank is the same that has circulated through the heat absorber, also known as collectors. This method is not appropriate in places where freezing temperatures appear (Shukla et al., 2009). Compared to an indirect circulation system, heated fluid circulate in a closed circuit as shown in Figure 1.3 (Hossain et al., 2011), and transfer hot water in a storage tank.

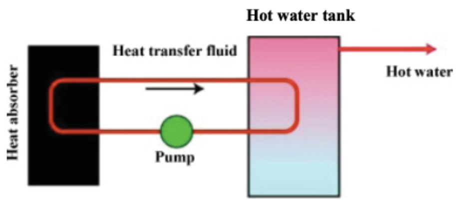

Figure 1.3 Indirect circulation system (Hossain et al., 2011)

A passive SWHS can be organized in an integral collector system (ICS) and in a thermosiphon system. An ICS can also be called a batch system, where the hot water tank acts as both storage and collector for the water. A disadvantage of this design is the relatively heat loss in this system, which is more distinct in the night when there is no radiation from the sun. A thermosiphon system uses the difference in density of cold and hot water as the driving force to move the water. When the water is heated, it will rise through the collector and to the top of the storage tank where the outlet will be situated (Jamar et al., 2016). Figure 1.4 shows the classifications of the different types of SWHS.

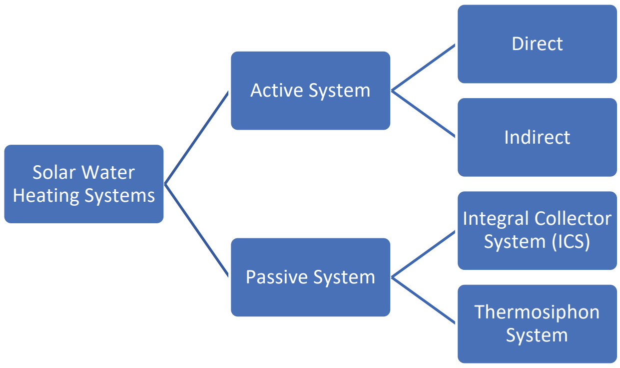

Figure 1.4 Classifications of Solar Water Heating Systems

In a SWHS, three main components have an important effect on the overall performance of the SWHS. These components are solar collector, heat exchanger and storage tank. Solar collectors absorb the solar radiation and transmit it to the moving fluid inside. The heat collected in the fluid can be used either for direct hot water supply, space heating or to a storage tank. There are mainly two types of solar collectors on the market today, which are flat plate collector (FPC) and evacuated tube collector (ETC).

The FPC is the most common collectors that are used for solar water heating applications. The working principle is that the sun heats a dark flat absorber plate and energy is then transmitted to fluid tubes that consist of water, air or another working fluid. The FPC can either be unglazed or glazed. The unglazed collector has a dark absorber plate made of metal or polymer without a cover and is most suitable for low temperature applications, such as outdoor swimming pools. The glazed collectors have a cover of glass above the absorber and are insulated to reduce the heat losses from both the front and the backside. This makes the collector suitable for moderate temperature applications up to 70 degrees. The life cycle of a FPC is known to be 20-25 years (Gautam et al., 2017). An illustration of a typical flat plate collector is shown in Figure 1.5.

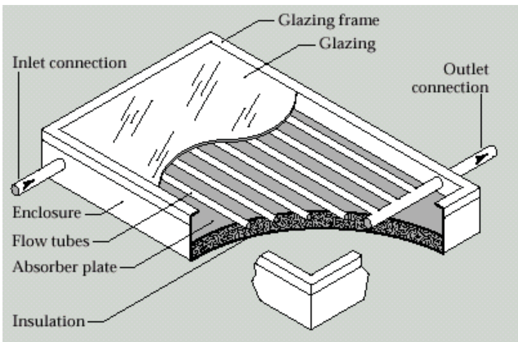

Figure 1.5 A typical flat plate collector (Hossain et al., 2011)

The ETC consists of two concentric tubes with a small space. Many tubes are attached to a frame to form a unit solar collector. The heat transfer fluid flows within the inner tube while the absorber plate is located on the external surface of the inner tube as shown in Figure 1.5 (Gautam et al., 2017). An advantage of using ETC is that the convection heat loss is low due to the vacuum in the annular space, which improves the efficiency. Vacuum glass tubes provide greater daily heat output due to the cylindrical absorber shape always being perpendicular to the sun, as a natural sun tracking. This can generate temperatures above 100 degrees Celsius (Kalogirou, 2004). The ETC obtain heat even in the coldest areas and during cloudy or overcast days. A weakness of the ETC compared with FPC is the life cycle of 10-20 years (Shah, 2018).

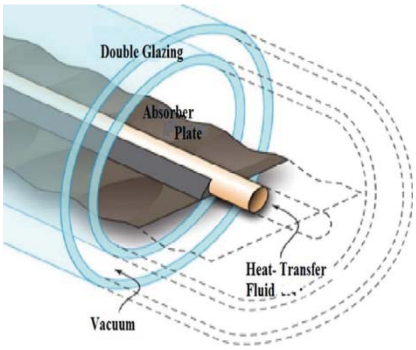

Figure 1.6 An evacuated tube collector (Gautam et al.,2017)

The hot water storage tank is a component of the SWHS that has a major role in dictating the systems performance. The tank is used to store the collected thermal energy and deliver the hot water demand at the preferred temperature to the end user (Shukla et al., 2013). Storage tanks are usually made of steel, concrete, plastic or fiber glass, where steel tanks are mostly available for commercial use. To avoid legionella and other bacteria to develop, the water should be at least 60 degrees in the tank (Hossain et al., 2011).

A heat exchanger is used in an indirect type of SWHS to move absorbed solar heat from the heat transfer fluid to the storage tank. Conductive materials such as aluminum, stainless steel and bronze can be used, but to ensure good thermal conductivity, copper is commonly used (Hossain et al., 2011).

Risk of legionella

The legionella bacteria are usually found in water and survive best where temperatures are between 20-45 degrees Celsius. Legionella can occur in all parts of a SWHS, from the cold-water inlet to the hot water outlet. The risk of legionella rises if the water is not circulated in the system for 2 days or more (Amerongen et al., 2013).

Solar collector efficiency

The efficiency of a SWHS reflects how much energy that can be converted into useful heat. The losses in the SWHS depends on the quality and components used, the design and operation of the system. Figure 1.7 illustrates typical efficiency curves for swimming pool absorber, flat plate collector and evacuated tube collectors.

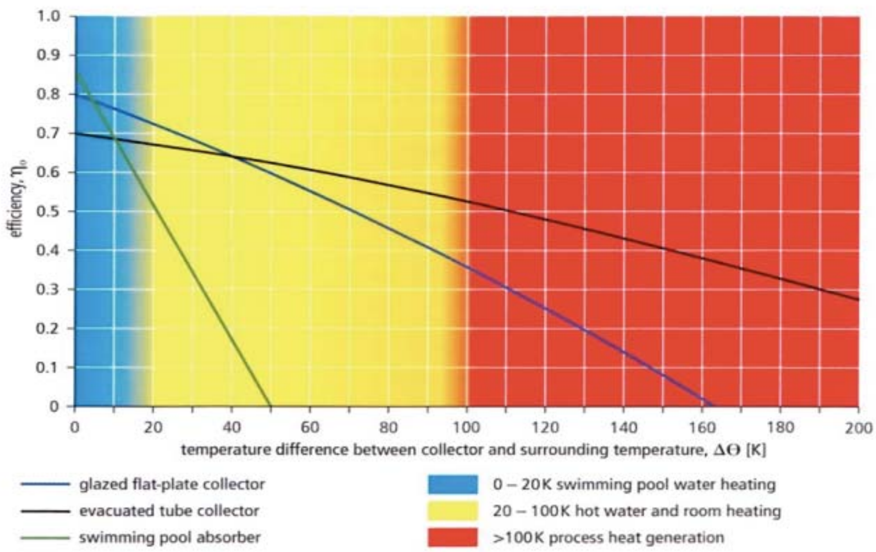

Figure 1.7 Efficiency characteristic curves for different types of collectors at irradiation of 1000 W/m2K (DGS, 2010)

For tropical climates such as Uganda, the proposed SWHS is a direct passive system, where both flat plate collectors and evacuated tube collectors would be considered. A passive system requires that the inlet water is located above the collector to ensure sufficient pressure without use of an electric pump.

1.3 Goal and objectives

The aim of this thesis is to design and select an optimal design Solar Water Heating System (SWHS) for a Learning Centre (LC) in rural Uganda and thereby, reduce the amount of firewood used for boiling water and cooking. The thesis is based on fieldwork at Nyenga Foundation and examines the Foundation's hot water demand and available and usable local energy resources within its premises. The specific objects are:

- Estimate the hot water requirement at the selected site – quantity of water and temperature.
- Determine the optimum fixed tilt angle for the solar collector.
- Estimation of solar water heating size to meet specified hot water requirement.
- Determine the cost of producing hot water and compare this with cost of using firewood.
- Performance comparison of various solar water heating systems.
- Estimate the quantity of firewood saved and hence, CO_2 emission, by partially or fully using solar heating system.

1.4 Structure of analysis

The thesis is structured into five chapters arranged in the following order:

Chapter 1 introduces the background of the thesis and relevant literature on the SWHS. Furthermore, objective and goals are presented.

Chapter 2 presents the methodology used in the thesis together with information about the field research that was conducted in February 2019.

Chapter 3 contains the results calculated from chapter 2. The results are summarized in a Multiple-Criteria Decision Analysis (MCDA).

Chapter 4 presents a discussion on the results.

Chapter 5 gives the conclusion and recommendation for further work

2 Methods

2.1 Site description

The proposed solar water heating system is for Nyenga Foundation. This Foundation is located 15 km from Jinja, which is the second largest city (after Kampala) in Uganda. The latitude, longitude and elevation of the Foundation's site are shown in Table 2.1.

Table 2.1 Latitude, longitude and elevation of Nyenga Foundation

Parameter	Value
Latitude (ºN)	0,36
Longitude (ºE)	33,12
Elevation (m)	1100

The Foundation consists of New Horizon Primary School, the Kabizzi Community Health Centre and a children´s home. In addition, there is accommodation for staff and guests of the foundation. The property of Nyenga Foundation covers 52 acres, where farmland is leased to low-income farmers. The primary school consist of 200 pupils, who are served two meals per day at the school, from 1st grade to 7th grade. The children's home has between 15 and 24 kids, which also attends the primary school. A map of the site layout is presented in Figure 2.1.

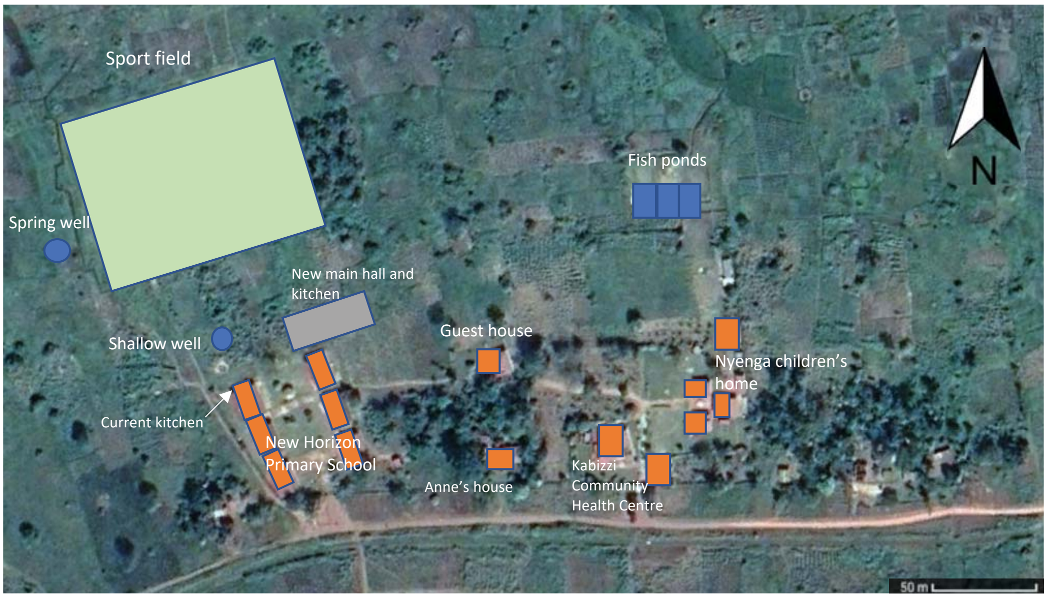

Figure 2.1 Layout of the property of Nyenga Foundation

There are plans to build a new main hall and kitchen next to the school. As shown in Figure 2.2, the construction work was already begun during the fieldwork in February 2019 and it is expected to be finished in August 2019. In addition to the planned installation of a SWHS, there is a desire to build a biogas digester to compliment the SWHS and eliminate the use of firewood as the cooking energy source within the Foundation's premises. However, the assessment and design of this biogas system is not considered in this present study.

Figure 2.2 Construction site of the main hall and kitchen

2.2 Field research

The groundwork of this thesis is done by a field research trip to Nyenga Foundation in February 2019, where information and data on the energy situation was obtained. Demand of hot water and how it was collected was also a part of the field research. Visits to potential local suppliers of solar water heating systems was carried out to have an overview of SWHS market situations in Uganda and to obtain specifications on the different solar water heating systems as well as their respective prices. The field research also helped to evaluate the area and the available resources currently in use and solar energy resource within the Foundation's premises.

2.3 Energy situation and water facilities at Nyenga Foundation

Like the rest of Uganda, biomass is the primary source of energy at Nyenga Foundation. Wood and charcoal are used for cooking food for the school and children's home. The guesthouse and health center are equipped with solar panels and batteries for small appliances like a fridge and lighting. Furthermore, there is one solar panel that provides electricity to a water pump in the shallow well, which is situated about 50 meters from the current kitchen's location. The shallow well consists of a manual hand pump, shown in Figure 2.3, and an electric pump. The electric pump delivers water to two overhead 3000 liters tanks on

Figure 2.3 The manual hand pump with the shallow well

the property, which is used by the guesthouse and the children´s home. The well is the main source of water collection for the kitchen. However, there is a spring well (close to the Foundation), which serves as an additional source of water, but the pressure of this spring is unstable, which makes it an unreliable water source.

2.4 Cooking and hot water demand

The kitchen has three employees that cooks food for more than 200 people twice a day, 5 days a week. In addition to that, they also prepare the dinner for the children's home at the same time. Currently, they normally fetch 10 jerry cans of water (each has a capacity of 20 liters of water) every evening which are being used the following day. Figure 2.4 shows the jerry cans that are used to fetch and store water. During the day, the hot water demand is 200 liters with temperature ranging between of 60 ºC to 100 ºC. The hot water is used for cooking and cleaning the large kitchenware's. The pupils at the school clean their plates by themselves in cold water after eating. The two meals are prepared around 9.00 and 11.00 am and served at around 10.30 (breakfast) and 13.00 (lunch), respectively. The lunch is served at 13.00 and lasts until 14.00, thereafter the cleaning of the plates begins. Figure 2.5 illustrates the hot water demand during the day where the peaks are at 09.00, 11.00 and 14.00.

Figure 2.4 Jerry cans for fetching the water

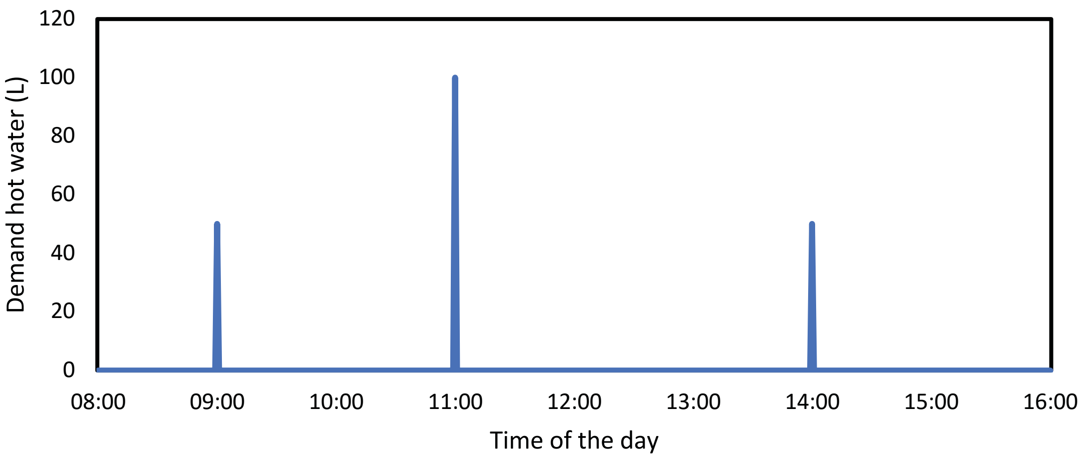

Figure 2.5 Hot water profile at the kitchen

2.5 Firewood

Currently, firewood is used for cooking. The cost of electricity in Uganda the first quarter of 2019 was 519,9 UGX/kWh (approximately 1,19 NOK/kWh) set by the Electricity Regulatory Authority of Uganda (ERA, 2019). The high electricity price in combination with a low electrification rate, explains the Foundation´s preference for using firewood instead of electricity. The firewood is mostly bought from neighboring suppliers of firewood; however, firewood is sometimes collected from nearby forest. As shown in Figure 2.6, the wood is put in to three openings on the back of the kitchen. The gases from the burning on the outside has a short way through the window opening and in to the kitchen, as shown in Figure 2.7. The

Figure 2.6 Outside the kitchen where the firewood is put inside.

Figure 2.7 The stove inside the kitchen where the food is prepared

reason why there is much soot (as can be seen in Figure 2.6) is that the firewood is too large to fit in the oven and protrudes from the opening. This makes the burning process less efficient and can cause hazardous gases to be inhaled by staff menbers. It is estimated that the kitchen uses 2-3 wheelbarrows of firewood five days a week, which is equivalent to 150 kg. During the fieldwork, it was difficult to obtain information about the type of wood that was used for cooking. Therefore, information provided by Tabuti et al., (2003) about wood species used for firewood in central Uganda is adopted in this study. Table 2.1 illustrates the three most common wood species. The calorific values for these wood species are found through published scientific articles (as indicated in Table 2.1). To calculate the total energy yield from the firewood consumption, an average specific energy of 5,8 kWh/kg was used for the three species. It is assumed that the cooking stove for the kitchen has an efficiency of 15%, both from considering the way of combustion and the analysis of (Jetter et al., 2012). The total cost of wood and charcoal that the school spend was obtained from the staff at Nyenga Foundation and are shown in Table 2.2. This is the cost for heating the water and cooking the food. On monthly basis, the total cost for these fuels are UGX 203 333 (which is equivalent to NOK 468[1]).

Table 2.2 Three most common species used for firewood in Central Uganda with Calorific Value and Specific Energy

Species[a]	Family	Calorific value (MJ/kg)	Specific Energy (kWh/kg)*
Acacia	Fabaceae	17,5[b]	4,9
Ficus sycomorus	Moraceae	24,9[c]	6,9
Milicia Excelsa	Moraceae	20,20[d]	5,6

[a](Tabuti et al., 2003); [b](Marsoem & Irawati, 2016); [c] (Chakradhari & Patel, 2016); [d] (Ogunsola et al., 2018)
*1 kWh=3,6 MJ

Table 2.3 Cost of firewood and charcoal for the kitchen at Nyenga

	Firewood	Charcoal	Total
UGX per month	133 333	70 000	203 333
UGX per year	1 600 000	840 000	2 440 000
Total UGX firewood and charcoal			**2 643 333**

2.6 Sources metrological data

The solar water heating system requires evaluation of the meteorological data, such as solar radiation and ambient temperature, at the project site. Due to lack of ground measured data at Nyenga, data from NASA Surface Meteorology (NASA, 2019) have been collected and used in this study. The meteorological data is an average value per month over a period of 30 years (Jan 1984 – Dec 2013) while the solar climatology data is an average over 22 years (Jul 1983 – Jun 2005).

Solar radiation

Uganda is suitable for utilizing solar energy as it obtains great amounts of solar energy due to its location close to the equator.

Global solar radiation consists of three main components of radiation as shown in Figure 2.8. Direct radiation (H_{DH}) is the radiation that comes directly from the sun without any modifications on the way. Diffuse radiation (H_{BH}) is scattered by clouds and dust while

[1] 1 NOK=433,9 UGX (XE Corporation, 2019)

reflected radiation is reflected from ground surface. The amount of the reflected radiation is a function of the ground surface conditions and different reflectance capability and it is generally referred to as albedo (ρ) (Kalogeropoulos et al., 2013).

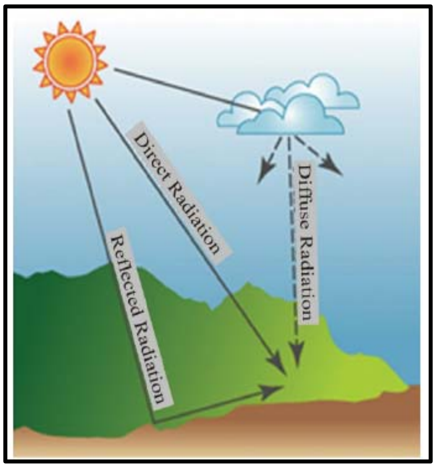

Figure 2.8 Main components of solar radiation (Kalogeropoulos et al., 2013)

Clearness Index

Clearness index (K_T) is a measure of the clearness of the atmosphere and it is the amount of solar radiation at the top of the atmosphere at an exact location on the earth surface. The index varies from 0 to 1 where the value 0 signifies that no irradiance is to be received on the ground while the value 1 indicates that the maximum theoretical amount of radiation will be received on the ground. It is not normal to exceed a value of 0,8 with the clearest conditions (Lai et al., 2017). It is used to find what percentage of the radiation that is diffuse and what is direct.

Figure 2.9 shows the variations of daily monthly average global solar radiation in kWh/m^2 on horizontal surface and the clearness index at the project site. The solar radiation varies from 4,90 kWh/m^2 in June and July to 5,90 in March, which indicates a stable insolation throughout the year. The clearness index has a minimum of variation of 0,55 which implies the weather conditions at Nyenga to be partly cloudy. Therefore, the average solar radiation is considered very good for solar energy conversion systems.

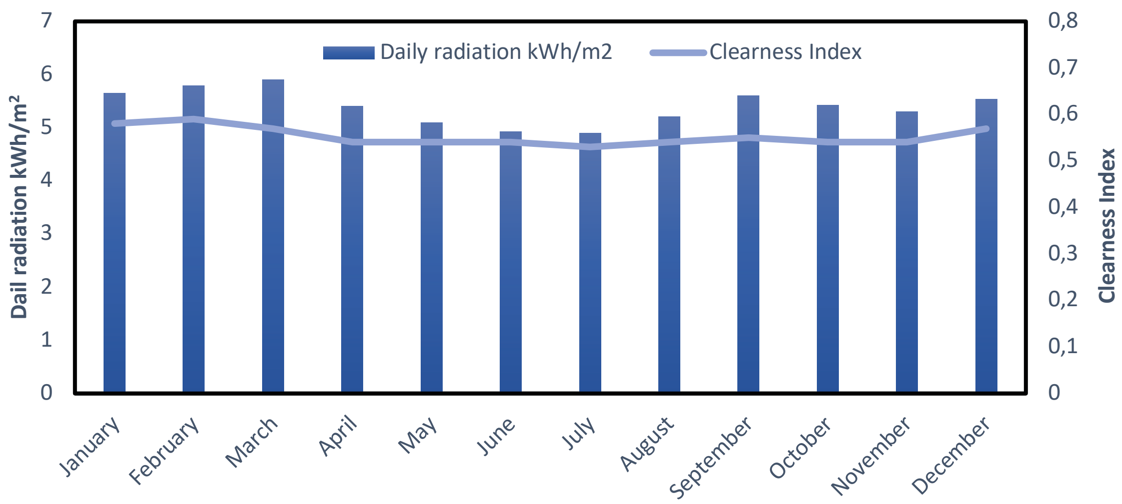

Figure 2.9 Daily monthly average solar radiation and Clearness Index for Nyenga

Altitude and azimuth angle

Solar angles can be used to choose the optimal tilt angle for the solar collector in order to obtain the highest insolation. The altitude angle (β) is the angle between the sun and horizontal plane while the azimuth angle (φ_s) is the angular deviation of the solar collector surface due to the direction south of the Northern Hemisphere or due to north of the Southern Hemisphere. At solar noon, the sun will be on the north-south line and solar azimuth is 0 degrees (Kalogirou, 2014). To calculate the altitude and azimuth angles, Equations (2.1) and (2.2) are used respectively.

$$sin\beta = \cos L * \sin \delta * \cos H + \sin L * \sin \delta \quad (2.1)$$

$$sin\varphi_s = \frac{\cos \delta * \sin H}{\cos \beta} \quad (2.2)$$

Where L is the latitude of the site, δ is the declination angle and H is the hour angle.

Hour angle

The hour angle (H) is the angle through which the earth would rotate to bring the sun directly over a local meridian. The hour angle is positive before solar noon and negative after solar noon. At noon the hour angle is zero (Kalogirou, 2014). The following equation is used to calculate H,

$$H = \left(\frac{15°}{hour}\right) * (12 - ST) \quad (2.3)$$

Where ST is, approximately, the local time at the site

Declination angle

The Declination angle (δ) is the angle relative to equator and differ from 23,45 to -23,45 over the year. An illustration of the declination angle can be seen in Figure 2.10. The angles north of equator are positive while the angles south of the equator are negative (Masters, 2013). The declination angle can be calculated using the following formula.

$$\delta = 23{,}45 * \sin\left(\frac{360}{365}(N - 81)\right) \tag{2.4}$$

Where N is the given day of the year starting with January 1st N=1. For convenience, when calculating the monthly average declination angle, the 15th in every month was used.

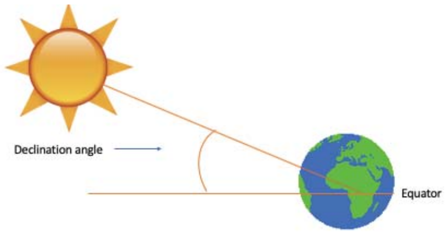

Figure 2.10 Illustration on declination angle

Optimal placement of the SWHS

The orientation and tilt angle relative to the horizontal surface of the solar collector has a great influence on the systems performance. The best way to achieve maximum daily energy is to incline the solar collectors towards the sun at 90°. Because the position of the sun varies throughout the day as well as seasonally, it is preferable to use tracking systems that follows the direction of the sun during the day. However, these trackers are expensive and not always applicable. It is then often practical to mount the solar collector at an optimum tilt angle, which normally faces the equator. The optimum tilt angle is taken to be equal to the geographical latitude of the solar collector's location, but it is possible to adjust the angle depending on latitude and declination angle (Yakup & Malik, 2001). Optimal tilt angle can be estimated using Equation 2.5:

$$\theta_{opt} = L - \delta \tag{2.5}$$

Solar radiation on inclined surface

Estimating the solar radiation on an inclined surface requires calculation by use of different equations that depend on time of the day, day of the year, the position of the sun relative to the project site and the tilt angle of the collector. In addition to this, direct and diffuse solar radiation has to be determined to be able to calculate solar radiation on an inclined surface (Al-Rawahi et al., 2016). To estimate the total global solar radiation on an inclined surface (H_C), Equation 2.6 can be utilized.

$$\frac{H_C}{H} = R_B * \left(1 - \frac{H_{DH}}{H}\right) + \frac{H_{DH}}{H} * \left(\frac{1 + \cos(\theta)}{2}\right) + \rho * \left(\frac{1 - \cos(\theta)}{2}\right) \tag{2.6}$$

Where is H is the total global solar radiation on a horizontal surface, H_C is the total global solar radiation on an inclined surface, R_B is the direct beam radiation factor, H_{DH} is the diffuse radiation, ρ is the albedo value and θ is the solar collector tilt angle.

$\frac{H_{DH}}{H}$ is a function of the clearness index (K_T) and can be calculated from Equation 2.7.

$$\frac{H_{DH}}{H} = 1{,}390 - 4{,}027 * K_T + 5{,}531 * K_T^2 - 3{,}108 * K_T^3 \tag{2.7}$$

The direct beam radiation factor is a function of the site´s latitude, declination angle and hour angle. For a surface in the northern hemisphere tilted towards the equator the R_B can be determined from Equation 2.8 (Mertens, 2014):

$$R_B = \frac{\sin(\beta + \theta)}{sin\beta} \tag{2.8}$$

2.7 Ambient temperature

The ambient temperature for Nyenga is relatively stable throughout the year, with a peak in February/March with an average of 24,5°C, which can be seen in Figure 2.11. The temperature of the water source that will provide water for the SWHS is measured to be 22°C and it is assumed that this will be stable during all months since it is a minimum variation in the ambient temperature.

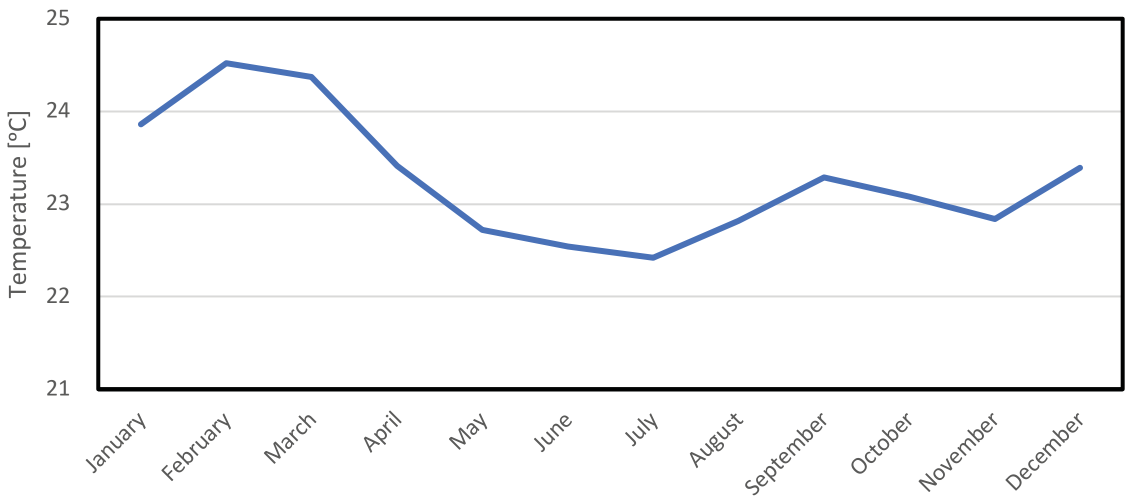

Figure 2.11 Average daily monthly ambient temperature at Nyenga

2.8 Heat equation for water and solar energy equation

The daily hot water consumption can be determined from Equation 2.9:

$$Q_w = V_w * \rho * C_p * \Delta T \quad (kWh) \tag{2.9}$$

Where

V_w is the daily water requirements (m^3), ρ is the density of water (1000 kg/m^3), C_p is the specific heat constant of water (0,001163 kWh/kg∗K) and ΔT is the temperature difference between inlet and outlet water (K or° C). The energy from a solar collector can be found through Equation 2.10

$$Q_{solar} = \eta_{coll} * A_c * H_c \ \text{(kWh)} \tag{2.10}$$

Where η_{coll} is the collector efficiency, A_c is the area of the collector (m^2) and H_c is the total solar radiation on the collector surface (kWh/m^2/day).

Both the heat equation for water and the solar energy equation will be used to calculate the outlet water of the SWHS.

2.9 Heat loss in hot water tank

An important aspect of the SWHS performance is the heat loss. As the water at Nyenga mainly is used in the morning before the solar radiation is at its strongest, it is important to have knowledge about the heat loss in the hot water tank. Heat loss characteristics are often represented by an average heat loss coefficient or U-value, however, this depends on the materials used (Cruickshank & Harrison, 2010). After a consultation with a manufacturer of SWHSs in Uganda (Davis & Shirtliff Ltd), they stated that it is around 10 % heat loss from the hot water tank during the night if the water is not used in the evening. In case the hot water is used in the evening, cold water would then displace the hot water and there would be significantly reduction in the water temperature the following morning. The heat loss is considered in the heat equation for water with the temperature difference of inlet and outlet water.

2.10 Solar fraction

The solar fraction (SF) is the percentage of hot water load that can be met by solar energy on an annual basis compared to the original source of heating the water. It depends on the quality of the solar resource, the technical characteristics of the SWHS and the pattern of water use (Denholm, 2007). The Equation 2.11 is used to estimate SF.

$$SF = \frac{Q_{solar,a}}{Q_{other,a} - Q_{solar,a}} \tag{2.11}$$

Where $Q_{solar,a}$ is the annual energy from solar (kWh/year) and $Q_{other,a}$ is the annual energy from other sources (kWh/year)

2.11 CO_2 savings

During production of hot water by the solar water heating system, no greenhouse gases (GHG) such as CO_2 is emitted. The alternative heating of water at Nyenga is done by burning firewood. To calculate the amount of CO_2 that is emitted by burning firewood, the emission factor reported by (Bhattacharya et al., 2002) was used in the study. They presented emission factors from different wood-fired cook stoves which varied from 1,3 kg to 1,6 kg CO_2 per 1 kg wood. An average of 1,45 kg is used for calculating the reduction in CO_2 emission in this analysis. The emissions related to the manufacturing of the SWHS is not considered and taken into account when calculating the CO_2 savings.

2.12 Economic evaluation

The economical assessment of a SWHS depends on several factors such as the hot water load, system performance, solar resource, the cost of conventional fuels and available financing or incentives.

2.12.1 Cost allocation

The cost allocation for solar thermal installations is found through Eicker (2003), which has a percentage allocation for solar thermal installations in Germany, as shown in Figure 2.12. In this economic evaluation of a solar water heating system in Uganda, it is assumed the same cost allocation as in Germany.

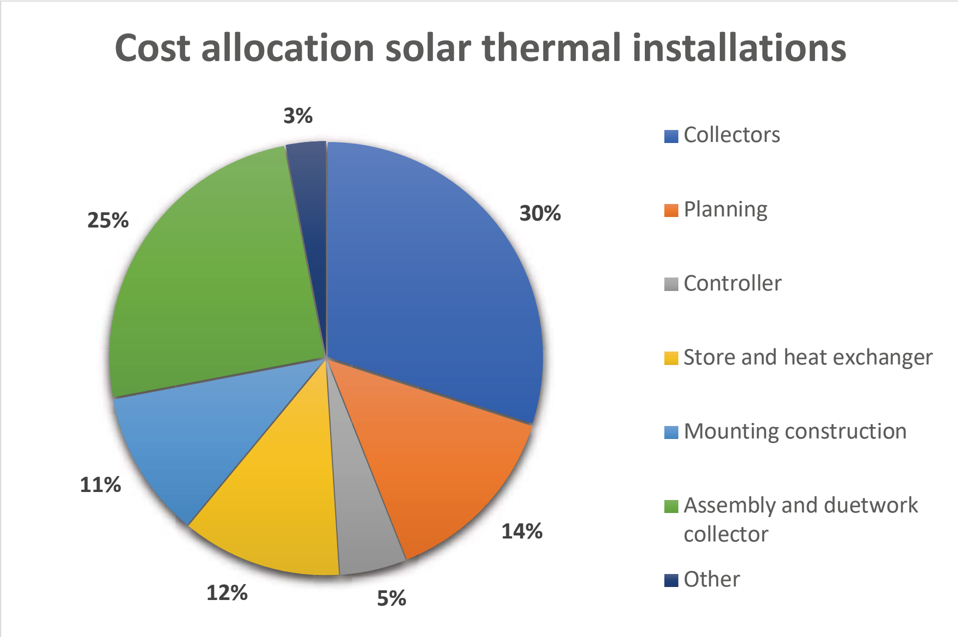

Figure 2.12 Cost allocation for solar thermal innstallations in the Solarthermie 2000 programme (Eicker, 2003)

The solar water heating system itself with collectors, storage and heat exchanger accounts for 42 % of the total installment cost, while the remaining 58 % is planning, mounting and installation of the system. The cost allocation for evacuated tube collectors are slightly different due to a higher installment and mounting cost.

2.12.2 Investment cost (C_i)

The total investment cost (Ci) of the solar water heating system can therefore be calculated from the cost allocation distribution if some components are known. In this analysis, cost data from the distributor Davis & Shirtliff Ltd is obtained for the collector and hot water storage tank and are shown in Table 2.4

Table 2.4 Cost data for collector and water storage tank obtained from Davis & Shirtliff Ltd the 19th of February 2019

	Price collector and water storage tank UGX
300L Flat plate collector	6 500 000
200L Flat plate collector	4 500 000
200L Evacuated tube collector	3 323 387

2.12.3 Operation and maintenance cost

Operation and maintenance (O&M) cost of a solar water heating system are estimated to be 0,5-2% of the investment cost per year. The cost depend on the system type and design, as a flat plate collector typically has 1% O&M cost per year while an evacuated tube collector has 2% O&M cost per year (Walker, 2016).

2.12.4 Savings from wood reduction

The total amount of money spent on firewood for cooking and heating of water at Nyenga is found to be 2,64 million UGX (or about NOK 6 000) per year. To calculate the savings associated with firewood reduction, the amount of firewood used for heating the water has to be estimated. This is done by using Equation 2.9 to calculate the energy needed to heat the water using firewood, and calculate the energy needed to heat the water using SWHS. The specific energy of the wood is then used to find the mass of the firewood that is used for heating the water. The parameters used for calculating the amount wood saved are presented in Table 2.5.

Table 2.5 Parameters for calculating savings from wood reduction

Parameters	Value
Price of wood per year (UGX)	2 643 333
Amount of firewood (kg/year)	36 000*
Specific energy (kWh/kg)	5,8
Efficiency cooking stove	0,15
Energy from wood (kWh/year)	31 320
Price per kg firewood (UGX/kg)	73,43
Price per kWh (UGX/kWh)	84,40

*150 kg per day, multiplied with how many days a year the kitchen is open, assumed to be 240.

2.12.5 Net present value (NPV)

The net present value method is a profitability analysis used to determine whether an investment is profitable or not. This is done by discounting future cash flows to the present value. In a situation where the NPV is positive, the project is considered profitable; otherwise, the project is not profitable. The NPV is calculated using Equation 2.12 as given below.

$$NPV = -C_i + \sum_{t=1}^{n} \frac{C_F}{(1+r)^t} \tag{2.12}$$

Where C_i is the investment cost, C_F is the net cash flow, r is the discount rate and t is the time of the cash flow. Net cash flow consists of the project´s inflow and outflow. In this analysis, the outflow contains the operation and maintenance cost while inflow is the savings from less wood consumption.

2.12.6 Discount rate

The discount rate is a risk-adjusted return requirement that is used to calculate the present value of future cash flows. This rate represents the minimum acceptable real return on the investment that is made (Shaw et al., 2013). In this study, a 10% discount rate was used based on current rates from the Bank of Uganda (TradingEconomics, 2019).

2.12.7 Simple payback period (SPP)

The simple payback period is a method to compare alternative investments. The method calculates the number of years that is needed to recover the project cost of an investment. A disadvantage with SPP is that it does not take into consideration the time value of money (Şerban et al., 2016).

$$SPP = \frac{C_i}{Annual\ income/savings} \tag{2.13}$$

Annual income for the SWHS is the amount of money saved each year due to less expenses of buying firewood.

2.13 Multi-Criteria Decision Analysis

In order to evaluate which of the SWHS configurations is the best option for Nyenga Foundation, a multi-criteria decision analysis (MCDA) was applied. A MCDA is a decision-making tool used to discover and quantify considerations about several parameters in order to compare alternative options (Huang et al., 2011). Each parameter is weighted from 1-5 where 1 is the least important and 5 is the most important according to the project. The weighted numbers are multiplied with the grade of three options and summed up. The option with the best total score may be considered as the optimal solution for Nyenga Foundation.

The weighted values and the justifications for the values are shown in Table 2.6. The background for the justifications is based on experience and interviews gained during the fieldwork.

Table 2.6 Weighted values for the different parameters and their justifications

Parameters	Weighted value	Justifications/comments
Energy output	3	The energy output from the SWHS are essential to meet the hot water demand and therefore, it is given a weighted value of 3.
Solar Fraction	3	Solar fraction in itself is not a very important decision criteria, but in combination with other sources like biogas, this parameter will be weighted higher.
Reduction firewood	5	Nyengas' goal is to reduce the amount of firewood used for cooking. This parameter is therefore prioritized with the highest value.
Reduction CO_2	4	The reduction in CO_2 is related to the reduction in firewood and HSE. This parameter is important both for the employees and the local environment.
O&M	4	Ability to operate and maintain the SWHS locally at Nyenga is essential in order to be independent. In addition, it could create ownership for the locals and the weighted value is therefore set to 4.
Financial **- Investment cost** **- Payback period** **- Savings** **- Net present value**	2	There is no financial framework for the project at this time, but an investment is likely to be done within reasonable limits and the weighting is therefore set to 2.
Health Safety & Environment (HSE)	5	Health, safety and environment is valued as an important factor for the staff and children at Nyenga. To reduce the pollution, the burden on the employees by carrying heavy cans and the

		possibility to use hot water for cleaning the plates puts the weighted value to 5.
Future hot water demand	5	The population of Uganda is growing and so are the number of students and staff that are likely to attend the New Horizon Primary school. That means demand for food thus larger hot water demand could be increased. The parameter will therefore be weighted with the highest value of 5.

2.14 Selected SWHS

Based on the findings in field research, the amount of required hot water, the solar radiation at the project site and collector area, three alternative SWHS have been selected in order to be compared.

A direct solar water heating system with a storage tank of 200 liters and flat plate collectors (200L FPC). A direct solar water heating system with a storage tank of 300 liters and flat plate collectors (300L FPC). A direct solar water heating system with a storage tank of 200 liters and evacuated tube collectors (200L ETC). The product specifications are attached in Appendix A and B.

The current hot water demand at Nyenga is 200 liters per day, but with a plan of building a new kitchen and conference hall, the demand may increase. Therefore, one of the alternative SWHS has a storage tank of 300 liters When analyzing the three alternative SWHS they will be given a score from 1 to 3 where 3 is the best for each factor.

The efficiency of the SWHS is based on Figure 1.7 and a temperature difference of 50^{o}C. This results in an efficiency of 65% for the FPC and 70% for the ETC. Information about the life expectancy of the systems is obtained from the supplier to be about 20 years for the FPC and 10 years for the ETC.

3 Results

The results derived from the resource assessment and economic evaluation are presented in chapter 3.

3.1 Declination angle and optimal collector tilt angle

The optimal collector tilt angle varies every month and depends on the declination angle. Figure 3.1, which illustrates the average declination angle and optimal tilt angle, shows that the optimal tilt angle will vary from about 22° in January and December to -22° in June and July. Negative tilt angles indicate that the collector should be faced away from the equator, while positive angles signifies that the collector should be faced towards the equator. This applies to latitudes on the northern hemisphere.

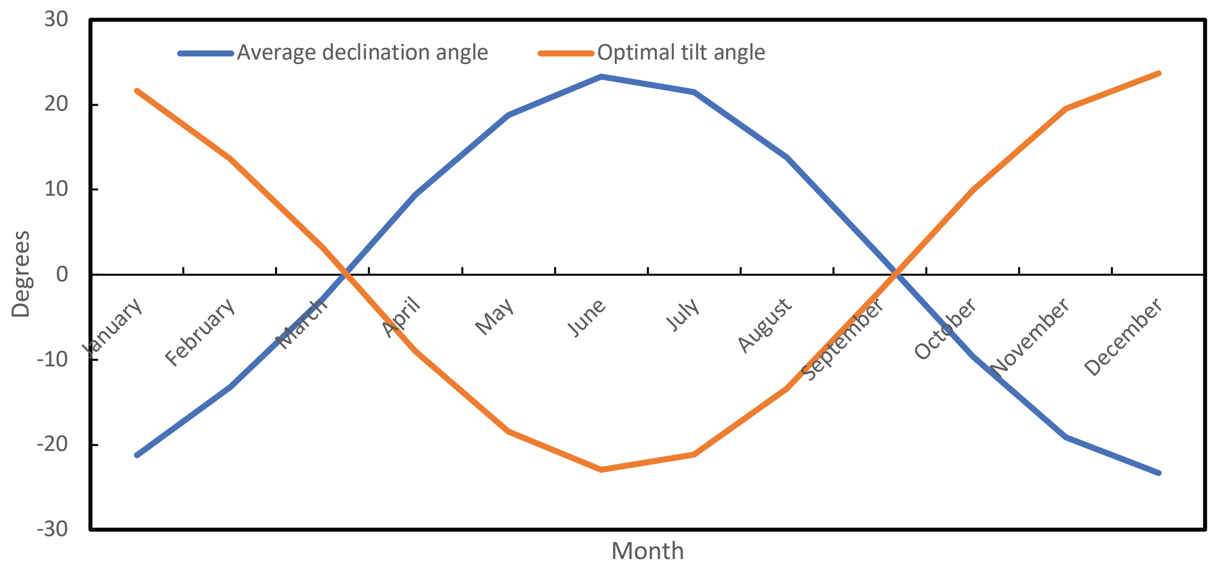

Figure 3.1 The average declination angle and optimal collector tilt angle for Nyenga Foundation

3.2 Solar radiation on inclined surface

The solar radiation on inclined surface also vary with different tilt angles during the year. In Figure 3.2, the average solar radiation per month is illustrated for collector's fixed tilt angles from 0° to 25°. It can be seen that, on a monthly basis, the difference in global solar radiation on the inclined solar collector among these tilt angles is not significant, however tilt angles of 10° and 15° received the most radiation in total during the year (see Table 3.1). Therefore, a fixed tilt angle of 15° is recommended for the solar collector in this location and other locations in Uganda.

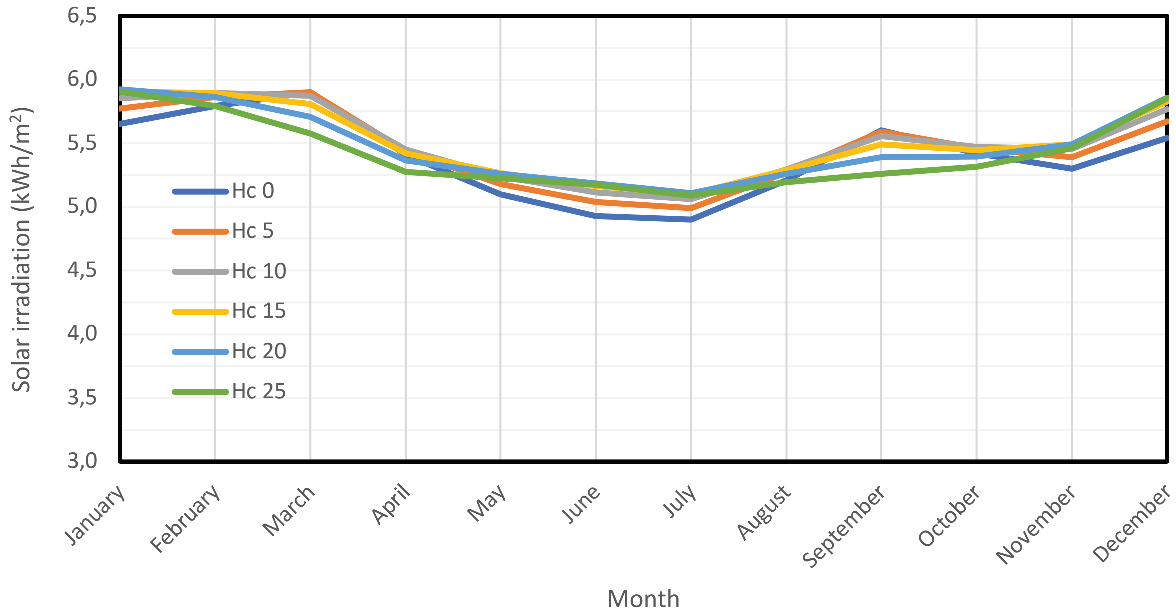

Figure 3.2 Monthly average solar radiation at Nyenga Foundation on inclined surface with angles from 0º to 25º.

Table 3.1 Annually solar radiation with variations of solar collector angles

Solar collector angle	Annual solar irradiation (kWh/m^2)
0	1969
5	1994
10	2008
15	**2010**
20	2001
25	1980

3.3 Sizing of solar collector – area

The solar collector area required to reach a specific water temperature is calculated using Equations 2.9 and 2.10 with results presented in Figure 3.3. The temperature indicates the maximum attainable temperature for each system. The markers on the figure illustrates the area of the selected SWHS and the related water temperature that can be obtained.

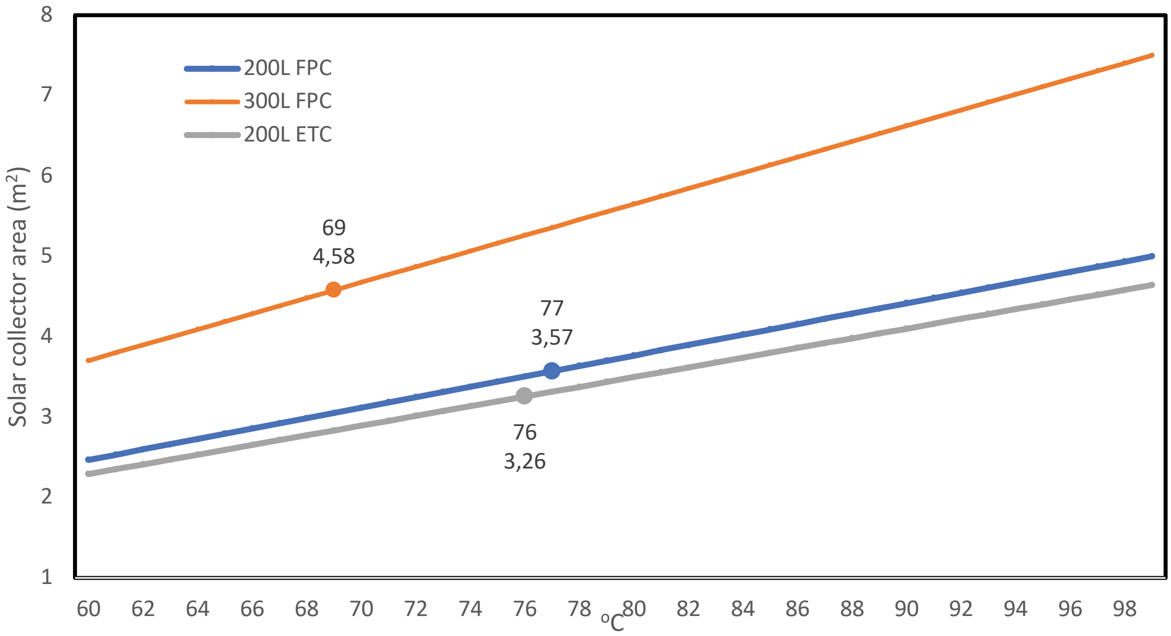

Figure 3.3 Collector area required to reach a given temperature with marks that indicated the size of the selected SWHS

3.4 Performance of selected solar water heating systems

In order to find out what the different type of SWHSs can provide of energy for the different tilt angles, the solar energy equation has been used. In Figure 3.4 the results are illustrated for the three alternatives. The 200L FPC is the one that provides the lowest amount of energy compared to the two others.

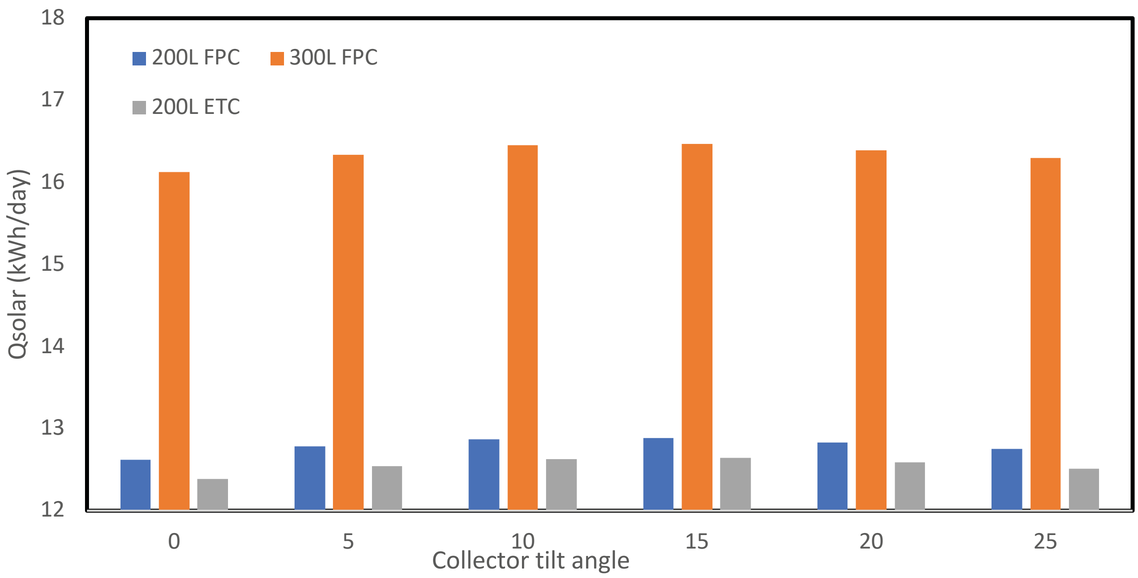

Figure 3.4 Daily energy from the three types of SWHS with collector tilt angles from 0 to 25 degrees

To be able to compare the systems more accurately, a normalized value, which is defined as daily thermal energy (in kWh/day) divided by capacity of the installation (in liters), was determined. The results are shown in Table 3.2, where 200L FPC has the best production of the three for all tilt angles with values from 0,0631 kWh/L to 0,0644 kWh/L. Furthermore, it can be seen in this Table that a tilt angle of 15 degrees generates the most energy, even though it is a marginal difference between 10 and 15 degrees. Hence, in the further calculations on the SWHS, a tilt angle of 15 degrees is used.

Table 3.2 Qsolar (kWh/day) normalized for capacity

Tilt angle	200L FPC (kWh/L)	300L FPC (kWh/L)	200L ETC (kWh/L)
0	0,0631	0,0538	0,0619
5	0,0639	0,0544	0,0627
10	0,0644	0,0548	0,0632
15	0,0644	0,0549	0,0632
20	0,0641	0,0546	0,0629
25	0,0638	0,0543	0,0626

As the energy output in Table 3.2 indicates, the grading of the alternative systems will be 3,1,2 respectively for 200L FPC, 300L FPC and 200L FPC.

3.5 Solar fraction

The solar fraction for the alternative SWHS are presented in Table 3.3 together with the energy delivered by the solar heating system and the energy delivered by firewood. From the results it is clear that the 200L FPC has the highest SF of 0,63 which indicates that 63% of the hot water demand at Nyenga can be met by this type of solar water heating system. This alternative will therefore be graded with a 3. The 200L ETC and 300L FPC have a solar fraction of respectively 0,62 and 0,54 and will have a grade of 2 and 1.

Tabell 3.3 Solar fraction for the three alternative SWHS

	200L FPC	300L FPC	200L ETC
Demand kWh/year	4912,8	7368	4912,8
Qsolar (kWh/year)	3093,6	3952,8	3036,0
Qother (kWh/year)	1819,2	3415,2	1876,8
SF	**0,63**	**0,54**	**0,62**

3.6 Reduction of firewood

Based on the information that was collected in the field research it is assumed that the kitchen uses around 150 kg of firewood every day to heat water and cook the food for the school and children´s home. To find the amount of energy that is needed to heat the water, the heat equation for water is used with both 200 L and 300 L.

The original amount of firewood and energy used to heat water from 22°C to 110°C are shown and compared in Table 3.3, with the energy needed and reduction in firewood per day after the SWHS are installed.

Table 3.3 Reduction in the amount of firewood after installing the SWHS

	200L FPC	300L FPC	200L ETC
Heat water from 22 to 110 degrees (kWh/day)	20,47	30,7	20,47
Amount of firewood (kg)	23,53	35,29	23,53
Water outlet temperature (°C)	77,41	69,20	76,37
Energy from wood (kWh/day)	7,58	14,23	7,82
Reduction firewood (kg/day)	14,82	18,93	14,54
Reduction firewood (%)	63 %	54 %	62 %

The alternatives 200L FPC, 300L FPC and 200L ETC will have the following grading in the MCDA: 3,1,2.

3.7 Reduction CO_2-emission

Results from section 3.6 show that there will be a reduction in use of firewood, which likewise will lead to a reduction in greenhouse gas emission such as CO_2. In combination with the emission factor of 1,45 kg CO_2 per kg wood and the amount of firewood saved, the reduction in CO_2 is presented in Table 3.4. The reduction in kg CO_2 per liter per year is presented in the last row, where the 200L FPC has the highest reduction of 25,78 kg CO_2/L/year and will get the grading 3. The 300L FPC and 200L ETC will get correspondingly 1 and 2.

Table 3.4 Reduction in CO2 emission related to installing three types of SWHS

	200 L FPC	300 L FPC	200 L ETC
Emission factor		1,45	
Emission CO2 today (kg CO2/day)	34,12	51,17	34,12
Reduction (kg CO2/day)	21	27	21
Reduction (kg CO2/year)	5156	6588	5060
Reduction (CO2/L/year)	25,78	21,96	25,30

3.8 Economic analysis

Investment cost, O&M costs, savings, payback period and NPV are used as economic indicators to analyze the project. Payback period and NPV are indicators that evaluate the project in total and describe two different performance aspects.

3.8.1 Investment cost

The investment costs of the three installments are presented in Figure 3.4 where the two alternatives 200L FPC and 200L EPC have almost the same investment cost with respectively 9,2 million UGX and 9,3 million UGX. The 300L FPC has the highest investment cost of 13,3 million UGX and will therefore be graded with 1 in the MCDA while the 200LFPC will be rated with a 3 and 200L ETC with a 2.

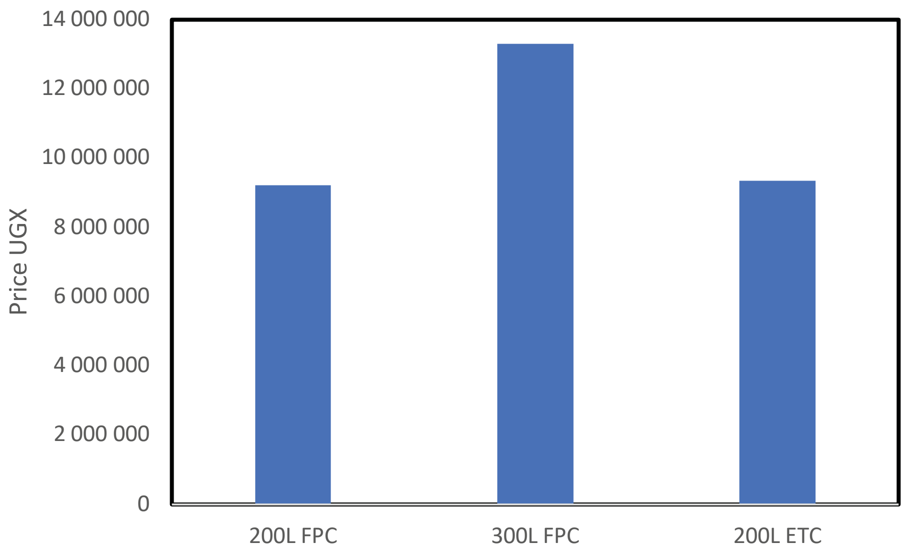

Figure 3.5 Investment cost of the SWHS

3.8.2 Operation and maintenance

The operation and maintenance cost for each of the systems are shown in Table 3.5. The 200L ETC has the greatest O&M cost and will be graded with a 1 in the MCDA. The 200L FPC and 300L FPC will respectively get a 3 and 2.

Table 3.5 O&M costs for the three alternative SWHS

	200L FPC	300L FPC	200L ETC
O&M (UGX/year)	92 143	133 095	186 941

3.8.3 Savings in wood expenses and NPV

The savings in wood expenses are not significant compared to the total amount of money spent on firewood which is 2,6 million UGX per year. By installing a solar water heating system at Nyenga foundation the firewood expenses can be reduced by 9,9%, 12,6% and 9,7% respectively for the 200L FPC, 300L FPC and 200L EPC. Figure 3.6 illustrates the savings in wood expenses by installing solar water heating systems both per year and per liter.

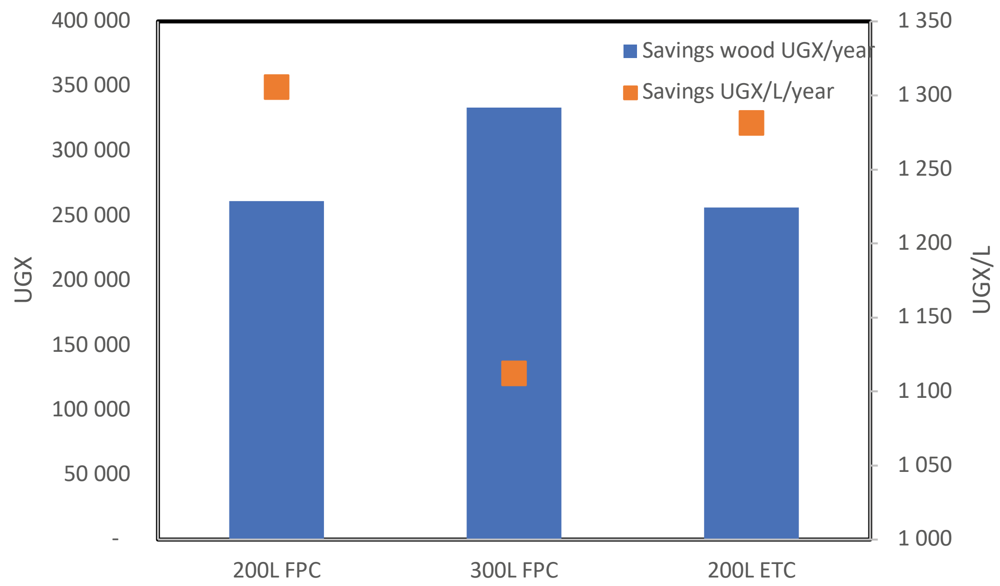

Figure 3.6 Savings in wood expenses for the three systems

The 200L FPC has the largest savings with 1305 UGX/liter/year and will be graded with a 3 in the MCDA while the 300L FPC will get 1 and 200L ETC will get a 2.

The NPV is shown in Table 3.6 and is negative for all of the alternatives which means that the installation of the SWHS is not a profitable investment economically. The alternatives will therefore be rated with the lowest value of 1.

Table 3.6 Net present value of the SWHS

	200L FPC	300L FPC	200L ETC
NPV	- 7 432 575	- 11 180 635	- 8 446 713

3.8.4 Payback period

Figure 3.7 depicts the payback period for the three types of solar water heating systems. The system with FPC and 200 liters capacity has the lowest payback period of 35 years. The 200L ETC has a payback period of 36 years while the 300L FPC has a payback period of 40 years. Since all of the systems have a longer payback period than the lifetime, they will all be graded with 1 in the MCDA.

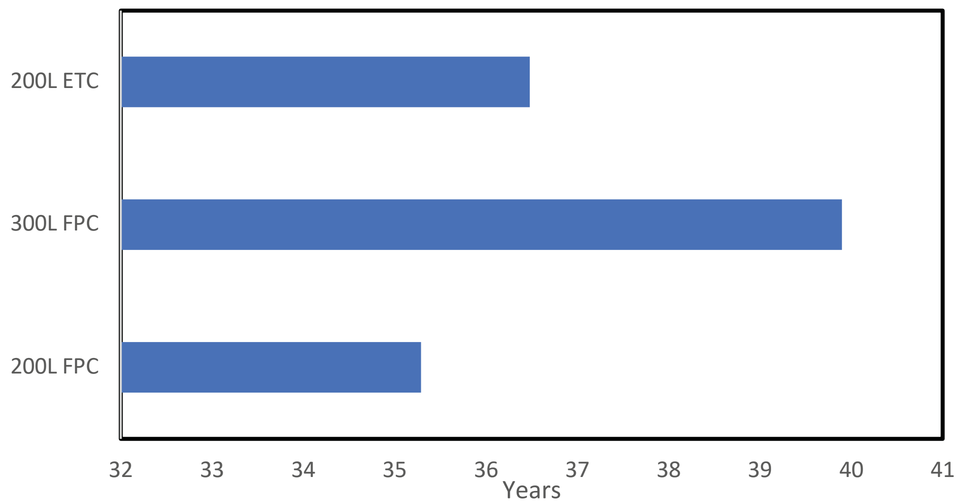

Figure 3.7 Payback period for the three SWHS

3.9 Health, Safety and Environment (HSE)

The solar water heating system is an installment with no rotating or loose parts that can cause damage. Although, injury due to heat and possible hot water leakage from the system can occur. The whole system is proposed to be placed on a roof top which is not accessible to people. Installation and service is to be done by professionals trained to do the work. The water may have a temperature up to 77ºC and has the potential of causing injury. In case of a major leakage from the system, the water will flow down the roof and enter the gutter and will be cooled down quickly. The grade for the two flat plate collectors will both be 3, and 2 for the evacuated tube collector due to the risk of broken vacuum tubes that can be harmful.

3.10 Future hot water demand

In case the hot water demand will rise in the near future due to population growth and greater living standard, there is only one of the alternative SWHS that will fulfill this parameter: 300L FPC. Thus, is this alternative graded with 3 whereas the two other alternatives, 200L FPC and 200L ETC are graded with 1.

3.11 MCDA summary

Table 3.7 presents a summary of the MCDA and the final score for the three alternative SWHS.

Table 3.7 Summary of the Multiple Criteria Decision Analysis for the three SWHS

	Weighted values	Alternatives		
		200L FPC	300L FPC	200L ETC
Energy output	3	3	1	2
Solar Fraction	3	3	1	2
Reduction firewood	5	3	1	2
Reduction CO2	4	3	1	2
Investment cost	2	2	3	1
O&M	4	3	2	1
Savings	2	3	1	2
NPV	2	1	1	1
SPP	2	1	1	1
HSE	5	2	2	2
Future demand	5	1	3	1
Total sum		**86**	**60**	**59**

4 Discussion

4.1 Resource assessment

The optimal collector tilt angle throughout the year was found to be 15 degrees towards south. Yakup and Malik (2001) suggest that the fixed optimal tilt angle should be equal to the latitude of the project site. The latitude of Nyenga Foundation is approximately zero (0,359°N) which corresponds with the placement of the Equator. After considering the resource assessment of solar radiation for several tilt angles it was clear that a tilt angle of 0,350° (almost horizontal) is not a good option. Furthermore, with horizontal collectors there will be no self-cleaning possibilities, which has a great effect on the performance of the SWHS because of possible accumulation of dirt.

Once the tilt angle was set to 15 degrees, the energy output for the SWHS were calculated and compared. The 200L ETC was the best SWHS in terms of output/L, while the 300L FPC was the best system when considering the total energy output. The solar fraction of the three systems were found to be best for the 200L ETC of 86%. This is due to the evacuated tube collectors being able to obtain a higher temperature. Because of this, the use of firewood could be reduced.

With the sun being an intermittent energy source, the Nyenga Foundation could potentially be without hot water for long periods. Therefore, a reserve of firewood would be necessary, which can be used as a substitute SWHS during persistent cloudy days. According to Shah (2018), the evacuated tube collector can also obtain solar heat during cloudy days. This makes the ETC more favorable compared to the flat plate collectors which lack that ability. Although the performance on cloudy days could be different, the clearness index indicates that the location is in a region with few overcast days.

Compared to the total amount of firewood of 150 kg/day used by the kitchen to heat water and cook food, it is not a substantial reduction by installing a SWHS. Although, the amount of firewood used for heating 200 liters of water is 23,53 kg and a reduction of 16,61 kg which constitutes with a reduction of almost 71%. This could potentially contribute to reducing deforestation if the system is adopted on a large scale.

The reduction in firewood has some uncertainties due to lack of information from the fieldwork. This is connected to the species and specific value used in the calculations which are based on (Tabuti et al., 2003), (Marsoem & Irawati, 2016), (Chakradhari & Patel, 2016) (Ogunsola et al.,

2018) studies and these may not apply for the project site at Nyenga Foundation. Furthermore, the quality of the firewood could have an impact on the amount of reduced wood which is not taken into considerations in the calculations. An alternative to reduce the use of firewood further, is upgrading to a more efficient cookstove. The current cookstove has an estimated efficiency of 15%, one of the reasons why it is low is that the firewood is burnt in long piles of wood still being outside the stove when combusting. Given the proposed upgrade of the kitchen, it would be advisable to upgrade it to improve cooking.

There is a close relationship between the reduced CO_2 emissions and the reduction in firewood. Regarding the reduction in CO_2 emissions, there is likely to be some uncertainties due to the assumptions made previously. In addition to the uncertainty considering wood species, CO_2 emissions from the manufacturing process are not within the scope of this analysis. To obtain a realistic view of how much reduction in CO_2 emissions there will be by installing a SWHS, it is necessary to account for the whole life cycle of the system. The SWHS will most likely not be produced in Uganda. The emissions from the production will therefore be emitted in another location. Nevertheless, the effect of GHG emissions is not only a regional problem, but a global one, because climate change is affecting the whole planet. Hence, a small reduction in CO_2 from Nyenga Foundation would contribute to fight against climate change.

4.2 Economic analysis

The economic analysis indicates that the installation of SWHS will not be viable for any of the systems that are compared. Table 4.1 presents a summary of the economic aspects. The foundation for the investment costs are based on Eicker (2003). This is done due to lack of comparable costs found in African countries. The cost allocation found in Germany is likely to be different from the one found in Uganda. Therefore, it is possible that there would be some uncertainties connected to this assumption. The discount rate of the project is set to 10%.
To analyze the possible effects of variation on the discount rate, a sensitivity analysis could be performed. However, in the project for the Nyenga Foundation the economic feasibility is not critical for the investment decision. This is because it is already decided to implement a SWHS, but within reasonable costs.

Table 4.1 Summary of the economical evaluation

	200L FPC	300L FPC	200L ETC
Savings in wood expenses (UGX)	261 092	333 607	256 231
Lifetime of installment (years)	20	20	10
Net present value (UGX)	- 7 432 575	- 11 180 635	- 8 446 713
Payback period (years)	35	40	36

Installation of solar water heating systems will generate positive effects which are hard to define in monetary value. For example, the system could be used as an education tool for the children at the primary school. This will enable them to learn about renewable energy and experience how it works. The effects of experiencing new technologies could be inspiring, and it would also make the education more practical.

The same uncertainty as the investment cost, also applies for the O&M which is estimated to be 92 143 UGX/year, 133 000 UGX/year and 187 000 UGX/year respectively for the 200L FPC, 300L FPC and 200L ETC. The costs are based on Walker (2016) that estimates an O&M cost of 1% of the investment cost yearly for the FPC and 2% of the investment cost yearly for the ETC. The O&M estimates are based on SWH installments from the United States. Therefore, it could be some uncertainties in the comparison of Uganda and the US. Furthermore, during the dry season (February, March and August, September), the collector's efficiency could be reduced due to the dust developed form nearby roads. To obtain an optimal performance, the work of cleaning the collectors could results in higher O&M costs.

4.3 Health, Safety and Environment

Health, Safety and Environment are important aspects when designing and installing a SWHS. Especially since there will be children involved around the kitchen area. When the SWHS will be installed, it will cause positive repercussions for both the staff at the kitchen and the local community. The SWHS will eliminate the need of carrying water every evening. The reduced workload on the staff will give them more time to prepare nutritious food. The system will also reduce harmful gases in the kitchen, and the hygienic effects of washing dishes in hot water would be substantial. In addition to installing a SWHS it is planned to invest in a biogas digester. With a combination of SWHS and biogas, it may be possible to eliminate using firewood in the kitchen. Which will reduce the firewood expenses and reduce the GHG emissions. The kitchen at the primary school is not open during the weekends and there is therefore a risk of the water being stagnant for several days. This could lead to the development of legionella bacteria. The installment of a SWHS will heat the water beyond 60 degrees, therefore reducing the risk of legionella to develop. Nevertheless, it is recommended to test the water for legionella when there has been no or little circulation in the system to ensure that it's safe to use.

4.4 MCDA

The result from the multicriteria decision analysis indicates that the 200L FPC is the optimal SWHS for Nyenga Foundation with a score of 86 compared to 60 and 59 for the 300L FPC and 200L ETC respectively. The 200L FPC scored best due to its capacity of 200 liters and collector area of 3,6 m^2. The 200L ETC would have a significant higher score if the collector area was the same as the 200L FPC due to higher efficiency, but this was not provided by the SWH market in Uganda. Disadvantages of the 200L ETC is that it has a lower life expectancy than the flat plate collectors, has a higher O&M cost and the vacuum tubes are fragile and may break during operation of the system. Moreover, the 200L ETC will have the same problem as the 200L FPC if the water demand rises. If the children should be able to clean dishes in hot water, there will not be sufficient water for that purpose. A solution can be to install the 200L FPC, and after a year, when the demand for hot water is rising, another 200L FPC can be installed. On the other hand, with 400 liters capacity, large amount of hot water could be left unused. This can increase the possibility of legionella and other bacteria to develop.

Even though the 200L FPC had the highest score in the MCDA, the 300L FPC would be a better solution if children and staff are able to clean plates in hot water. With a capacity of 300 liters is it possible that the future hot water demand will be fulfilled. The FPC will have a lower O&M cost; and, hence, it will be easier for the staff to operate than the ETC which is an important factor so as to create ownership of the system.

5 Conclusion and further work

The aim of this study was to design and select an optimal Solar Water Heating System (SWHS) for a Learning Centre (LC) in rural Uganda so as to reduce the amount of firewood and make a better work environment for the employees.

Information about the hot water load and available SWHSs are based on a field research conducted at Nyenga Foundation. A resource assessment of the project site has been done together with an economical evaluation. Equations from Chapter 2 has been used in combination with a Multiple-Criteria Decision Analysis to find and select the optimal SWHS. It was found that the optimal tilt angle and orientation is 15 degrees towards South. Three different SWHSs has been compared to find the optimal solution. After considering the future hot water demand and the possibility of cleaning plates in hot water, a SWHS with flat plate collectors and storage capacity of 300 liters is the recommended solution for Nyenga Foundation. This system will contribute to a reduction in firewood use and a reduction in CO_2 emissions by 58%. Furthermore, the SWHS will be able to obtain a temperature of 69 degrees, which eliminates the risk of legionella bacteria.

In spite of the promising environmental effects of these systems, the SWHS were found to be not economically viable. However, the societal and environmental factors such as healthy work environment and green energy footprint, has a greater advantage compared to the economic perspective. Therefore has this been weighted higher when selecting the SWHS, By installing a SWHS, Nyenga Foundation can be a pioneer for the community to promote clean and sustainable energy.

5.1 Suggestions for further work

Based on the experience and limitations in the scope of this analysis, some recommendations for further work are suggested:

- Simulation program such as TRNSYS and T*SOL can be used to compare and verify the results.
- The impact of a combination of a SWHS and a biogas digester on potential reduction or elimination of firewood as cooking fuel in this facility should be examined. It should be noted that biogas can also be used as energy for lighting.

- Carry out life cycle assessment of the SWHS in order to get a realistic reduction in GHG emissions and other environmental and social benefits.

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Appendices

Appendix A: Product specification for the 200L FPC and 300LFPC

DAYLIFF

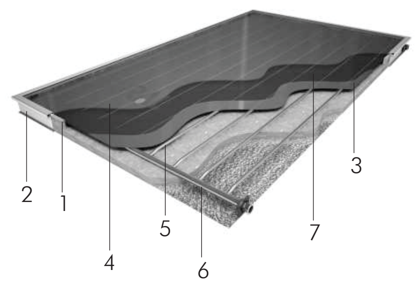
DATA SHEET | **Solar Water Heaters** | **Ultrasun Premium**

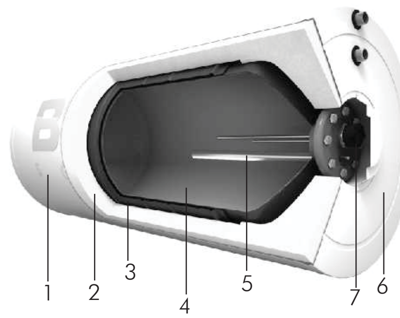
Ultrasun Premium hot water systems are high specification thermosyphon type hot water heaters designed for long life operation in extreme conditions. Options are available for Open Loop(AD) and Closed Loop(KD) systems, Open Loop heating the water directly through the collector and Closed Loop separating the collector flow water from the process water, heat being transferred through the tank jacket. This is suitable for mineralised and brackish water that may corrode or scale the collector's capillaries. Features include:-

- Heavy duty tank which includes a steel powder coated outside casing, steel storage tank internally coated with glazed enamel and fitted with a magnesium sacrificial anode for exceptional corrosion protection, UV resistant plastic end caps and a 2kW heating element with thermostat.
- Solar collectors that incorporate full area copper absorption plates ultrasonically welded to copper circulation tubes, high specification insulation and tempered security glass to provide energy absorption of up to 95%.
- Low thermal conductivity high specification flexible stainless steel circulation piping with silver foil coated polystyrene insulation jackets.
- Connection piping that includes an incoming non-return valve, pressure release valve rated at 8bar and drain cock. An extra 3bar pressure release valve is provided for the closed loop tank.
- Galvanised mounting frame for both flat or inclined roof installations that ensures high durability in all weather conditions

Ultrasun Premium solar systems are available in various tank sizes and collector configurations to suit domestic and small-scale installation applications. They are efficient and robust products guaranteed for five years to demonstrate the high material speciation. Designed for many years of trouble free operations, they are the ideal solution for all water heating applications.

DESIGN FEATURES



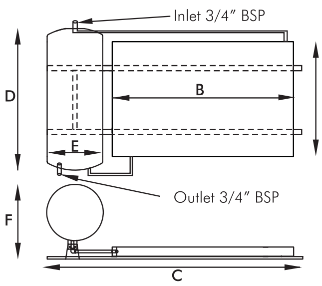


1. UV resistant 100% EPDM sealing and gaskets
2. Extruded pure aluminium frame with electrostatic powder coating finish
3. Aluminium foil faced, direct-injected monoblock polyurethane insulation
4. Tempered solar glass with high solar transmittance
5. Copper riser tubes
6. Copper manifold tubes
7. Full plate sputtering selective coated copper absorber, ultrasonically welded

1. Steel outside casing coated by electrostatic powder coating baked at 220^{0}C to protect the tank from outdoor conditions and UV rays
2. Direct-injected, CFC-free polyurethane foam Insulation in 50mm thickness
3. Heat exchanger jacket
4. Enameled low-carbon steel hot water tank
5. Magnesium anode bar cathode protector
6. UV resistant plastic cap
7. 2Kw electric heater

SPECIFICATIONS

Model		AD/KD150		AD/KD200		AD/KD300	
System Tank Size (Litres)		150		200		300	
Typical Household (People)		5		7		10	
Collector Model		1x ST230		2 x ST180		2 x ST230	
Collector Area (m^2)		2.3		3.6		4.6	
Collector Weight (kg)		41		66		82	
Collector Fluid Capacity (litres)		1.5		1.8		3.0	
Max Heat Output/Day (kWhrs)		12		20		24	
Min Heat Output/Day (kWhrs)		8		13		16	
Dimensions (mm)	A	1175		1970		2590	
	B	1960					
	C	2760					
	D	1000		1200		1750	
	E	600					
	F	700					
Empty Weight (kg)		73	76	82	86	115	121
Full Weight (kg)		223	226	282	286	415	421



NOTE

Maximum heating output is based on average irradiation levels of 6000W/m^2/day prevailing in September- March and minimum Heating output is based on average irradiation levels of 4000W/m^2/day prevailing in June/July and are for indicative purposes only.

DS355A-09/16

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Appendix B: Product specifications 200L ETC

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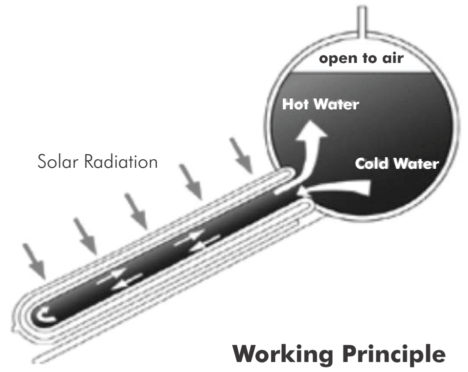
DATA SHEET | **VacTube Solar Water Heaters** | **Ultrasun UVT**



Working Principle

Ultrasun UVT VacTube Vacuum Tube solar hot water systems are the most efficient water heating systems available. Solar energy is captured in the vacuum sealed glass void heating the water in the glass tube. The heated water rises to the top of the pipe and collects in the tank. The large surface area of the vacuum tube and high water turbulence within the internal chamber provide rapid transfer of heat to the water flowing through the tank. The sealed evacuated tubes and tri-oxide coating provide maximum solar gain even in the coldest areas and during cloudy or overcast days. System features include;

- Individual high efficiency concentric tube and glass heating elements
- Storage tank comprising a stainless steel inner cylinder, plastic painted insulated galvanised external casing and 1.5kW heating element
- Separate 8L cold water header tank
- Anodised aluminum frame
- Flat roof mounting kit
- Supplied with 4 extra glass tubes

Due to the limited pressure capacity of vacuum tubes supply must be via the included header tank and systems must not be connected directly to the main supply.

SPECIFICATIONS
Capacity: Hot water 200litres, Cold water 8litres
Vacuum tubes: 20pieces
Absorber Area: 3.28m^2

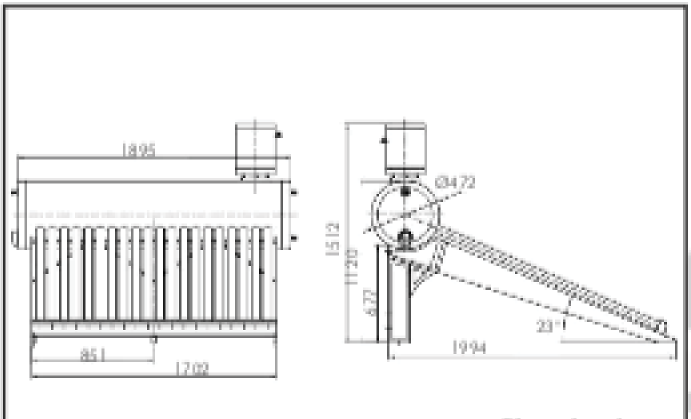
OPERATING CONDITIONS

Water Quality: Water outside the following limits should be appropriately pre-treated, clarity: clear, TDS < 600mg/l, Hardness < 200mg/l $CaCo_3$

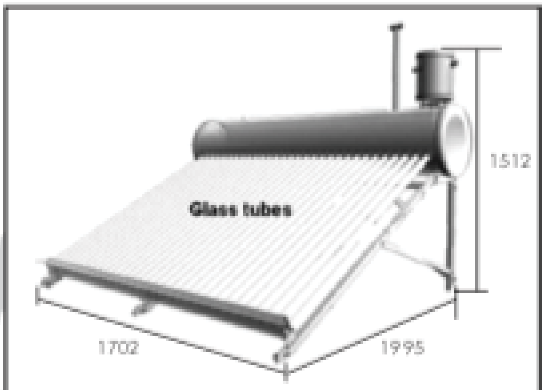
Maximum Operating Temperature: 200°C

Maximum Operating Pressure: 0.1 Bar

DESIGN FEATURES



Dimensions in mm



Empty Weight: 115Kg
Full Weight: 315kg

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