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Thermal Solar Energy: Comparison between direct and indirect systems

Master's thesis in Industrial Engineering
Supervisor: Ole Jørgen Nydal
June 2020

Master's thesis

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Abstract

World energy consumption grows day by day, and so does the environmental concern. Consequently, the use of renewable energies, such as solar energy, is very important to meet the energy demand without damaging the planet. Mostly, it is in developing countries where more solid fuels are used to satisfy the demand for hot water and energy for cooking. Consequently, many people face the harmful effects of the pollutants that these fuels emit in the combustion.

With the aim of solving these problems, this thesis analyzes direct and indirect solar technologies. Most of the study focuses on analyzing and comparing the response and feasibility of three technologies for obtaining hot water. These technologies are a solar thermal system, a PV system, and a PV system with battery support. The analysis begins with the data collected in a project carried out between the University of Stellenbosch (South Africa) and the Institute for Sustainable Technologies of Austria. The financial analysis gives a result of 6, 15, and 10 years of payback for the three cases, respectively. Adding the battery to the PV system, apart from considerably decreasing the payback, makes the LCOH value drop from 0.155 $/kWh to 0.085$/kWh. While in the case of the direct system, the LCOH value remains the lowest, with a value of 0.043$/kWh.

Although the addition of the battery improves the results of the PV system, when it comes to low temperatures, the direct system continues giving better results.

Acknowledgement

First of all, I would like to express my sincere gratitude to my supervisor, Ole Jørgen Nydal, for giving me the opportunity to research and analyze in this area and for the guidance that he has provided during the process of this thesis.

Additionally, I would also like to thank my fellow students for sharing their work and progress during this semester.

Udane Astobitza Eguren

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Nomenclature

Abbreviations

AC	Alternating Current
DC	Direct Current
DoD	Depth of Discharge
FF	Fill Factor
IRR	Internal Rate of Return
LCOE	Levelized Cost Of Energy
LCOH	Levelized Cost Of Heat
NPV	Net Present Value
PV	Photovoltaic
SHC	Solar Heating and Cooling
STC	Standard Test Conditions
SWH	Solar Water Heater
TVM	Time Value of Money

Greek symbols

η	Solar system efficiency	[-]

Latin symbols

A_c	Solar collector area	[m^2]
A_t	Tank area	[m^2]
C_0	Total initial investment cost	[$]
C_t	Net cash inflow during the period t	[$]
E	Solar irradiance	[W/m^2]
i	Discount rate	[-]
I_{SC}	Short circuit current	[A]
P_m	Maximum power generated by the solar collector	[W]

Q_{loss}	Heat loss	[J]
R	Thermal resistance of the tank insulation	[$m^2 \cdot °C/J$]
R_t	Net cash inflows-outflows during a single period t	[$]
T_{in}	Temperature inside the tank	[°C]
T_{out}	Exterior temperature	[°C]
V_{OC}	Open circuit voltage	[V]

1. Introduction

Due to the impact that conventional energy sources have on the environment, more and more renewable energy sources have been used in the last decades. In 2018, almost 11% of the energy consumed worldwide came from a renewable source [1]. Although it may seem a small percentage, the increase in energy consumption in developing countries must be considered, since in these places the vast majority comes from non-renewable sources. Even so, in the last decade, the consumption of renewable energy has grown by 450% [1]. This percentage shows the good path that the renewable energy sector is taking.

Apart from the help they offer to the environment, some of the renewable energy resources have been of great help to supply isolated areas with energy. Among them, we can find solar energy or geothermal energy.

As for solar energy, there are several types of technologies. But the most used are photovoltaic (PV); solar thermal or solar heating and cooling (SHC); and concentrating solar power (CSP). Although SHC technology has been a leader for a long time, in recent years, PV technology has come to be in the first place [2].

The sun is an important and powerful source of energy. But both the generation of electrical and thermal energy depends on environmental conditions. While direct radiation predominates on sunny days, diffuse radiation is the main one on cloudy days. This means that on cloudy days the total radiation is less than in sunny days. And this must be taken into account when designing a solar system.

1.1. Background

This thesis has as its starting point the project carried out between the University of Stellenbosch (South Africa) and the Institute for Sustainable Technologies of Austria [3]. In this project, they carry out the comparison between Photovoltaic and Solar Thermal Hot Water Systems in the South African context. Based on the data collected at their facilities, a more specific analysis is carried out in this project.

2.2. Objective

The goal of this thesis is to analyze and compare solar direct and indirect technologies when it comes to obtaining energy. The main objective is to deeply analyze direct solar systems, that work with low temperatures, with indirect systems (PV systems). And starting from this first analysis, achieve results that can lead to conclusions for direct systems that work at medium temperatures, such as solar cookers. Also, to demonstrate if indirect technologies such as photovoltaics can be competitive in this area.

2.4. Motivation

According to the World Health Organization, more than three billion people depend on solid fuels to satisfy their cooking and heating needs [4]. The combustion of this type of fuel generates many pollutants. According to the same organization, these pollutants have negative effects on people's health. This problem more specifically affects women and children living in developing counties such as Africa, Latin America, and South Asia. In these mentioned countries, it is the woman who spends several hours cooking every day. In turn, they are usually in charge of childcare. Consequently, both women and children suffer the negative consequences of cooking with solid fuels.

On the other hand, from an environmental point of view, renewable energies are very interesting. According to the International Energy Agency, CO2 equivalent emissions in developing countries have increased from 9.2Gt to 22Gt in the last 30 years [5]. For this reason, any alternative to traditional solid fuels will help to stop the rise.

Therefore, it is extremely important to find technologies that respect the environment. And that at the same time, does not negatively affect the health of its users. Besides, the use of technologies that are less dependent on solid fuels provides users with independence. As a result, these types of alternative energy sources are also an excellent choice in hard-to-reach or isolated locations.

Among these technologies, those that have solar energy as their source are one of the most attractive ones. Since these technologies can be completely self-sufficient and have no dependence on any other type of fuel. But, within solar energy, there are different technologies, and it is important to know which can be the most efficient both energy and economically.

2.5. Report structure

This report is divided into seven chapters, including the introduction. Since solar energy is the basis of this study, the second chapter makes an introduction to this area. Starting from how the sun emits energy to the different ways of taking advantage of that energy. The third chapter focuses on solar cookers. Offering a bit of background and knowledge of technologies. The fourth chapter offers a theoretical background on financial analysis, which will later be used to compare different technologies. In the fifth chapter, first, three technologies are analyzed and compared to satisfy the needs of hot water. And then, based on the results obtained, some references are also made to comparing medium temperature solar thermal technologies with PV technology. Chapter six gives a conclusion of the work done. And finally, chapter seven gives some recommendations of further work.

2. Solar Energy

2.1. Introduction

In this chapter, the concept of solar energy is presented, which is the main base of this study. To begin with the chapter, the sun will be introduced as a resource. In turn, the different ways in which this valuable energy reaches the earth will be exposed. In the second part of the chapter, the different ways that the human being has developed to take advantage of this energy will be explained.

2.2. Solar resource

To start, the terms *solar resource* and *solar energy* must be differentiated. Specifically, the term solar resource refers to all the radiation that reaches the earth as electromagnetic energy, and that is used by the human being in different ways. Whereas the term solar energy refers to the energy that reaches the earth, whether it is used by humans or not [6].

The sun is the star in the center of the solar system that has a black body temperature of 5777 K [7]. And is mainly composed of hydrogen (74.9%) and helium (23.8%), in turn, is made up of different layers. In the center it has the core, where high temperatures and pressures give rise to nuclear fusion reactions [8]. In these reactions, energy is released as electromagnetic energy, which is received by the earth as solar irradiance. Furthermore, if the solar irradiance is integrated over a given certain time, the solar irradiation is obtained, which refers to the energy received from the sun per unit area (kWh/m2).

Due to the high energy consumption of this time and the negative effect that traditional energy sources have on the planet, the sun is an exceptional source to deal with all this. During the last decades, numerous technologies have been developed to take advantage of this energy emitted by the sun. All these technologies can be divided into two large groups. On the one hand, the thermal conversion technologies and on the other hand the electrical conversion technologies.

2.2.1. Solar irradiation

From the sun to the earth, the radiant energy goes through different transformations. Once it reaches the outside of the atmosphere, it continues its way to the surface of the earth. But on this path, both absorption and dispersion take place. As a result of the scattering, not all radiation reaches the earth's surface as direct radiation, but also as diffuse radiation. And the sum of the two makes the global radiation, which in turn, part of this one is reflected [9].

Depending on the geographical location, the percentage of each of the components of the radiation will vary. In places where the weather is mostly cloudy, direct radiation will be very rare. On the other hand, in sunny places, most of the radiation will be direct, and therefore more useful for different uses.

2.2.1.1. Direct radiation

Direct radiation is the part of the solar radiation that reaches the earth's surface directly [10]. This type of radiation is the main one in sunny days. And it is the most useful and advantageous of all when it comes to generating energy.

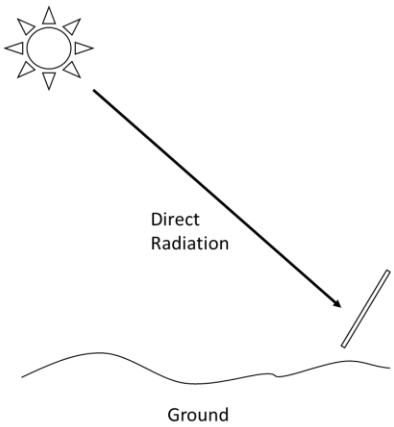

Figure 2.1 Direct radiation

2.2.1.2. Diffuse radiation

As it passes through the atmosphere, another part of the radiation that comes from the sun is absorbed, reflected, or dispersed by water vapor, dust, or pollution. This type of radiation is called diffuse radiation. [11]

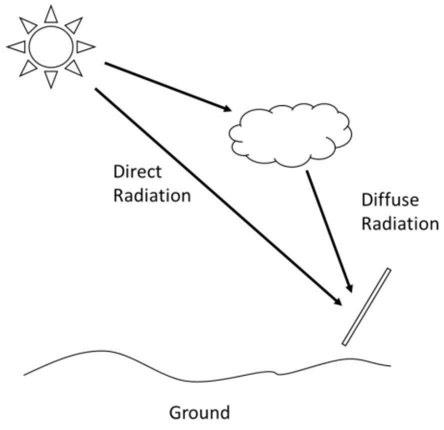

Figure 2.2 Direct and diffuse radiation

2.2.1.3. Reflected radiation

Lastly, the reflected radiation is that part of the radiation that is reflected by the earth's surface [12].

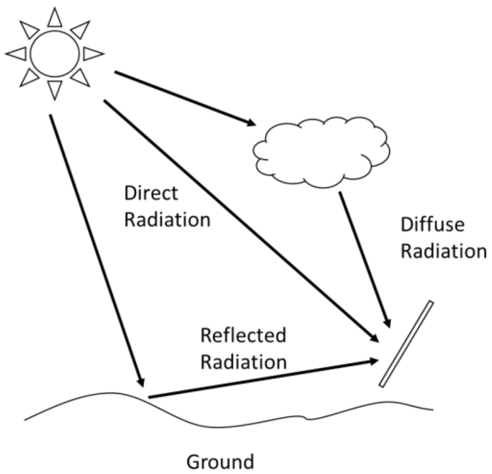

Figure 2.3 Direct, diffuse, and reflected radiation

2.3. Use of solar energy and conversion

It is known that solar energy is essential for life. For years, thermal solar energy has been used to satisfy different needs. Needs such as cooking, space heating, or water heating for domestic use. Having such a powerful source of energy, new technologies and techniques have been created to take advantage of it. According to the way of capturing, converting, and distributing solar energy, the technologies can be classified as active or passive.

Passive ways to harness this energy include, for example, the orientation of buildings and the type of material used in construction. In this way, these techniques can help keep the interior temperature of a building at a comfortable level. Both in warm and cold places. These techniques are part of the design of a house and their particularity is that they do not depend on mechanical systems.

On the other hand, regarding active techniques or technologies, photovoltaic panels (electrical conversion) or thermal solar collectors (thermal conversion) can be found. These types of systems are usually more complex than the previous ones. Even so, they are usually designed to get the most out of solar radiation.

Although passive technologies are very interesting, this project focuses on active technologies. The difference with passive technologies is that active technologies have devices that convert solar energy into heat or electricity [13]. In the next two sections, these two active ways of converting solar energy are explained more fully.

2.3.1. Thermal solar energy

When solar energy is used to produce heat, we talk about thermal solar energy. The main component of this type of technology is the collector and is responsible for collecting the energy that comes from the sun and starting with the transformation. In turn, these solar thermal energy collectors can be classified as low, medium, or high temperature collectors. And depending on the temperature range, they are usually used for different purposes.

2.3.1.1. Low temperature collectors

Low temperature collectors work at temperatures below 65ºC [14]. For this reason, they are used to heat swimming pool water, to heat domestic water, or in processes such as pasteurization.

This type of installation is one of the simplest and consists of the solar collector, a primary and a secondary circuit, a solar exchanger, an accumulator, an expansion vessel, and pipes. On the other hand, the most widely used solar collectors in this type of installation are usually flat panels, vacuum tube panels, and absorber collectors.

2.3.1.2. Medium temperature collectors

This type of collectors reaches temperatures between 100 and 300ºC [14]. Although collectors in this temperature range have great potential for harnessing solar energy, today it is difficult to find collectors that are cost-effective [15]. District-heating and cooking are among the most widely used applications in this temperature range.

2.3.1.3. High temperature collectors

Finally, high temperature collectors get to work with temperatures of up to 500ºC [14]. These types of collectors are used for the generation of electrical energy. In this temperature range, there are several types of technologies that take advantage of that solar energy, for instance: the parabolic trough sensors, the central tower, the parabolic discs, and the Fresnel linear receivers [16]. All of them concentrate heat at a specific point to generate steam, which in turn will generate electricity in a thermal machine.

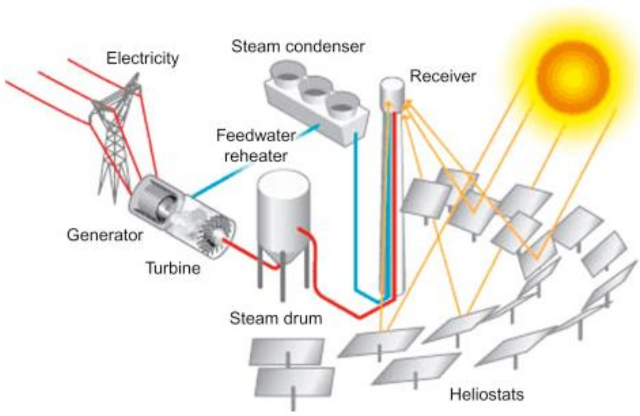

Figure 2.4 Solar central tower scheme [17]

2.3.2. Photovoltaic solar energy

The second active way to take advantage of solar energy is to make use of photovoltaic technology. The principles of photovoltaic panels date back to 200 years ago when scientists began to work with solar cells. More specifically, it was in 1839 when Becquerel discovered the photovoltaic effect. Over the next decades, several scientists continued to work in this area.

Using all the information and technologies that previous scientists developed, in 1954 the first photovoltaic cell was manufactured [18]. Still, the efficiency and power of this first panel were very low. But years and years of research have led these panels to 20% efficiencies [19].

Regarding the generation of electricity in the panels, the generation begins when some photons from the solar radiation hit the surface of the panel. These photons are absorbed by the semiconductor materials causing the electrons to be released. Finally, the circulation of these electrons is what generates electricity.

The current generated is Direct Current (DC). Therefore, this current is carried to an inverter. In this way, at the inverter output, Alternating Current (AC) is obtained. Once these steps have been taken, the current is ready for example to use it in a house.

Within these panels, a classification can be made depending on how the cells are formed. When silicon has not crystallized it is said that there are amorphous. Otherwise, they are said to be crystalline. And within this category the panels are classified into monocrystalline and polycrystalline.

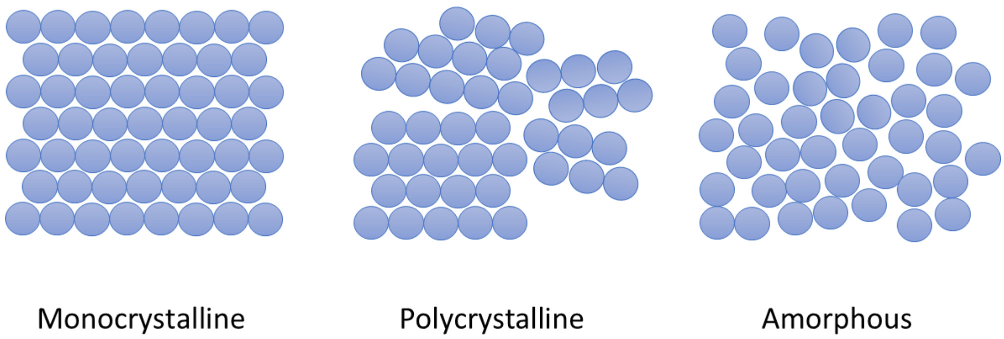

Figure 2.5 Monocrystalline, polycrystalline, and amorphous cells structure

Nowadays most of the photovoltaic panels are monocrystalline. Since they are more efficient than the others and comparing them with polycrystalline, the cost has become similar [20].

Photovoltaic panel installations can have different objectives, and therefore their size can vary greatly. The smallest facilities may be those designed to meet the demand of a house and its collector area is a few square meters. And the biggest ones can be the big solar power plants equipped with hundreds of panels. Within this category is the solar plant located in Sweihan (Abu Dhabi), among other plants. This plant occupies an area of 7.8 km^2 and has an installed capacity of 1,177MW [21].

Figure 2.6 Sweihan solar plant [22]

Each time more and more solar installations are started up, both small and large. And according to the International Energy Agency, in 2018 there was a total of 580TWh of production from PV installations worldwide [23].

2.3.2.1. Efficiency of a solar panel and factors that affect

The companies that manufacture photovoltaic panels, usually publish different characteristics of their products among these characteristics is the efficiency of the panels. In order to be able to compare different panels, the efficiency is usually measured under Standard Test Conditions (STC), that is, at 25ºC and irradiance of 1000W/m^2.

Although some years ago the efficiency of these panels was low, after years of technology development, photovoltaic panels with efficiencies above 20% can be found on the market [24],[25].

The efficiency of a solar panel is the percentage of energy that is converted into electrical energy of the total absorbed.

$$\eta = \frac{P_m}{E \cdot A_c}$$

Where,

P_m: maximum power generated (W)

E: solar irradiance (W/m^2)

A_c: solar collector area (m^2)

Therefore, for the same power generated, the smaller the area, the greater the efficiency. And for the same irradiance, the greater the collector area the greater the power generation.

Another important term when calculating efficiency is the fill factor (FF). This is the relationship between the maximum power and the open circuit voltage and the short circuit current. And like the information on panel efficiency, these parameters are also published by the companies that produce the panels.

$$FF = \frac{P_m}{V_{OC} \cdot I_{SC}}$$

Where,

P_m: maximum power generated (W)

V_{OC}: open circuit voltage (V)

I_{SC}: short circuit current (A)

Finally, in this section, the temperature of the solar panel must be considered, since it has been shown that the higher the temperature, the lower the efficiency [26]. And as mentioned before, the information on the efficiency of the panels is usually given at a temperature of 25ºC, so it must be taken into account that if the ambient temperature is higher, the panel response will probably be worse. Moreover, there are several studies and experiments that have been done over the years that demonstrate this fact. Proof of this is the experiment carried out by M. Senthil Kumar, K. R. Balasubramanian, and L.Mahewari, where they demonstrated that increasing the ambient temperature by 15ºC, decreased the efficiency of some panels from 15% efficiency to 12.51% [26].

2.3.2.2. Use of batteries

As explained at the beginning of this section, electricity is generated through photovoltaic panels. But many times, as can be seen in the *Figure 2.7* the generation hours do not match the consumption hours. Or it may be that generation is greater than consumption. Therefore, when it comes to small facilities, adding batteries to the installation of photovoltaic panels can help balance the entire system.

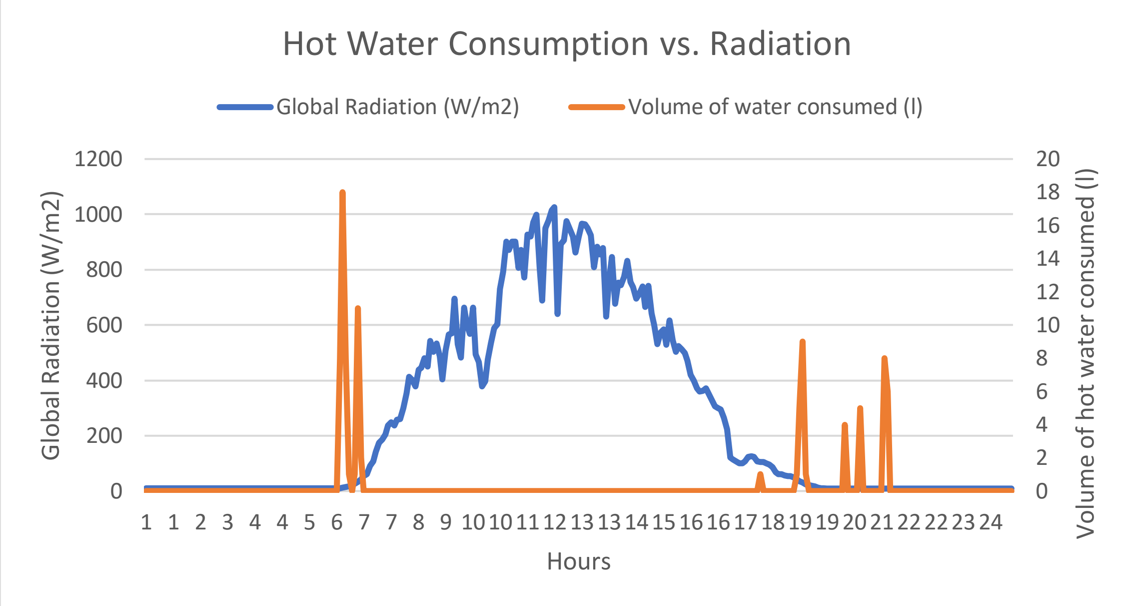

Figure 2.7 Hot Water Consumption vs. Radiation during an average day

Another advantage of this option is that dependence on the electrical grid is decreased. This makes the use of batteries very interesting in remote locations where there is no option to connect to the grid.

The parameters that must be taken into account when a battery is purchased are the voltage, the number of cycles, the capacity and the Depth of Discharge (DoD).

The voltage refers to the operating voltage of the installation in direct current. And usually depends on the power demanded by the system.

Table 2.1 Battery voltage [27]

Power demanded by the system (W)	*Operating voltage (V)*
< 1500	12
> 1500 and < 5000	24 - 48
> 5000	120 -300

On the other hand, the number of cycles is used to express the lifetime of the battery. And each cycle refers to each of the times the battery is charged and discharged. As the use of each battery can be completely different, the number of times that the battery can be discharged is usually given to calculate its useful lifetime.

The third parameter is the capacity of the battery. This can take values such as C50, C100 or C200. And this number indicates the number of hours the discharge lasts. This parameter is used to compare different batteries that for example, have the same capacity as C100. Since depending on consumption, the discharge time will vary and therefore a common parameter is needed between them.

Finally, the DoD indicates the percentage of the battery that can be discharged of its total capacity.

3. Solar Cooking

3.1. Introduction

The results obtained from the study of the low-temperature thermal solar system are to be used as a starting point for an analysis of medium-temperature systems such as solar cookers. Therefore, this chapter explains the history and evolution of these technologies. Additionally, the different technologies that have gained strength and have become the most widely used will be explained.

In developing countries, the combustion of solid fuels is used to obtain heat for cooking. As already mentioned, apart from the environmental contamination that this brings, it also produces serious health problems. Additionally, solar cookers can help to make the population of these places independent from other types of fuels. And this can be of great help in combating world hunger. For all this reasons, numerous tests have been carried out to cook with the energy provided by the sun.

3.2. History of solar cooking

Human beings have used solar energy since historical information is available. But it was about 200 years ago when solar cookers began to be developed. Specifically, it was in 1776 when the first box type solar cooker was developed in Switzerland [28]. In this first attempt, a temperature of 90°C was achieved inside the insulated box. But it was not until the year 1869 when in France the idea of using parabolic reflectors began to be developed by Mouchot.

Although during the first years of development of these technologies in Europe there were several studies, in the rest of the world different technologies were also developed. Among them is the solar cooker with flat mirrors developed in India in 1876 [28].

The biggest problem with the prototypes developed during these early years was that they were too expensive for most of the population. But from then until now, new types of solar cookers have been developed, and all of them have undergone improvements, and in some cases the cost has even been reduced. These improvements have even caused higher temperatures. For instance, nowadays concentrating type cookers can achieve 300°C [29].

Although today it is not the most popular way of cooking in the world, several organizations like Solar Cookers International have projects that distribute solar cookers in needy places and in developing countries. These projects have several objectives, among them are: to improve the health of the inhabitants, to empower them, to protect the environment, and to provide solutions to people who for economic reasons cannot have access to other types of cooking fuels [30].

3.3. Types of solar cookers

All these years of research have created various types of solar cookers. In most cases, three types of technology are distinguished: the box cooker, panel cooker, and the parabolic collector cooker [31]. Even so, there are authors who make a more detailed classification where more details are considered [29], example of this is the *Figure 3.1.* The principal of all of them is to take advantage of solar radiation as an energy source for cooking.

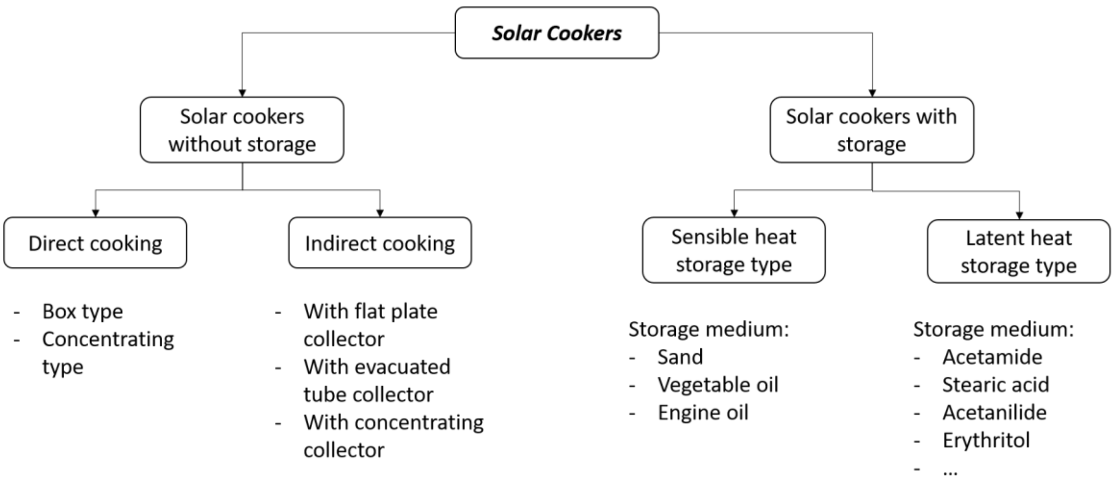

Figure 3.1 Solar Cookers classification [29]

As the image above shows, *R.M. Muthusivagami* and *R. Velraj* classify solar cookers into two types: solar cookers without storage and solar cookers with storage [29]. Between these two types, the biggest difference is that solar cookers with storage allow cooking even on cloudy days or during off-sunshine hours. Even so, in their report they conclude that today there is no system that allows indoor cooking for all time.

3.3.1. Solar cookers without storage

3.3.1.1. Direct cooking

3.3.1.1.1. Box type cookers

In the early development of solar cookers, box cookers were the first to be created. But from the beginning until now they have undergone several changes and improvements. As its name indicates, this solar cooker is a thermally insulated box with a glass cover and is designed to capture solar energy and to maintain a certain temperature. The metal pot where the food will be cooked is located inside the box. And depending on what is going to be cooked, the cooking process can take between 1 hour and 3 hours [32]. This type of solar cookers is among the most popular due to the simplicity and low cost.

Figure 3.2 Box type solar cooker [33]

3.3.1.1.2. Concentrating type cookers

In this second type of solar cooker, the pot used for cooking is in the focus of the concentrating mirror. Thanks to this technology and the one or two axes tracking, temperatures of up to 300ºC can be achieved.

Within this category of solar cookers, those that concentrate the light from below and those that concentrate the light from above are distinguished. The most convenient of the two, is the one that concentrates the light from below. Since it makes the cooking process more natural and comfortable.

Although they are very popular, concentrating type solar cookers have a drawback: they are very sensitive to the change in position of the sun. Therefore, they must have a continuous tracking system. Other important disadvantages can be the large size and high cost.

Like all technologies it also has two great advantages: that is the high temperatures that are achieved and the short cooking time that it needs.

Figure 3.3 Concentrating type cooker (concentration from below) [34]

3.3.1.2. Indirect cooking

Nowadays there are several technologies with different collectors within this category of solar cookers, such as the solar cooker with flat plate collector, with evacuated tube collector, or with concentrating collector. But all of them have the same characteristic that the pot where the food is cooked is displaced from the collector. This makes cooking more comfortable and can be adapted to the different needs of the user. On the other hand, the fact of separating these two elements makes it necessary to use a medium to transfer the heat to the pot. Usually, peanut, or sunflower oil is used as a medium [29].

The main advantage of this type of solar cooker is that it can be used to cook indoors. But it also has more advantages such as shorter cooking time and larger pot volume.

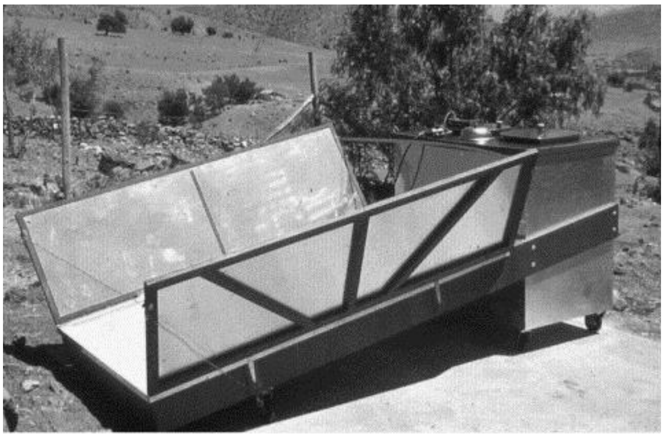

Figure 3.4 Indirect type solar cooker [35]

3.3.2. Solar cookers with storage

Many times, the hours of solar radiation and the hours of energy consumption do not coincide. To solve this problem, solar cookers with storage began to be developed. The two variants that exist within this category are those that store energy as sensible heat or latent heat [36].

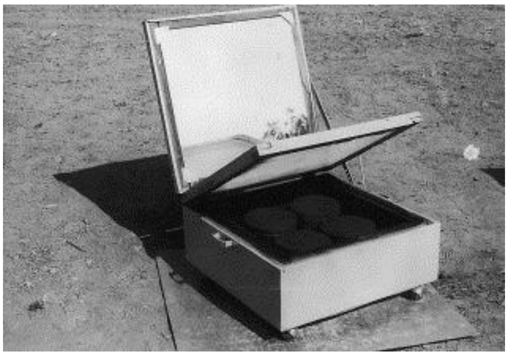

Figure 3.5 Box type solar cooker with engine oil as storage material [37]

In solar cookers with heat storage, heat losses must be considered and keep in mind that the higher the temperature of the storage material, the greater the losses. Therefore, isolation is of great importance. The losses will depend on both the tank temperature, the ambient temperature, the storage tank area, and the insulation.

4. Financial Analysis

4.1. Introduction

This chapter aims to present the different parameters that are used when making a financial analysis. The parameters that are presented are the system payback period, NPV, IRR, LCOE, LCOH and total savings. These parameters are used to analyze the economic viability of a project or to compare different projects.

4.2. Payback period

The payback period is simply the time it takes to recoup the investment that has been made in a project. It is a parameter widely used when comparing different projects. The lower the payback, the greater interest the project will cause, since that means that the investment will be recovered before.

But this parameter is not enough to compare different investments since it does not take into account the TVM. Consequently, the payback periods for longer investments may have more errors. Furthermore, the payback period does not provide any information on the situation after the payback. That is why it is important to consider other parameters before making a final decision. Therefore, parameters such as NPV or IRR are also usually calculated, since these usually consider TVM and these provide information on the situation after the payback.

4.3. Net Present Value (NPV)

NPV is another of the parameters used to carry out the financial analysis of different projects or investments. Many times, it is given more importance than the payback, since the NPV considers the TVM. On the other hand, it is more complex to calculate than the payback.

This parameter is the difference between the present value of cash inflows and the present value of cash outflows over a period of time [38]. And this is the formula to calculate the NPV:

$$NPV = \sum_{t=0}^{T} \frac{R_t}{(1+i)^t}$$

Where:

R_t: Net cash inflows-outflows during a single period t

i: Discount rate or return rate

t: Number or time periods

The value achieved can be both positive and negative. But the investment will be profitable only when the NPV is positive. Otherwise, this investment is not considered to be economically viable.

One of the disadvantages of calculating this parameter is that it is done based on assumptions and inevitably this leads to errors.

4.4. Internal Rate of Return (IRR)

IRR refers to the discount rate that makes the NPV of a project equal to zero [39]. Like the previous two parameters, this parameter is also used to compare different investments and make decisions. In this case, the formula to calculate the IRR is the following one:

$$0 = NPV = \sum_{t=1}^{T} \frac{C_t}{(1+IRR)^t} - C_0$$

Where:

C_t: Net cash inflow during the period t

C_0: Total initial investment cost

t: The number of time periods

In general, when comparing different projects, the higher the IRR value the more interesting the project will be economically. Since IRR can be considered as the growth rate expected of a specific project.

4.5. Levelized cost of energy (LCOE)

The LCOE is a measure that allows to compare different technologies of energy production. This parameter refers to the cost of construction, maintenance, and production of a technology per unit of energy produced ($/kWh). In this case, the formula to calculate the LCOE value of a technology is the following one:

$$LCOE = \frac{NPV\ of\ total\ costs\ over\ lifetime}{NPV\ of\ energy\ produced\ over\ lifetime}$$

Like the other parameters that have been presented, the LCOE is also used to compare different technologies and make decisions. Furthermore, when it comes to large installations with the objective of selling energy, this value defines the minimum price at which energy should be sold so as not to have losses.

4.6. Levelized cost of heat (LCOH)

What this value expresses is almost the same as the LCOE, but in this case the cost is per unit of heat produced. That is why this parameter is used in thermal installations. As for the formula to calculate it, there is only a small difference with the previous parameter:

$$LCOE = \frac{NPV\ of\ total\ costs\ over\ lifetime}{NPV\ of\ heat\ produced\ over\ lifetime}$$

5. Solar direct and indirect technologies comparison

In the first part of this chapter, three technologies that aim to heat water are analyzed. Starting from data collected in the Stellenbosch project [3] such as solar radiation, hot water consumption, or heat transfer, an energy and economic analysis is carried out. In this way, you want to investigate which of the options is the most interesting. Once the results of these cases are obtained, the relationship that it may have with medium-temperature thermal solar systems will be analyzed.

5.1. Analysis of Low-Temperature Case

This section presents the energy and economic analysis carried out in three different technologies. The project carried out in cooperation by the University of Stellenbosch (South Africa) and the Institute for Sustainable Technologies (Austria) [3] has been used as a starting point for this analysis.

In their project they analyzed and compared two solar technologies, with a similar thermal capacity, that were installed in two houses in Mariendahl Farm (Stellenbosch, South Africa). The objective of these facilities was to satisfy the hot water needs of these houses. A 2.4 m^2 SWH system was installed in one of the houses and a 10.05 m^2 PV system in the other. Figures 5.1 and 5.2 show the schematic layout of the two systems they installed in Stellenbosch.

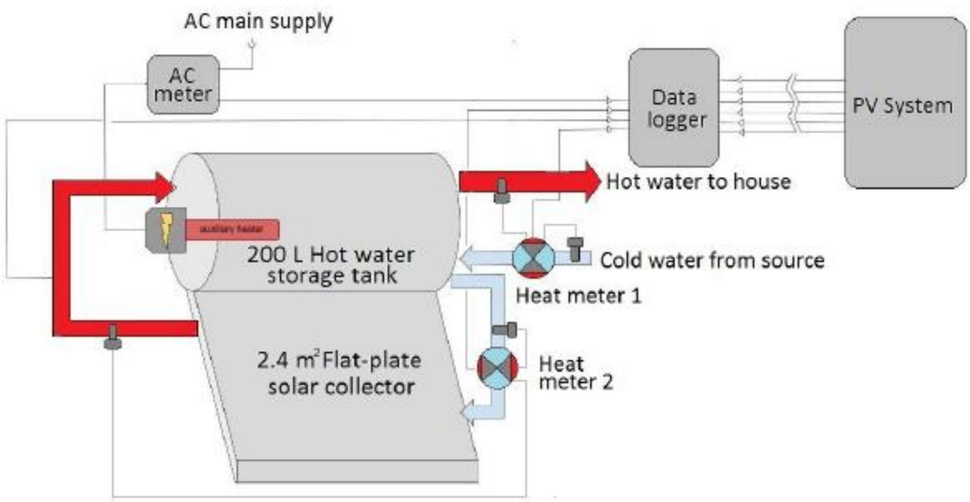

Figure 5.1 SWH system scheme [3]

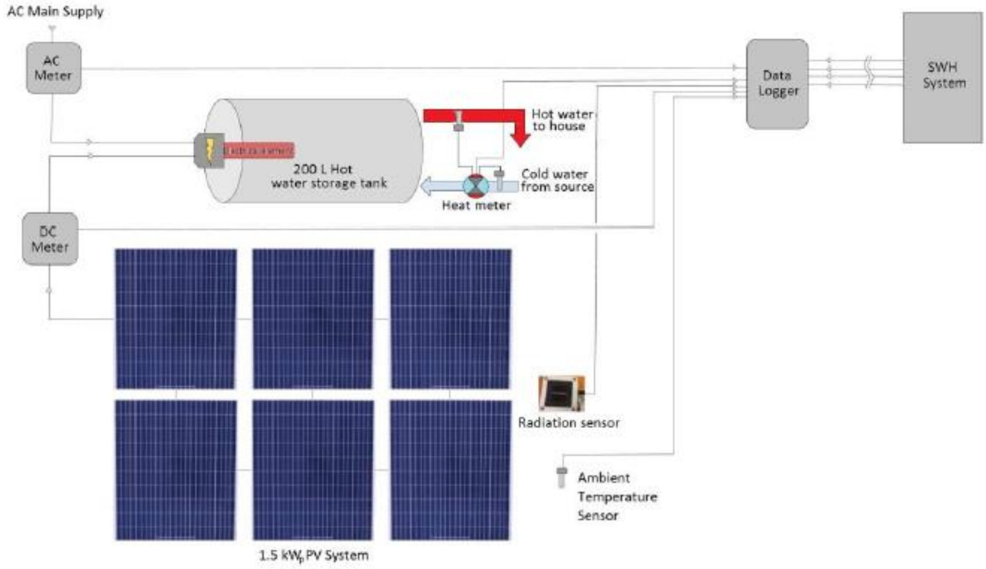

Figure 5.2 PV system scheme [3]

Thanks to these two facilities in the Stellenbosch project, they were able to collect a large amount of data, such as radiation, thermal energy production, or electrical consumption. And it is precisely from these data that this broader analysis begins.

Although a few years ago it was impossible to think that the use electricity to heat water was a good idea, but the reduction in cost that photovoltaic panels have had, has led to consider the idea that it may be a good option. It is precisely this idea that they wanted to analyze in the mentioned project.

In the project carried out in cooperation by the University of Stellenbosch (South Africa) and the Institute for Sustainable Technologies (Austria), they confirmed that in the case of low-temperature solar systems, the direct SWH system had more benefits from an economic point of view than the PV system. Since they got better values in parameters such as the payback period, NPV, or LCOH.

Even so, it would be interesting to delve into the case and see if, with small improvements, the PV system could become interesting. As the cost of these systems has been reduced in recent years, and they are simple to install and maintain, they can be a great solution for single-family homes. On the other hand, having analyzed the case of low temperature, it would be interesting to see if these same results are obtained in medium- and high-temperature installations. Or on the contrary, the PV systems are more beneficial in higher temperatures. So, starting by analyzing low temperature systems is one step to be able to draw conclusions about medium- or high- temperature systems.

5.1.1. Analysis on days of non-consumption

In order to carry out a more exhaustive analysis, the response of the systems was analyzed, specifically on days where there was no consumption of hot water by the houses. In this way, the relationship between the efficiency of the systems and the temperature of the tank was wanted to be analyzed.

In the following graph the relationship between the efficiency of the SWH system and the temperature of the tank has been plotted. The blue dots refer to the efficiency achieved during periods of one hour. Although there is solar irradiation for several hours each day, there is only energy input into the tank for a few hours a day. So, the average efficiency these days is lower, and is indicated by the orange line.

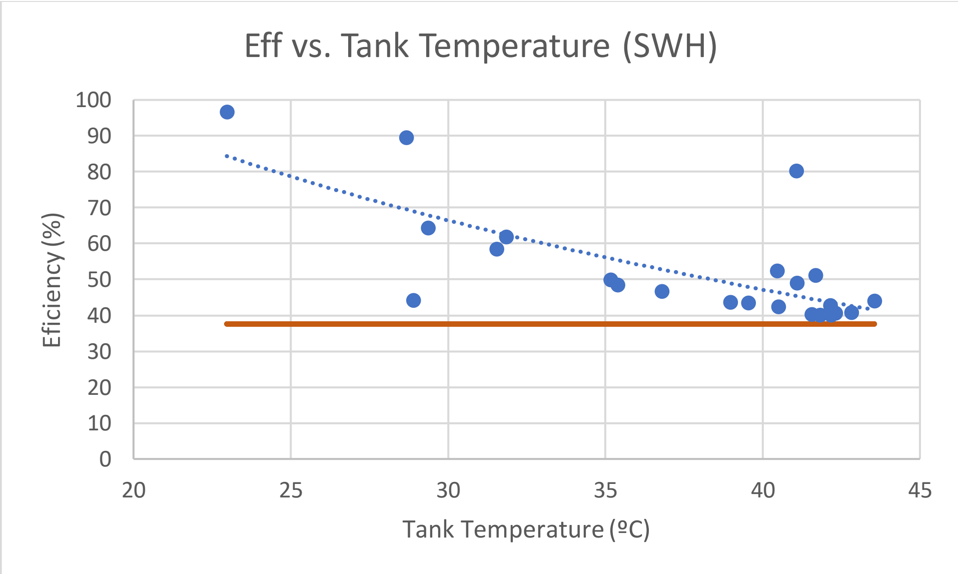

Figure 5.3 SWH system efficiency vs. Tank temperature (non-consumption days)

The graph above shows how the efficiency of the SWH system decreases as the tank temperature increases. Therefore, the decrease in efficiency in low-temperature installations has been proven. This fact confirms that in high-temperature installations, the efficiency will be even lower. But it would be necessary to see if this decrease in efficiency is sufficient to make PV systems more profitable than direct systems in medium temperature cases.

On the other hand, in the graph below the results for the PV system are showed. In the graph the non-relationship between the efficiency and the tank temperature can be seen.

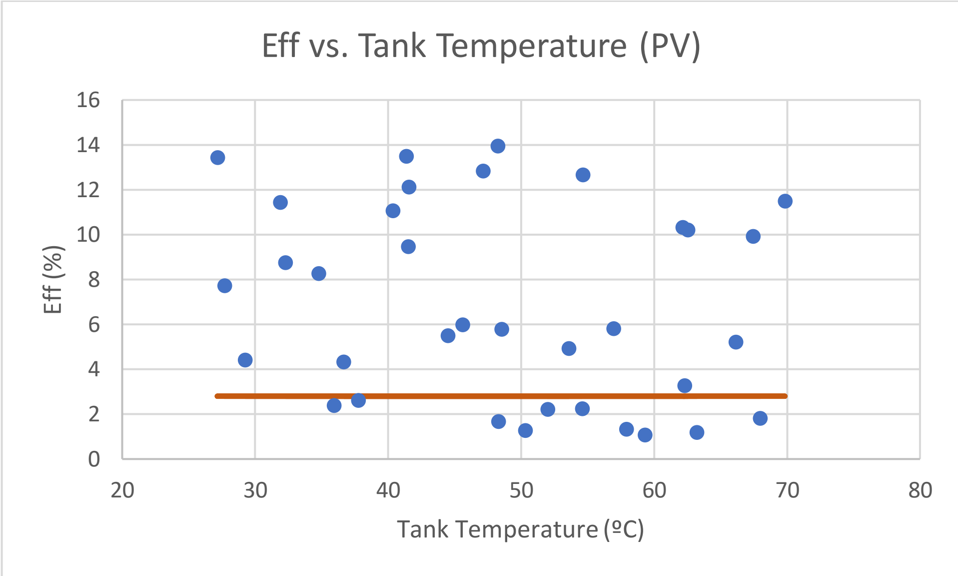

Figure 5.4 PV system efficiency vs. Tank temperature (non-consumption days)

As for the low average daily efficiency, it must be considered that the PV system stops heating the water when it reaches 55°C. So, in days of non-consumption, the system is hardly used, which leads to very low efficiencies.

As mentioned, the system stops heating the tank water when it reaches 55°C. Therefore, a lot of solar energy is wasted, which could be used to charge batteries. In this way, the efficiency of the PV system would increase when water does not need to be heated. Thus, it is possible to get the most out of the installed system. And maintain a constant efficiency during the period that there is solar radiation that can be used.

Being a small installation, a small battery like the *PlusEnergy GEL 150Ah* 12V [40] could be used to take advantage of the excess energy. For example, this energy could be used for lighting the house or for cooking. Considering all the energy wasted during a year, with the use of the battery a reasonable amount of money could be saved in the electric bill. And in a relatively short time, the investment would be profitable. But this will be seen a little later when the data is analyzed, and the calculations are carried out.

Table 5.1 PlusEnergy GEL Battery characteristics

PlusEnergy GEL 150Ah 12V	
Voltage	12 V
Lifetime	More than 3000
DoD	70 %
Capacity at C100	1500 Ah

With the characteristics of this battery, and only using the energy provided by the battery, it would be possible to cook for two hours in a row in a 900 W electric stove.

In the analyzed case, on average, 9kWh of energy is wasted every day that there is no consumption of hot water. Considering the dimensions of the house and the number of people living in it, this amount of wasted energy can be considered significant. On the other hand, to this amount of energy, must be added the energy wasted during the rest of the days. The sum of all this energy makes a total of 1279 kWh per year (data collected from 05/01/2018 to 04/30/2019), where it has been considered that the efficiency of the system is 14% [41]. And with the installation of a battery, part of this energy could be used to replace the electrical consumption when there is no solar radiation. Once this consumption is compensated, there would still be 1214.46 kWh that can be used for cooking or lighting.

5.1.2. Financial analysis

To see the viability of the PV installation with the support of the battery, the financial analysis has been carried out. In it, the three installations are compared (SWH, PV, and PV + Battery). For the financial calculations, an electricity price of 0.1315$/kWh [42] has been used. The electricity price increase after the first year has been taken as 7.32%. And after this, an annual increase of 8.6% year-on-year. These last values were intended to be maintained as in the Stellenbosch project to be able to compare the cases from the same starting point.

To carry out these calculations, parameters such as the capital cost rate and the inflation rate had to be assumed. In order to get comparable values, once again it was decided to use the same values as in the project carried out between the University of Stellenbosch and the Institute for Sustainable Technologies of Austria. Where the capital cost rate was 9.25% and the inflation rate 6.7%. Finally, it was assumed that the PV panels suffer a degradation rate of 0.5%/year.

Once all these parameters were defined, the annual savings of each system were calculated. And in the following graph, the annual generated financial savings can be seen for each of the three cases. And it can be seen that the PV system with battery is the one that gives the best answer from this point of view. Although it does not show a great difference with the values obtained for the SWH system.

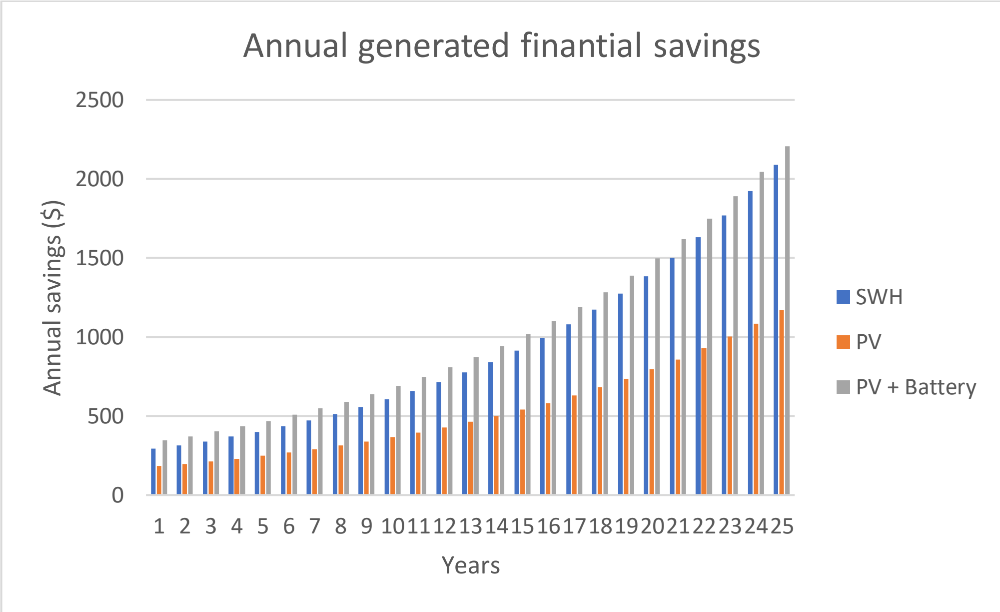

Figure 5.5 Annual generated financial savings in low temperature cases

On the other hand, the cumulative cash flow has also been analyzed in the three cases. This analysis has concluded that the SWH system continues to be the one with the lowest payback, 6 years payback period. But adding a battery to the PV system has reduced the payback from 15 to 10 years. However, in the long term, the SWH system and the PV system with the battery become competitive with each other.

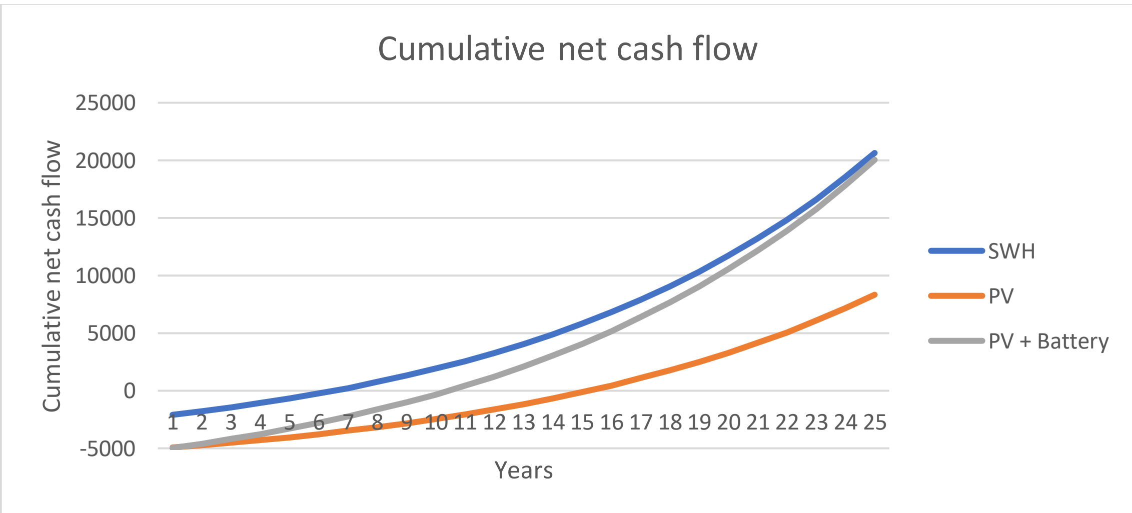

Figure 5.6 Cumulative net cash flow in low temperature systems

The negative value of the cumulative net cash flow in the first years is due to the investment involved in the installation of these systems. Being the investments of the

SWH installation, PV installation and PV + battery installation had a cost of 2383$, 5110$ and 5313$ respectively.

Regarding the NPV, these last two systems give us positive values, which makes the installations viable. Being the values 3768$ in the case of the SWH and 1611$ in the case of PV with the battery.

Another parameter to evaluate when carrying out the financial analysis is the LCOH. In this case, the SWH system remains the leader, with an LCOH of 0.043 $/kWh. But adding the battery to the PV system has reduced the LCOH value by half, going from 0.155 $/kWh to 0.085 $/kWh.

Table 5.2 Financial results for the low temperature case

	SWH system	PV system	PV + Battery system
Initial capital cost	2383 $	5110 $	5313 $
Payback	6	15	10
NPV	3768 $	-1438.43 $	1611 $
LCOH	0.043 $/kWh	0.155 $/kWh	0.085 $/kWh
IRR	23 %	7 %	13 %

All the parameters analyzed so far conclude that the support of a battery makes the PV installation more interesting than at the beginning. Even so, from a financial point of view it does not get to give better results than the SWH. But the improvement of the values leads to think that in high temperature installations the PV system may become a better option.

5.2. Introduction to Medium-Temperature Cases

Based on the analysis and comparison that has been carried out in the previous subchapter, this 5.2 subchapter makes a brief analysis of what could happen when comparing PV systems with direct solar systems of medium temperature.

Several reasons may lead to think that in this case, the PV system may be a better option than solar cookers. First, the decrease in the economic cost of PV panels makes it an increasingly interesting technology. Second, as it has been verified in the previous chapter in the case of direct systems, the higher the temperature of the liquid in the tank, the lower the efficiency of the system. While in the case of indirect systems (PV system) this relationship does not exist. And third, the higher the temperature of the liquid used for heat storage, the greater the heat losses. Therefore, PV systems can be even more interesting in medium-temperature cases.

Another important aspect to consider is the cooking time. When cooking in solar cookers, foods like rice or beans can take more than four hours to cook. On the other hand, if an electric stove powered by a PV system is used, cooking is faster. There are several experiments that have been done in this area, and in the specific case of cooking 0.5kg of rice with 1l of water, in a solar cooker it takes an average of 3 hours [43], while with an electric cooker 12 minutes is enough.

Since the cooking hours do not always coincide with the hours of solar radiation, it is important to have some method of energy storage. The addition of the energy storage method, many times, makes this type of solar cookers not accessible to the inhabitants of these developing countries [44]. In the case of PV systems, as has been done in the previous chapter, batteries would be used.

5.2.2. Heat losses in the tank

In the previous subchapter it has been seen the decrease in the efficiency of the direct system with increasing tank temperature, but it is also interesting to analyze the heat losses that will have to be compensated by the system. The heat losses that will be in a thermal storage tank can be estimated with the following equation:

$$Q_{loss} = \frac{A_t \cdot (T_{in} - T_{out})}{R}$$

Where:

Q_{loss}: Heat loss (J)

A_t: Tank area (m^2)

T_{in}: Temperature inside the tank (°C)

T_{out}: Exterior temperature (°C)

R: Thermal resistance of the tank insulation ($m^2 \cdot$°C/J)

Therefore, the larger the area of the tank, the greater the losses. And the greater the difference in temperature between the outside and the temperature of the liquid inside the tank, the greater the losses. On the other hand, the better the insulation of the tank, the less heat losses will be.

To really see the effect that the temperature at which the system works has on losses, the other parameters will be kept constant. These parameters are the tank area (1.96 m^2) and volume (200l); and the thermal resistance of the tank insulation. To notice the difference in heat loss, two types of insulation have been used in the analysis, on the one hand a Rock Wool Insulation (with a thermal resistance of 1.9 m^2 °C / W) [45] and on the other a Glass Wool Insulation (with a thermal resistance of 3.48 m^2 °C / W) [46]. In both cases the thickness used has been 120mm.

In figures 6.1 and 6.2 the heat losses on two different days have been plotted.

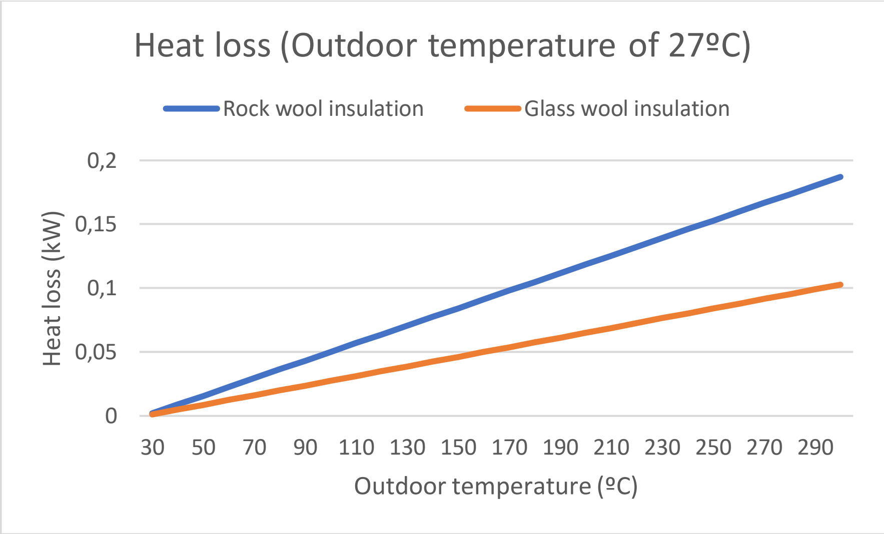

Figure 6.1 Heat loss (outdoor temperature of 27ºC)

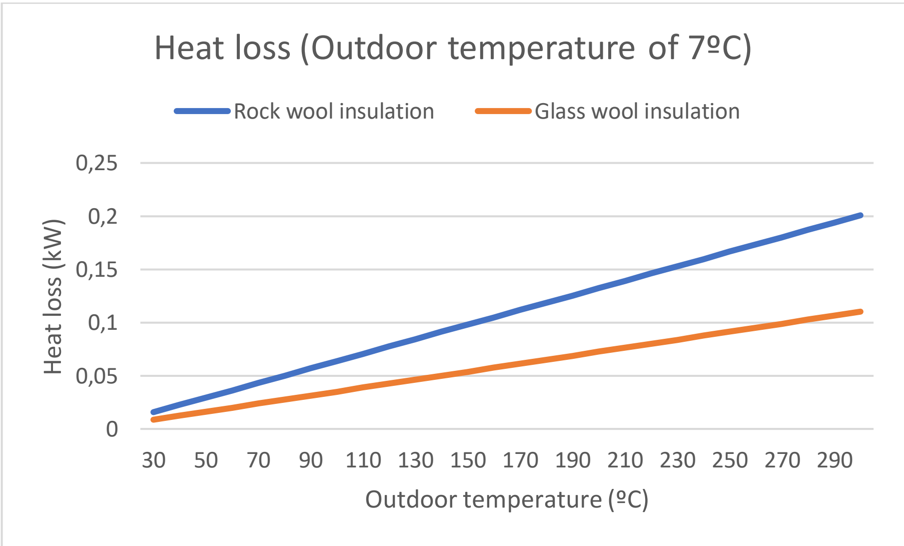

Figure 6.2 Heat loss (outdoor temperature of 7ºC)

In the two graphs above, the increase in heat loss can be seen as the tank temperature increases. And this is unavoidable no matter what insulation is used. On the other hand, the type of insulation used is of great importance. As the graphs show the losses can be doubled.

In this case, the worst case of those analyzed would be on the coldest day and with the rock wool insulation. Specifically, for this case, if the heat losses during one day in two tanks with different temperatures are compared, a big difference will be seen. For instance, if the tank temperature is 50°C, the heat loss during that day will be 0.8% of the accumulated energy. And if the temperature was 250°C the loss would be 3.35%. This small loss should be compensated with the contribution of energy that the solar collector system would provide.

6. Conclusion

After carrying out the analysis of the low temperature solar thermal system and the PV systems (both the installation without battery and with battery), it has been seen that from the economical point of view, the SWH system continues giving better results. Even so, adding the battery to the PV system has considerably improved its results.

With these results obtained, it is up to the user to choose one system or another. Because the PV system with battery offers the possibility of having total independence from the electrical grid. At least as far as water heating is concerned. And this point can be very positive, since the price of electricity may have a higher rise than the assumed for the analysis. Although a conservative approach has been made regarding the price of electricity, it is something that can never be controlled one hundred percent. And if the price of electricity had a higher rise than assumed, the PV system with the battery could become a better option than the SWH system. Since the electricity consumption of the SWH system is much higher compared to the two cases of PV.

Although the PV system has not outperformed the SWH system, it has been seen that the temperature of the tank water has a big influence on the efficiency of the SWH system. Decreasing the efficiency while increasing the temperature. That is why, the option that in medium and high temperature systems the PV system can give better results is not ruled out yet.

On the other hand, in medium and high temperature solar systems, it has been verified that the heat loss is greater and, consequently, quality insulating materials will have to be installed.

7. Recommendations of Further Work

Once this study is completed, the following recommendations are made for future work. First, to carry out a test that includes the support of a battery for the PV system in a real installation. And analyze the performance and the response of it, while comparing it to the SWH system and the simple PV system.

On the other hand, a test with solar cookers with storage could be carried out. And analyze the effect that the materials used for heat storage can have. For instance, different oils and fluids for heat storage or different insulations to control heat loss could be test.

References

[1] *BP Statistical Review of World Energy*: BP; 2019. Available from: https://www.bp.com/content/dam/bp/business-sites/en/global/corporate/pdfs/energy-economics/statistical-review/bp-stats-review-2019-full-report.pdf

[2] iea.org [Internet]. International Energy Agency; October 2019 [2020 April 28]. Available from: https://www.iea.org/reports/solar-energy-mapping-the-road-ahead

[3] Buckley A.I., Kritzinger K., Mamphweli S.N., Moschik R., Spörk-Dür M. *Comparison of Photovoltaic and Solar Thermal Hot Water Systems in the South African Context.*

[4] *Fuel for Life. Household Energy and Heath.* World Health Organization. 2006: p. 8-12. Available from: https://www.who.int/airpollution/publications/fuelforlife.pdf

[5] iea.org [Internet]. International Energy Agency; February 2020 [2020 May 28]. Available from: https://www.iea.org/articles/global-co2-emissions-in-2019

[6] Wang Z. *Chapter 2 – The Solar Resource and Meteorological Parameters. Design of Solar Thermal Power Plants.* 2019. p. 47-115. Available from: https://www.sciencedirect.com/science/article/pii/B978012815613100002X

[7] Tiwari G. N, Dubey S. *Solar Radiation. Fundamentals of Photovoltaic Modules and their Applications.* 1st ed. Royal Society of Chemistry; 2010. p. 1-28. Available from: https://bibsys-almaprimo.hosted.exlibrisgroup.com/primo-explore/fulldisplay?docid=TN_knovelkt00U5WD33&context=PC&vid=NTNU_UB&lang=en_US&search_scope=default_scope&adaptor=primo_central_multiple_fe&tab=default_tab&query=any,contains,solar%20radiation

[8] Wikipedia.org [Internet]. *Sun*; May 2020 [2020 May 28]. Available from: https://en.wikipedia.org/wiki/Sun#Structure_and_fusion

[9] K.IA. Kondrat´ev. *Radiant Energy. The Main Concepts and Definitions. Radiation in the atmosphere.* 1st ed. New York: Academic Press; 1969. p. 1-47. Available from: https://bibsys-almaprimo.hosted.exlibrisgroup.com/primo-explore/fulldisplay?docid=BIBSYS_ILS71519738350002201&context=L&vid=NTNU_UB&lang=en_US&search_scope=default_scope&adaptor=Local%20Search%20Engine&tab=default_tab&query=any,contains,solar%20radiation%20types&offset=0

[10] Gorse C., Johnston D., Pritchard M. *Dictionary of Construction, Surveying and Civil Engineering.* 2nd ed. Oxford University Press; 2020. Direct Solar Radiation. Available from: https://www.oxfordreference.com/view/10.1093/acref/9780198832485.001.0001/acref-9780198832485-e-8351

[11] Falcone J.D. *Solar Energy. How to Design, Build, Remodel & Maintain Your Home.* 1st ed. New York: Simon&Schuster; 1978. p. 271-276. Available from: https://books.google.no/books?id=KP6wqt-WX7sC&printsec=frontcover&dq=how+to+design+build+remodel+%26+maintain+your+home&hl=es&sa=X&ved=0ahUKEwjB1dmuuvDpAhWsxcQBHTdXCREQ6AEIKjAA#v=onepage&q=how%20to%20design%20build%20remodel%20%26%20maintain%20your%20home&f=false

[12] Li H. *Pavement Thermal Modeling: Development and Validation. Design and Management Strategies.* 1st ed. Butterworth-Heinemann; 2016. p. 239-262. Available from: https://www.sciencedirect.com/science/article/pii/B9780128034767000118

[13] Cross J.M., Yanez M. Environmental and Energy Study Institute. Washington [cited 2020 May 28]. Available from: https://www.eesi.org/topics/solar/description

[14] Eicker U. Multimodal networks and decentralized renewable generation: *Network modeling and energy/exergy performance evaluation. Urban Energy System for Low-Carbon Cities.* Academic Press: 2019. p. 181-239. Available from: https://www.sciencedirect.com/book/9780128115534/urban-energy-systems-for-low-carbon-cities

[15] Zauner C., Hengstbergen F., Hohenauer W., Reichl C., Simetzberger A., Gleiss G. *Methods for Medium Temperature Collector Development Applied to a CPC Collector.* In: Häberle A, editor. *Energy Procedia*. 2012. p. 187-197. Available from: https://www.sciencedirect.com/science/article/pii/S1876610212015391

[16] Planas O. Solar Energy; 2015 May 21 [2020 May 28]. Available from: https://solar-energy.technology/solar-thermal/high-temperature

[17] Breeze P. *Solar Tower Technology. Solar Tower Generation.* 2016. Available from: https://www.sciencedirect.com/topics/engineering/solar-tower

[18] Clark Howard B. National Geographic Blog. Washington: National Geographic. *The Evolution of Solar Technology*. [2020 May 28]. Available from: https://blog.nationalgeographic.org/2012/05/30/the-evolution-of-solar-technology/

[19] solar.com [Internet]. Solar Learning Center. [2020 May 28]. Available from: https://www.solar.com/learn/solar-panel-efficiency/

[20] Sendy A. SolarReviews blog. 2020 May 28 [2020 May 28]. Available from: https://www.solarreviews.com/blog/pros-and-cons-of-monocrystalline-vs-polycrystalline-solar-panels

[21] *The world´s biggest solar power plants.* Power Technology. 2020 [2020 May 28]. Available from: https://www.power-technology.com/features/the-worlds-biggest-solar-power-plants/

[22] Morais L. *Abu Dhabi´s 1.17-GW solar farm is fully operational.* 2019. [2020 May 28]. Available from: https://renewablesnow.com/news/abu-dhabis-117-gw-solar-farm-is-fully-operational-659851/

[23] iea.org [Internet]. International Energy Agency; May 2019 [2020 May 28]. Available from: https://www.iea.org/reports/tracking-power-2019/solar-pv

[24] sunpower.com [Internet]. [2020 May 28]. Available from: https://us.sunpower.com/products/solar-panels

[25] lg.com [Internet]. [2020 May 28]. Available from: https://www.lg.com/us/business/neon%C2%AE-2/lg-lg355n1c-v5

[26] Senthil Kumar M., Balasubramanian K.R., Maheswari L. *Effect of Temperature on Solar Photovoltaic Panel Efficiency.* Blue Eyes Intelligence Engineering & Sciences Publication: 2019. Available from: https://www.ijeat.org/wp-content/uploads/papers/v8i6/F8745088619.pdf

[27] *Baterias para paneles solares fotovoltaicos.* Areatecnologia.com [2020 May 28]. Available from: https://www.areatecnologia.com/electricidad/baterias-para-paneles-solares.html

[28] Garg H.P. *Solar Cookers. Advances in Solar Energy Technology.* New Delhi: Springer Science; 1987. p. 1-61. Available from: https://link.springer.com/book/10.1007/978-94-009-3797-0

[29] Muthusivagami R.M., Velraj R., Sethumadhavan R. *Solar cookers with and without thermal storage – A review. Renewable and Sustainable Energy Reviews.* 2010. p. 691-701. Available from: https://www.sciencedirect.com/science/article/pii/S1364032108001469?via%3Dihub

[30] Solar Cookers International. Aid for Africa [2020 May 28]. Available from: https://www.aidforafrica.org/issues/solar-cookers-international/

[31] Iessa L., De Vries Y.A., Swinkels C.E., Smits M., Butijn C.A.A. *What´s cooking? Unverified assumptions, overlooking of local needs and pro-solution biases in the solar cooking literature. Energy Research & Social Science.* 2017. p. 98-108. Available from: https://www.sciencedirect.com/science/article/pii/S2214629617301019?via%3Dihub

[32] Harmim A., Merzouk M., Boukar M., Amar M. *Performance study of a box-type solar cooker employing an asymmetric compound parabolic concentrator. Energy.* 2012. p. 471-480. Available from: https://www.sciencedirect.com/science/article/pii/S0360544212007153

[33] Indiamart [2020 May 28]. Available from: https://www.indiamart.com/proddetail/rectangle-box-type-solar-cooker-13076448973.html

[34] Indiamart. [2020 May 28]. Available from: https://www.indiamart.com/proddetail/dish-type-solar-cooker-6552636088.html

[35] Schwarzer K., Vieira de Silva M.E. *Solar cooking system with or without heat storage for families and institutions. Solar Energy.* 2003. p. 35-41. Available from: https://www.sciencedirect.com/science/article/pii/S0038092X0300197X

[36] Regin A.F., Solanki S.C., Saini J.S. *Heat transfer characteristics of thermal energy storage system using PCM capsules: A review. Renewable and Sustainable Energy Reviews.* 2008. p. 2438-2458. Available from: https://www.sciencedirect.com/science/article/pii/S1364032107001001

[37] Nahar N.M. *Performance and testing of a hot box storage solar cooker. Energy Conversion and Management.* 2003. p. 1323-1331. Available from: https://www.sciencedirect.com/science/article/pii/S0196890402001139?via%3Dihub

[38] Kenton W. *Net Present Value (NPV).* Investopedia; 2020 April 27 [2020 May 28]. Available from: https://www.investopedia.com/terms/n/npv.asp

[39] Hayes A. *Internal Rate of Return – IRR.* Investopedia; 2020 April 27 [2020 May 28]. Available from: https://www.investopedia.com/terms/i/irr.asp

[40] WccSolar. [2020 May 28]. Available from: https://www.wccsolar.net/product-page/bateria-gel-plusenergy-tpg150-12v-100ah-150ah

[31] Matuska T., Sourek B. *Performance Analysis of Photovoltaic Water Heating System.* Stoian Petrescu; 2017 [cited 2020 May 28]. Available from: https://www.hindawi.com/journals/ijp/2017/7540250/

[42] Stellenbosch Municipality Tariffs 2018/2019. Available from: https://www.stellenbosch.gov.za/afr/dokumente/verslae/quarterly-fin-reports/5895-final-draft-tariff-proposals-20182019/file

[43] Karande P.D., Kumbhar S.V., Sonage B.K. *Experimental Study on Collection Efficiency of Solar Cooking System.* India: IRJET; 2007. Available from: https://www.irjet.net/archives/V4/i2/IRJET-V4I2307.pdf

[44] Tesfay A.H., Nydal O.J., Kahsay M.B. *Energy storage integrated solar stove: A case of solar Injera baking in Ethiopia.* 2014. Available from: https://ieeexplore.ieee.org/document/6970353

[45] metalplanet.com [2020 June 02]. Available from: https://www.metalpanel.com/wp-content/uploads/2018/02/lana_roca.pdf

[46] thermal-engineering.org [2020 June 02]. Available from: https://www.thermal-engineering.org/es/que-es-la-conductividad-termica-de-la-lana-de-vidrio-definicion/#:~:text=Valores%20de%20conductividad%20t%C3%A9rmica%20t%C3%ADpica,conductividad%20t%C3%A9rmica%20de%20los%20gases%20.&text=El%20aire%20y%20otros%20gases%20son%20generalmente%20buenos%20aislantes.