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INVESTIGATION INTO APPLICABILITY OF EXISTING RENEWABLE ENERGY TECHNOLOGIES AND POSSIBLE EFFICIENCY INCREASE

CASE STUDY: RWANDA.

Marie Chantal Cyulinyana

A dissertation submitted to the Faculty of science, University of the Witwatersrand, in fulfilment of the requirements for the degree of Master of Science.

Johannesburg, 2011

Declaration

I declare that this thesis is my own, unaided work. It is being submitted for the Degree of Master of Science in the University of the Witwatersrand, Johannesburg. It has not been submitted before for any degree or examination in any other university.

_____

(M.C Cyulinyana)

_____day of _____ 2011

Dedication

In memory of my father

P. Kwitonda

1945-1995

Acknowledgements

I express my sincere gratitude to my supervisor Dr. Philippe Ferrer for his comments, suggestions, advices, valuable discussion and encouragement at every stage of this thesis.

I would like to thank the sponsors for this project: My supervisor, School of Physics, University of the Witwatersrand and (Africa Institute for Mathematical sciences (AIMS). Thank you for the financial support throughout this project.

I won't fail to thank my family and my friends for their emotional support, and for their help in proofreading the final report. Thank you for all your love and support.

Abstract

This thesis is in two parts. In part I, we discuss how the investigation into existing renewable energy contributes to a solution to the energy deficit, especially in African rural areas where many people do not have access to the national grid. In this part, we surveyed some aspects of those existing technologies.

In part II, we studied a solar thermal technology called a solar trough plant, for which we have looked at a receiver in order to improve its efficiency by comparing two different surface coatings: a selective coating coated on the outside of the receiver pipe and a hot mirror coating coated on the inside of a glass cover. Our theoretical study showed that a hybrid system performs better than either a system with only selective coating or a hot mirror.

Concerning a better technology to use in Rwanda, we conclude that solar energy technology (due to good insolation: 5.2 $kWh.m^{-2}.day^{-1}$) is a strong candidate, in addition to hydro-power which has been the primary source of our electricity. Biomass is an alternative option especially in rural areas.

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ACRONYMS AND ABBREVIATIONS

CSP: Concentrated Solar Power

STE: Solar Thermal Energy

PV: Photovoltaic

SHS: Solar Home Systems

N: Negative

P: Positive

P-N: Positive-Negative

DC: Direct Current

SELF: Solar Electric Light Find

AC: Alternative Current

SWH: Solar Water Heating

ICS: Integrated Collector Storage

CHS: Convection Heat Storage

HTF: Heat Transfer Fluid

SEGS: Solar Energy Generating Systems

MINEFRA: Ministry of Infrastructure in Rwanda

EDPRS: Economic Development and Poverty Strategy

KE: Kinetic Energy

MHP: Micro Hydropower Plant

NDBP: National Biogas Program

CITT: Center for Innovation and Technology Transfer

KIST: Kigali Institute Of technology

HDR: Hot Dry Rock

BRGM: Bureau of Geology and Mining

BRG: Bureau of Geology

HWATS: Horizontal Axis Wind turbines

VHWATS: Vertical Axis Wind turbines

µm: Micrometer

ºC: Degree Celsius

W: watts

MW:Megawatts

Wp: Watt peak

Wh: watt hour

kW: Kilowatt

Chapter 1

Introductory Chapter.

1.1 Introduction

Renewable energy is obtained from the continuing or repetitive currents of energy occurring in the natural environment such as the sun, wind, water and organic matter (biomass) [1]. These resources are constantly replenished by nature, and are mostly a cleaner source of energy than fossil fuels. Renewable energy systems turn these resources into usable forms of energy, most often electricity, but also heat or chemical power. By exploiting renewable energy more, countries can develop energy independence and security. (Meaning that, the dependence of external energy sources can be reduced).

Fossil fuels (non-renewable energy), are currently used much more rapidly than they are created (i.e. small amounts are still being created), and so they will run out. For this reason, we may need to rely more on renewable energies. Renewable energy is also among the solutions of reducing the overall CO_2 emissions in the atmosphere and is the key to sustainable development [2].

Due to the energy deficit in Rwanda as well as the most African countries, Rwanda is increasingly looking at alternative sources of energy to power the country. Currently, only 9% of Rwanda's population has access to electricity, with a greater percentage of these being in the urban areas. As such the government has set up a target of 16% of the population to access electricity by 2012 and up to 35- 40% by 2020 [3, 4, 5].

In order to improve economic growth and to reduce poverty in Rwanda, there is a need for substantial improvements within the energy sector. Therefore, the government through the ministry of infrastructure is increasingly examining

alternative sources such as solar power, geothermal, biomass, methane gas as well as wind, especially for rural areas which so far have no connection to electricity grid [4, 5].

Firewood is the most used energy sources in rural areas, but it has a negative impact on human health (i.e. heart and lung diseases), and it pollutes the environment by producing black carbon. Wood energy is used by 17.7% of the population for light, and 98.7% of the population uses wood energy for cooking [3, 5]. Even in urban areas charcoal remains the most used fuel for cooking because electricity is costly.

In this dissertation we will focus at the particular alternative energies listed above and try to compare relative energy efficiencies. To understand several renewable energy systems we start by looking at the basic physical laws governing them [5]. Heat transfer mechanisms often form key steps in processing renewable energy, particularly with direct solar, geothermal and biomass sources [1, 6]. Most energy transfer is by heat rather than by mechanical or electrical process [1]. In Part II, we aim to understand solar energy's thermal application and to improve the use of the materials used to construct those renewable energy systems.

1.2 Aim

The aim of this dissertation was to carry out a critical investigation into existing renewable energy technologies and to suggest which of them can be successfully applied in Rwanda. Our survey suggested the most promising energy technologies.

This research aims at contributing to the promotion of energy efficiency and conservation as a means towards cleaner production and pollution control measures in order to minimize health hazards primarily affecting women and children, and environmental degradation.

1.3 Hypotheses

The main hypotheses of this dissertation they are as follows:

- In Rwanda, we have renewable energy resources which can contribute to the reduction of the energy crisis for the country by implementing efficient renewable energy technologies appropriate to the geographical and financial situation of the country.
- In the standard solar trough, a hybrid system performs better than either a system with selective coating or hot mirror alone.

1.4 Methodology

The first part of our work is based on a review of the existing renewable energy technologies in general and their applicability in Rwanda.

In studying those technologies we used some basic laws of thermodynamics, mechanics, fluid dynamics and heat transfer mechanisms, in order to measure the efficiency (η) of each system.

We have also looked advantages and disadvantages of those technologies in terms of cost, feasibility, durability, easiness to build or maintain and resources.

The existing renewable energy technologies which are studied are the following:

1.4.1. Solar energy

Solar energy is created by light and heat which is emitted by the sun, in the form of electromagnetic radiation [5]. Solar energy is an alternative power source which is currently mostly used. Solar energy involves several branches which include, Photovoltaic Solar Energy Systems, Solar Heating Systems, Concentrated Solar Power (CSP) Systems, and Solar Lighting Systems [6].

Solar energy has also been exploited in Rwanda in recent decades by local and international organizations for electrification [4, 5]. Solar systems are available in areas which are not connected to the national grid and are good for hospitals, schools, and household especially in rural area. This technology is discussed in Chapter 2.

1.4.2. Hydro – Power

This term is restricted to generation of power from falling water [1], where gravitational potential energy can be used for direct mechanical purposes or, more frequently, for generating electricity.

Hydro-power is currently the most established and widely used renewable energy resource for electricity generation and commercial investment. It accounts about 20% of world's electric generation [1], and is the main source of electricity generated in Rwanda [5].

In this research, we did a review on the water cycle and we looked at the applicability and efficiency of that technology, based on the principles of hydro-power systems, particularly in Rwanda. This technology is discussed in Chapter 3.

1.4.3. Biomass

Biomass is the common name for organic materials used as renewable energy sources such as; wood, crops, and waste. Those materials react with oxygen during combustion and natural metabolic processes to release heat [1]. That heat especially at 400^{o}C, may be used to produce work and electricity [1]. We have looked at the basic process of transformation and efficiency. This is presented in Chapter 4.

1.4.4. Geothermal

The inner core of the earth reaches temperatures of about 4000ºC [1]. This heat may pass out through vents to either submarine or terrestrial surfaces, conducting heat directly or by causing convective currents of molten magma or hot water.

Rwanda is located in a region of intensive volcanic activities, and there is evidence of existence of geothermal fields which could be harnessed for energy generation purposes [5]. The geothermal potential in this areas is estimated to be about 150 – 350 MW.

We have looked at some regions where this technology could be applied successfully. Chapter 5 shows the details.

1.4.5. Wind Energy

Wind energy can be exploited where the wind regime allows, and could thus distribute power to remote area from national grid [1]. We have looked at its applicability in Rwanda. This technology is discussed in Chapter 6.

1.4.6. Solar Trough Plant

The second part in this dissertation concerns itself with solar trough technology. A solar trough plant is a medium to high-temperature solar collector which operates by concentrating the radiation from the sun on the receiver running along the trough above the reflectors. The receiver transfers heat to a fluid moving along inside it. The fluid goes to a power station where it is designed to boil water in a conventional steam generator to produce electricity.

Our aim in studying this technology is to improve the overall efficiency of the solar trough plant by comparing analytic relations and simulations of a system using a conventional selective coating and one using a hot mirror coating. This is discussed in the second part of this research; Chapter 8.

In the concluding chapters (7 and 10) we summarise our findings.

PART I

Chapter 2

Solar Energy

2.2 Introduction

In this chapter, we present an overview of some solar technologies, including their applicability, the physics behind them, their efficiencies, advantages and disadvantages.

2.1.1 The Solar Energy Resource

Solar energy technologies use the sun's energy and light to provide heat, light, hot water, electricity, and even cooling, for homes, businesses, and industry. The potential usefulness of solar radiation, amongst other factors, depends on geographical location. Solar radiation arrives on earth with a maximum power of approximately 1.0 $kW.m^{-2}$ and the available solar power varies between 250 and 2500 $kWh.m^{-2}.year^{-1}$ [1]. The total solar radiation intensity is highest at the equator, especially in sunny and desert areas, and the intensity of solar radiation reaching the atmosphere decreases with increasing latitude. The intensity depends also on how low or high in the sky the sun is (i.e. the time of the year), as such, the closer it is to the equator the higher the intensity [1].

Solar radiation reaches the surface of earth both as a ***direct beam*** and as ***diffuse radiation,*** and both depend on atmospheric conditions. Solar energy reaches the earth's surface mainly as short wave radiation (visible radiation: between 300 and 750 nm see Fig. 1). When solar radiation heats the earth it is re-radiated as long wave radiation (Infrared radiation: between 750 and 2500 nm); see Fig. 1.

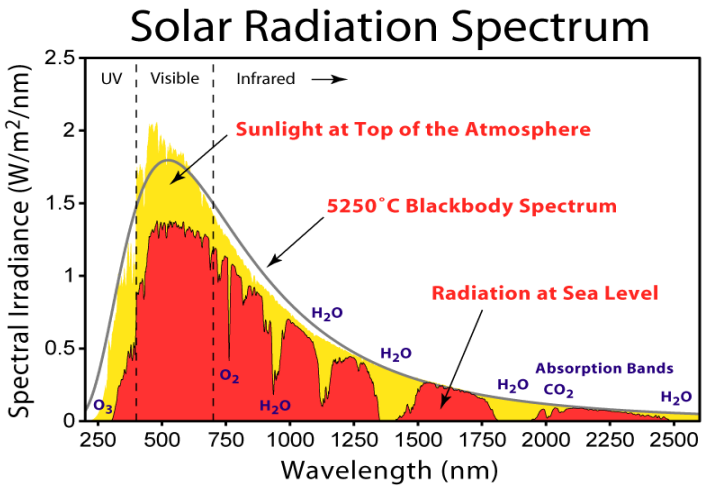


Figure 1 : Solar radiation spectrum [8]

The earth revolves around the sun with its axis tilted at an angle of 23.5^{o}, which gives rise to the seasons. The strength of solar flux density is dependent upon the angle at which it strikes the earth's surface. As such, as the angle changes for a given location during the yearly cycle, the solar insolation (a measure of solar radiation energy received on a given surface area in a given time ($MJ.m^2.year^{-1}$)) also changes [1]. Knowing the insolation of different regions we can harness the solar energy into different useful energies such as thermal and electrical energy.

2.1.2 The sun as a source of renewable energy

Solar energy is renewable because it is the energy radiated by our nearest star, the sun. The sun is estimated to have a life of about 10 billion years. And as long the sun is there we can still use it as our natural resource of solar energy.

Solar energy is one of the main sources of renewable energy and has enjoyed extensive development around the world. The sun is the very basis of the existence of life on our planet and is the driving force behind other sources of energy such as wind, biomass and hydro. Sunlight can be transformed directly into electrical energy through solar photovoltaic systems [6, 9].

Solar energy is also considered as a good option to serve as an energy source because it does not destroy the eco-system and is at present naturally occurring in the environment as opposed to fossil fuels.

Our investigation on this renewable energy technology ‘solar energy’ will help solar energy planners and sponsors to improve its applicability.

2.1.3 Historical Background of Solar Energy

Solar energy has been studied and documented for many centuries, making it one of the oldest renewable energy sources.

Solar energy was first converted to heat by Swiss scientist, Horace de Saussure. He built the first thermal solar collector in 1767, which was later used to heat water and to cook food. The first commercial patent for a solar water heater went to Clarence Kemp of the US in 1891. This system was bought by two California executives and installed in one-third of the homes in Pasadena by 1897 [10, 11, 12].

Solar energy was first directly converted to electricity in 1839, by French physicist Edmund Becquerel who noticed that the sun's energy could produce a "photovoltaic effect" (photo means light, voltaic means electrical potential). In the 1880s, selenium photovoltaic (PV) cells were developed that could convert light into electricity with 1 - 2% efficiency (defined as the percentage of available sunlight converted by the photovoltaic cell into electricity), but how the conversion happened was not understood [11, 12, 13].

Photovoltaic power therefore "remained a curiosity for many years, since it was very inefficient at turning sunlight into electricity” [13]. Albert Einstein proposed an explanation for the "photoelectric effect" in the early 1900s, for which he won the Nobel Prize [13].

2.2 What is Solar Energy?

Solar energy is produced by nuclear fusion inside the sun, where hydrogen atoms form helium through collisions. The mass of helium formed is less than that of Hydrogen combined. This difference of mass is the energy "lost" during the formation of helium, which we term as a "solar energy", radiant energy that sun emits into space [9, 14].

2.2.1 Types of Solar Energy Conversion

Conversion of solar energy into thermal and electrical energy can be either passive or active. Different types of technologies are being used to produce solar energy as discussed below.

2.2.1.1 Thermal energy

Solar thermal energy (STE) is a form of technology for harnessing solar energy for thermal energy (heat) [2, 15, 16]. The sun's energy can be collected directly to create high temperature steam (> 125ºC) and low temperature steam (< 100ºC-125ºC) for use in a variety of heat and power applications. High temperature steam can be used to drive turbine generators or to power chemical processes such as the production of hydrogen. Low temperature steam is used to heat air and water for industrial applications: for example, space heating for homes, offices and green house, domestic and industrial hot water, pool heating, desalinisation, solar cooking and crop drying, among many other applications [16].

There are two ways in which solar thermal system is used [6, 16, 17]:

1. Passive solar technologies: These are the technologies that use the energy absorbed from the sun without moving components (pumps or motors) [14].

2. Active solar technologies: These may have some additional features such as a pump to drive a system, or tracking motors which align the mirrors with the sun.

Most systems use pumps to circulate water or another heat absorbing fluid through a solar collector [17]. For example, when water is preheated before it is delivered to the cold inlet of conventional gas or electric water heater.

2.2.1.2 Electrical energy

Photovoltaic (PV), or solar cells produce electricity directly from sunlight. Photovoltaic technology is used to produce electricity in areas where power lines do not reach. In developing countries, it is significantly improving the living condition in rural area. It is flexible and offers unique opportunities to improve rural health care, education, communication, agriculture, lighting and water supply. Electrical energy can be applied in three ways [17, 18]:

1. Stand-alone. This is also known as Solar Home System (SHS). This system is not connected to the grid. SHS's are mostly installed in remote areas where there is no utility supply power, like remote holiday cottages. It is often cheaper to install such solar energy system than to lay electricity cables to the site. Excess energy can be stored in batteries for use during the time where there is no sunshine [19, 20, 21]. This is currently the most common system of renewable energy used in Rwanda.

2. Grid-connected: This is a system where utility supply electricity is connected to the property but the owners wish to harvest clean free energy from the sun. The electricity supply from the sun can be first from the solar system and then connected to batteries, if installed, and finally to the grid if there is a need [19].

3. Back up: Is a system connected to an unreliable grid or one of poor quality. These types are usually installed in areas where a lot of power blackouts occur [20, 21].

2.3 Principles of Solar collectors

Solar power systems aim at converting sun rays into electricity with the use of solar panels in order to supply power. These solar panels typically convert radiation from the sun into heat with the use of solar thermal collectors. The heat from the thermal collectors may be used for heating water for swimming pools or it can be converted into hot air and used for heating up of buildings during cold seasons [22, 23].

2.3.1 Photovoltaic Solar Energy Systems

Photovoltaic solar energy systems are used to convert solar energy directly from light into electricity, by the use of photovoltaic cells (PV cells). A photovoltaic cell consists of two thin sheets of a semiconductor, usually silicon (See Fig. 2.).
To get utilised two sheets, a process called doping is used during which impurities are added to the pure semiconductor (i.e. silicon) to increase the activity of free electrons [1, 14, 17, 24].
Doping can be done in two different ways:

- Doping with impurities that have more electrons on their outer shell (i.e. phosphorus has 5 electrons on its outer shell while silicon has 4) causes the sheet to become negative charged. This sheet of silicon is called **N-type**, and is a better conductor than pure silicon [17, 24].
- Doping with impurities having less electrons on their outer shell (i.e. boron has 3 electrons on its outer shell) creates **P-type**, positively charged, silicon. Instead of having free electrons, P-type silicon has shortage of electrons, or 'holes'. When the two sheets of silicon are sandwiched, an electric field is established between them due to those negative and positive charges. Thus, we have **P-N junction** [17].

The electric field acts as a diode, allowing electrons to flow from the positive side to the negative side just in one direction. See Fig. 2.

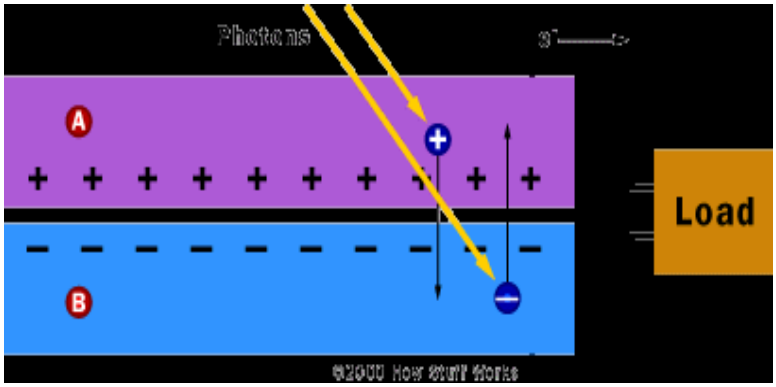


Figure 2: Solar Cell showing two sheets sandwiched together [19]

2.3.1.1 Photovoltaic Process

PV cells work using the **photovoltaic effect**. When photons strike a PV cell, they may be reflected, absorbed or they may pass right through. Only absorbed photons generate electricity. As the photons from the sun hit the solar cell, its electrons are freed, passing through the bottom of the cell to the electrical wire, thus producing electricity [19].

The current of the cell together with the cell's electric field allows computation of the cell's power output.

$$P = VI \qquad (2.1)$$

The greater the intensity of light, the more current is produced.

The usable voltage from the solar cells depends on the semiconductor material. The electrical field across the junction between the layers causes electricity to flow as DC. For example in Silicon, the voltage is about 0.5 V; this depends on light radiation, and current intensity increases with high luminosity. For example, 100 cm^2 silicon, reaches a maximum current intensity of approximately 3.3A when radiated by 1000 W. m^{-2}, (Fig. 3) [1, 7, 90].

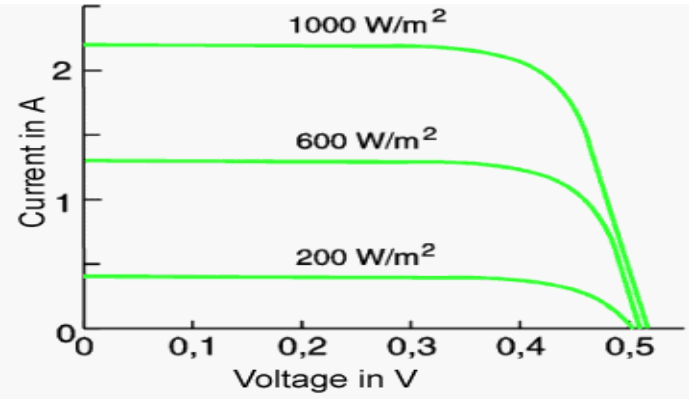


Figure 3: An example of current –voltage characteristic line of Si solar cell [14]

The Photovoltaic cells are then joined together to make modules which are positioned strategically to capture as much sunlight as possible around the distinguish building, as shown in Fig. 4.



Figure 4: Solar panel [25]

2.3.1.2 An example of operational plants

The solar electric light fund (SELF) has designed and installed Photovoltaic systems in five rural health clinics in Eastern Rwanda [24].

At the five clinics, (Mulindi, Rusumo, Rukira, Nyarubuye and Kirehe), solar power systems supply electricity for state of the art laboratories, refrigeration, computer record keeping and communication, including satellite dishes to transmit data. In the

laboratories, solar electricity powers microscopes, blood analysis machines, centrifuges, portable X-ray machines and sterilisation devices. The systems also provide extensive lighting, as these are 24-hour facilities with patient wards [24]. The size of those systems is between 12 - 120 Wp solar panels. There are also solar-diesel hybrids, which generate more than 90 percent of the power from the sun, with diesel generators available for back-up during prolonged heavy usage, or in rainy seasons. They are 12 volt (DC) stand alone systems which used PV to electrify small rural areas and the cost is about $0.66 per kWh.

2.3.1.3 Efficiency of solar cells

We have two terms to describe basic electricity production: **efficiency** and **capacity factor**. **Efficiency** refers to how much useful energy (electricity, in this case) we can get from an energy source**. Capacity** refers to the capability of a power plant to produce electricity.

Energy conversion efficiency is an expression of the amount of electrical energy produced in proportion to the amount of solar energy consumed or available to a device. For example, a commercial PV is about 7% to 17% efficient, which seems low. For comparison to a typical fossil fuel generator has an efficiency of about 33% to 48% of converting chemical to electrical energy [24, 27].

There are three main types of solar cells, which are distinguished by the type of crystal used in them. They are mono-crystalline, poly-crystalline, and amorphous. To produce a mono-crystalline silicon cell, an absolutely pure semiconducting material is necessary [7]. Mono-crystalline rods are extracted from melted silicon and then sawed into thin plates. This production process guarantees a relatively high level of efficiency

Table 1: Efficiency of solar cell

Material	Efficiency in lab (%)	Efficiency of production cell (%)
Mono-crystalline silicon	about 24	14-17
Poly-crystalline silicon	about 18	13-15
Amorphous silicon	about13	5-7

The production of polycrystalline cells is the most cost-efficient. In this process, liquid silicon is poured into blocks that are subsequently sawed into plates. During solidification of the material, crystal structures of varying sizes are formed, at whose borders defects emerge. As a result of this crystal defect, the solar cell is less efficient [27]. See Fig. 5.

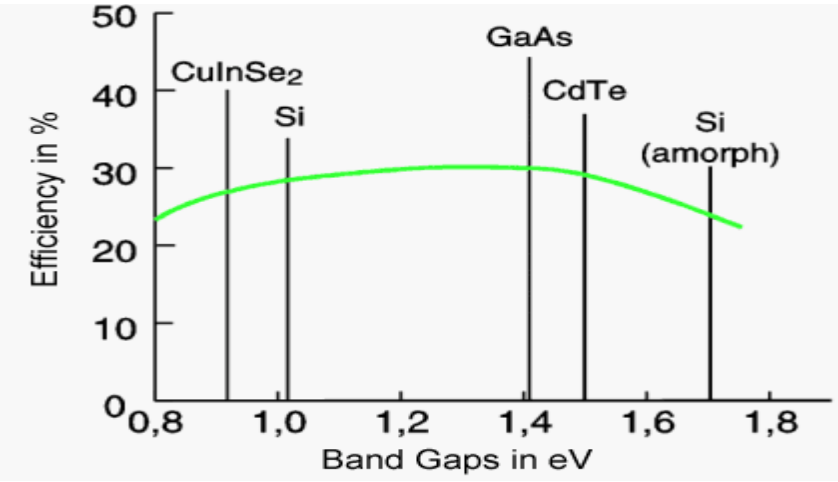


Figure 5: Theoretical maximum levels of efficiency of various solar cells at standards conditions [24].

2.3.1.3 Advantages and Disadvantages of Solar photovoltaic cells

a) Advantages

They do not use turbine or other moving parts that can wear out, making them very reliable. As more PV cells are connected together in series. And as such the amount voltage increases increasing the power. Finally, the PV cell technology requires minimal maintenance.

b) Disadvantages

Photovoltaic are costly to install. Solar cells produce DC which must be converted to AC (using a grid tie inverter) when used in current existing distribution grids. This incurs an energy loss of 4 - 12%. PV systems work within the limited power density of their location's insolation. The fact that solar panels are flat makes them inefficient at capturing all available solar energy when stationary.

2.3.2 Solar water heating

Solar water heating (SWH) has been used for several years as renewable energy technology. SWH has two types; **passive** based on natural convection (movement of hot water upward) to and **active**, based on pumps [14].

2.3.2.1 Passive systems

In a passive with system integrated collector storage (ICS) (see Fig. 6), the tank has two functions: storage and collection of heat. ICS is pressurised and depends on the gravity flow to deliver their water. It is simple, efficient and less costly than plate and tube collectors. They are productive especially in moderate climate with high insolation [16, 17].

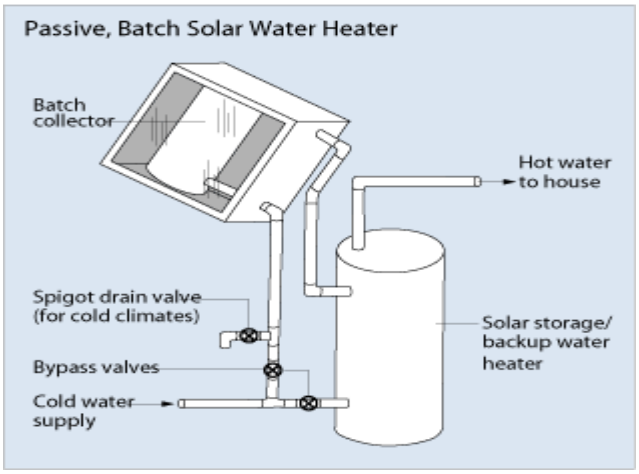


Figure 6: **Passive, Batch solar water heater [23]**

Apart from ICS, there is a convection heat storage unit (CHS or thermosiphon), which uses convection movement of water from the collector to the tank. There is no external agent to enforce the circulation. CHS is more efficient than ICS and it can be used in areas with less sunshine. Both systems will function by natural convection or heat pipes to transfer the heat energy from the collector to the tank [17, 22].

Direct (open loop) passive systems use water from the main household water supply to circulate between the collector and the storage tank. When the water in the collector becomes warm, convection causes it to rise and flow towards the water storage tank. They are often not suitable for cold climates since, at night, the water in the collector can freeze and damage the panels [22].

Indirect (close loop) passive systems use a non-toxic antifreeze heat transfer fluid (HTF) in the collector. When this fluid is heated, convection causes it to flow to the tank where a passive heat exchanger transfers the heat of the HTF to the water in the tank [16, 23].

Passive systems are simple, with few mechanical or electrical components which can break and ask for special maintenance. However, their maintenance is simple and cheap. Their efficiency is less than that of active systems.

2.3.2.2 Active systems

An active system (Fig .7) is one where the exchange fluid is actively pumped from the storage tank through the collectors and back into the tank. An electronic controller, a small pump, valves and other components are needed for proper operation and future ability to service. Active systems are more expensive and require more maintenance over the years; passive systems are less expensive and more reliable [22].

However, active systems are much more efficient and it is this factor which can make them more attractive than passive. With the active solar water heating systems available, there are two principal types of water circulation: Direct (or Open Loop) and indirect (or Closed Loop) [15, 23].

Indirect circulation is more complicated with a heating fluid pumped through the collector and then into water storage tank, where a copper heat exchanger transfers the heat from the fluid to the consumable water. The heating fluid is generally a mixture of water and anti-freeze and, as such, this system is well-suited to climates were freezing can occur.

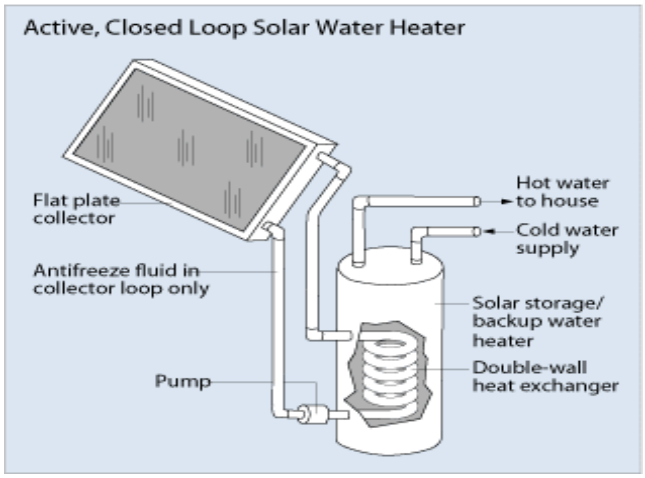


Figure7: Active, closed loop solar water heater [23]

There is greater maintenance required when it comes to active solar water heating, with yearly or half-year checks advised. In an indirect system, the heating fluid will need to be changed about every 3 years. There is also the matter of the heat exchanger in the storage tank, which will age and will need to be replaced in time. However, the system is highly efficient and is suitable for commercial use [16, 22].

Technically, the direct system is known as an "active open loop" type. In an "active open loop" system, water from a large storage tank or tanks is heated by the sun as the water passes through solar panels. The system is called "active" because it uses a small pump to circulate the water from the storage tank through the collectors and back into the storage [23].

2.3.3 Concentrating Solar Power (CSP) Systems

Concentrating solar thermal power and PV are two major technologies for converting sunlight into electricity. Sunlight can be converted directly into electricity with PV and indirectly with CSP. Solar panels can be extremely inefficient at capturing all of the available energy because of their flat shape and the fact that the sun shines at different levels throughout the day [28]. The use of CSP systems can correct this problem.

CSP systems use mirrors such that the sunlight reflects back to the solar collectors, enabling them collect solar energy more efficiently. In fact, CSP systems focus the sun's energy to boil a liquid which is then used to provide power. They use lenses, mirrors, and tracking systems to focus a large area of sunlight into a small beam. The concentrated radiation is then used as a heat source for a conventional power plant.

CSP plants produce electricity by converting the sun's energy into high temperature heat, using various mirror configurations. A plant has two parts [17, 29]:

1. Solar energy collection,
2. Conversion of heat energy to electricity.

CSP systems can only concentrate direct beams of sunlight, not diffused components. They must track the sun to keep the sunlight concentrated on the receiver at the focal point of the collector. The three basic designs of CSP are troughs, towers and dish-engine systems [28].

The annual solar irradiatio2n variation has impact on their annual efficiency, specific output and electricity generation cost (as with any solar system).

2.3.3.1 Physics behind CSP

CSP principles are based on the three mechanisms of heat transfer; conduction, convection and radiation which are functions of temperature.

In solar energy conversion especially for solar thermal energy heat transfer mechanisms are used [1, 15].

2.3.3.1.2 Heat Transfer mechanisms

1. Conduction

Conduction is heat transfer by means of molecular agitation within a material without any motion of the material as a whole (i.e. the energy transfer through a material) [1, 16].

The equation which describes this process through a homogeneous material is:

$$H = KA\frac{T_{hot} - T_{cold}}{L} \qquad (2.2)$$

where H is the quantity of heat flowing through the homogeneous material per unit time (heat current); A is the cross-section area of the material; K is the thermal conductivity of a material; and L is the thickness of the barrier. Importantly, heat transfer is directly proportional to the temperature gradient in the system $\sim \frac{\Delta T}{L}$.

This expression can also be investigated to define a parameter for how well a material conducts heat

$$K = \frac{HL}{A(T_{hot} - T_{cold})} \tag{2.3}$$

and we define the effective thermal resistance (R_c) as

$$R_c = \frac{L}{KA} \tag{2.4}$$

which can help us to calculate K.

2. Convection

Convection is the transfer of heat by the actual motion of material from one region of a space to another (i.e. in a liquid or a gas) [1, 16]. There are two kinds of convection:

(a) Forced convection, when the material is made to move by an external force, such as a wind or a pump.

(b) Natural or free convection, when the material flows owing to differences in density caused by thermal expansion (i.e. heat in fluid is driven by a buoyancy force) [1, 15].

The convective heat transfer is a complex process, and there is no simple equation to describe it, as there is for conduction. Here is a commonly used approximation to calculate the heat current (H) as:

$$H = h_v A \Delta T \tag{2.5}$$

Where ΔT is the temperature difference between the surface and the main body of the fluid and h_v is a quantity called the convection coefficient (h_v is not a constant, but

depends on T in practice, values of h_v are determined by experiment and are tabulated for materials) [30].

3. Radiation

Radiation is the energy transfer in form of electromagnetic waves [1, 16]. Unlike the first two processes, this occurs between objects which are not in physical contact.

The emission of radiation by a hot body increases very rapidly with increased temperature. The rate of radiation of energy from a surface is proportional to the fourth power of temperature. In addition, the rate of heat loss depends on the nature of the surface, called its emissivity. Therefore, some surfaces are better emitters of radiation than others at the same temperature due to their composition.

The following equation describes radiation:

$$H = A\alpha\varepsilon {T_0}^4 \tag{2.6}$$

where σ is the Stefan-Boltzmann constant; A is a radiating area; and ε is the emissivity.

2.3.3.2 How CSP systems work

Concentrating solar power systems can be classified by how they collect solar energy.

The following pages discuss and illustrate the basic operation of each of the three main technologies of CSP systems: Linear concentrator systems, Dish/engine systems and Power tower systems [16, 29].

1. Solar Tower

A power tower, also known as a central tower power plant or heliostat power plant, uses an array of flat, moveable mirrors (heliostats) to focus the sun's rays upon a collector tower (receiver). This uses a higher temperature than a parabolic trough (described below) which is an advantage because thermal energy can be converted to electricity more efficiently at higher temperatures and can be cheaply stored for later use. But this design must have a dual axis control, while for the parabolic trough design; one axis can be shared for a large array of mirrors (See Fig. 8) [29]. For

example Ciudal Real Torre solar is constructed in Spain should stand 750 m tall and it is expected to have an output of 40 MW of electricity.



Figure 8: Solar tower design [31]

2. Solar Trough

Its function is to concentrate the radiation, and to heat a transfer fluid (i.e. oil, molten salt and pressurised steam). Designs use parabolic trough power plants which use a curved trough that reflects the direct solar radiation onto a receiver (i.e. collector) running along the trough, above the reflectors. This particular system will be discussed in more details later, in chapter 8 of the second part of this dissertation. The trough is parabolic in one direction and straight in the other (See Fig. 9) [32].



Figure 9: Solar trough plant design [12].

3. Dish Designs

A dish system uses a large, reflective, parabolic dish (similar in shape to satellite television dish). It focuses all the sunlight that strikes the dish up onto to a single point above the dish, where a receiver captures the heat and transforms it into a useful form. Typically the dish is coupled with a Stirling engine in a Dish-Stirling-System, but sometimes a steam engine is used [29, 33]. These create rotational kinetic energy that can be converted to electricity using an electric generator.



Figure 10: Solar Dish design [34]

2.3.3.3 Advantages and Disadvantages

(a) Advantages

The sun supplies much energy in areas of high insolation, serving a virtually inexhaustible source of fuel. Environmentally friendly, there is no emission of contaminants or greenhouse gases. It can be used as supplement to other sources (wind energy, hydropower...). Being versatile, it can be used for hot water, heating, cooling, and power generation. The cost savings arise from not having to transport, mine, or prepare it. CSP technologies such as SEGS [35] are the most cost-effective solar option for large-scale electricity generation.

(b) Disadvantages

Some geographical areas may not be adequate to produce sufficient energy. It requires a large area to ensure its effectiveness, and initial installation cost may be prohibitive. The collection of solar energy depends on weather conditions, and no energy is produced during night time. Concentrating systems requires sun tracking to maintain sunlight focus at the collector.

2.3.3.4 Energy Efficiency of CSP

A tracking (moving) collector compared to horizontal collector at the same site will collect 1.5 times more energy per day. The more direct the radiation the higher is the energy generation from sun's radiation. The upper limit of the concentration ratio of round concentrating collectors is about 4000 whereas that of linear parabolic systems is about 200 [28].

Table 2: The capacity CSP

	Parabolic trough	Power tower	Dish/engine
Size	30 -320 MW	10-200 MW	5.25 KW
Operating temperature (^oC)	400	600	750
capacity factor	23 - 50%	20 - 70%	25%
peak efficiency	20%	23%	29.9%
Net annual efficiency	11 - 16%	7 - 20%	12 - 25%
Cost ($) /Wp	4.0 - 1.3	2.4 - 0.9	12.6 - 1.2

2.4 Situation of Solar Energy Technology in Rwanda

In rural areas and particularly in developing countries there is little access to electricity. The access of electricity services can be found in urban areas but it is not reliable. In Rwanda, 9% of the population has access to electricity. To survive, people

are using other forms of energies such as wood, paraffin and gas. These sources are not renewable and as such are bound to run out with time [4, 5].

Looking at the availability of the solar radiation in Rwanda solar energy can be a viable source of electricity. The potential for solar energy in Rwanda is 4.5-5.5 kWh m^{-2} day^{-1} at an average of 8 hours of sunshine a day. The government is trying to invest in solar energy, so that those who live in rural areas can have access to electricity [3, 4].

Solar energy has been exploited recently in Rwanda by local and international organizations for the electrification of churches, schools and households in rural areas. However, the relatively high cost of solar systems has been a barrier to widespread dissemination until now [36].

Currently, solar energy is mainly used for two purposes in Rwanda:

- Electric power production through solar photovoltaic systems and
- Direct heating, for example in solar water heaters or for sun-drying agricultural produce.

2.4.1 Photovoltaic Solar Energy for electricity

Solar energy can be converted into electric energy and is a means of electrifying rural populations far from the national grid. This transformation is achieved through photovoltaic panels on rooftops. The produced electricity is then transported to a battery where it is stored for later use. This means that energy generated by day can be used at any time including for lighting purposes at night [36, 37]. Depending on the size of the system, solar methods can power health centres, schools, administrative offices and houses far from the grid that would otherwise have to rely on diesel generation. In addition to these off grid installations, Rwanda also has a 250 KW solar installation, Kigali Solaire, connected to the national grid. This plant, located on Mount Jali in the vicinity of Kigali and owned by the Stadtwerke Mainz of Germany, is the first independent solar power plant in the country. Under Rwanda's Economic Development and Poverty Reduction Strategy

(EDPRS), it is expected that all health centres, administrative offices and 50% of schools further than 5 km from the grid will be electrified by off grid renewable energy sources such as solar. There is also a target to have installed at least 1MW of solar photovoltaic power generation capacity by 2012 to satisfy about 15,000 households or subscribers in rural areas [5, 36, 37, 38].

Ministry of Infrastructure (MININFRA) is also developing the idea of Solar Kiosks, which will consist of a central solar battery charging station, where rural communities can rent charged batteries for a small fee to power their lighting and equipment at home. Currently, the MININFRA in collaboration with development partners, is working on establishing technical standards for all components of solar equipment to ensure the supply of high quality products [36].

2.4.2 Solar Water Heating Potential in Rwanda

The Rwandan climate is favourable to the use of solar water heaters. A lot of electric energy is currently used to heat water in households, hotels, hospitals etc., while solar water heating is a very efficient and low cost way of heating water, thus saving electricity for other purposes [37]. Under EDPRS targets, it is expected that by 2012, electricity connections shall have moved from the current 92,000 to 350,000. These estimates that at least 20% of the population will be using electricity for domestic purposes as solar water heating will be installed in approximately 70,000 households and some hotels, health centres, schools and hospitals [4, 37].

Despite of the high cost for electricity in Rwanda (USD 0.21 kWh) at present, the solar PV market is still undeveloped. Current demand for PV is less than 60 kWp/annum and total installed capacity is estimated to be below 1 MWp.

Chapter 3

Hydropower Energy

3.1 Introduction

In this chapter we discuss hydropower. We are also presenting different hydropower technologies and their applicability in Rwanda.

3.1.1 Natural Energy Resource

Hydro-power is the energy obtained from moving water. The fall and movement of water is a part of a continuous natural cycle called the ***water cycle***. Hydropower is called a renewable energy source because water is continuously replenished by precipitation. Hydro-power draws its energy from the sun which drives the hydrological cycle, which in turn provides a continuous renewable supply of water with high potential energy [39, 40, 41].

3.1.2 Historical Background of Hydropower Energy

Humans have been using water to perform work for thousands of years. For example the Greeks used water wheels for grinding wheat into flour more than 2,000 years ago [42].

Besides grinding flour, the power of the water was used to saw wood and power textile mills and manufacturing plants.

The evolution of the modern hydropower turbine began in the mid-1700s when a French hydraulic and military engineer, Bernard Forest de Bélidor wrote "*Architecture Hydraulique"*. In this four volume work, he described using a vertical-

axis versus a horizontal-axis machine. During the 1700s and 1800s, water turbine development.

In 1880, a brush arc light dynamo driven by a water turbine was used to provide theatre and storefront lighting in Grand Rapids, Michigan, and in 1881, a brush dynamo connected to a turbine in a flourmill provided street lighting at Niagara Falls, in New York. These two projects used direct current technology [43].

The capacity of total worldwide installations has grown at 5% per year since 1940. Hydropower now accounts for about 20% of world's total electricity generation which is very much dependent on the amount of rainfall [44].

Hydropower is the most established and widely used renewable resource for electricity generation and commercial investment.

3.2 Water Cycle

3.2.1 What is Hydraulic cycle?

The hydraulic cycle is the continuous circulation of water between the earth and the atmosphere, involving the following components: **condensation** (processes whereby water is changed from gas to liquid), **precipitation** (rain, sleet, hail, snow and other forms of water falling from the sky), **runoff** (water flow that occurs when soil is infiltrated to full capacity and excess water from rain, melt water, or other sources flows over the land), **percolation** (concerns the movement and filtering of fluids through porous materials.), **evaporation** (process whereby water is changed from liquid to gas) and **transpiration** (the process by which plants give off water vapours into the atmosphere.) . Those processes occur in water cycle and begin from the ocean where most of earth's water exists [39, 45, 46].

Hydropower plants work is mainly based on hydraulic cycle and depends on water flow. If it is not raining near the plant, there is no collection upstream and less water flows through the hydropower plant and hence less electricity is generated.

We have two sorts of water cycle: **Water cycle in nature** and **in hydraulic power plant.**

3.2.2 Water cycle in nature

All natural bodies of water are heated by the sun, which causes evaporation. The water vapours move towards the upper layers of the atmosphere where they form clouds. Upon precipitation of clouds rain occurs. Due to heavy rains large quantities of water flows through various parts of the earth in the forms of streams, channels and rivers. All the water from rivers is collected back to the oceans, where evaporation of water occurs again [39]. See Fig. 11.

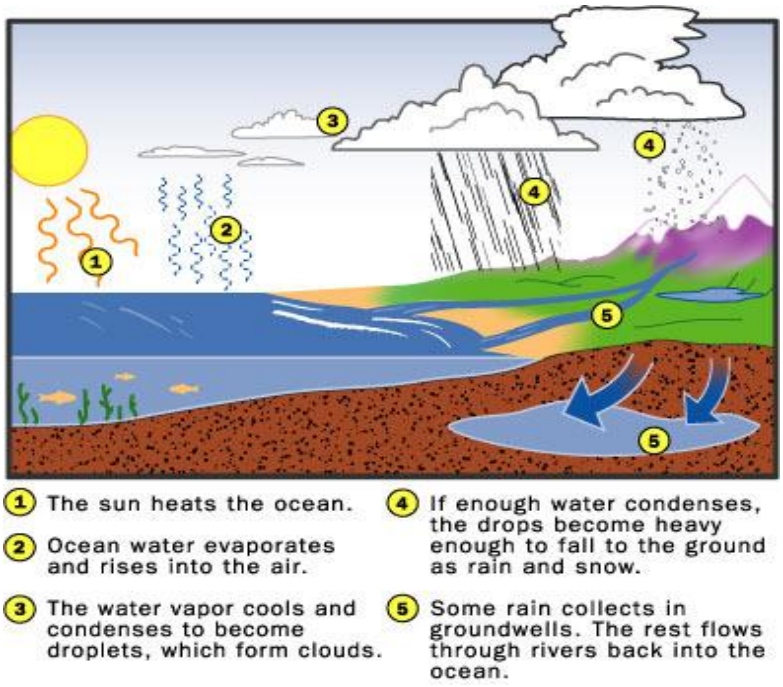


Figure 11: Water Cycle in Nature [47].

3.2.3 Water cycle in the hydraulic power plants

The water in rivers possesses potential energy and kinetic energy due to the level water and movement. Depending on the type of hydraulic power plants, the kinetic or potential energy of water is used to generate electricity [39, 40].

The most commonly used method of production of electricity from hydropower is by the use of **dams**, which are constructed across large rivers. The large quantities of water from river are diverted by pipelines (called 'penstocks' see Fig. 12) towards the main plant where large turbines are located. Hydropower plants harness the water's energy and with the use of simple mechanism, this energy is converted into electricity. Flowing water turns a turbine which in turn turns a generator [9, 40, 45].

The flow of water represents a huge supply of Kinetic energy (KE) that can be put to work. The water from penstocks is allowed to fall on the large turbine blades that start rotating. The shaft of the turbine rotates the electric generators. This electricity is then passed to a transformer from where it is connected to the main national grid. The water leaving the turbine flows back to the river at the lower levels with much of its Kinetic Energy lost to the turbine [40, 41].

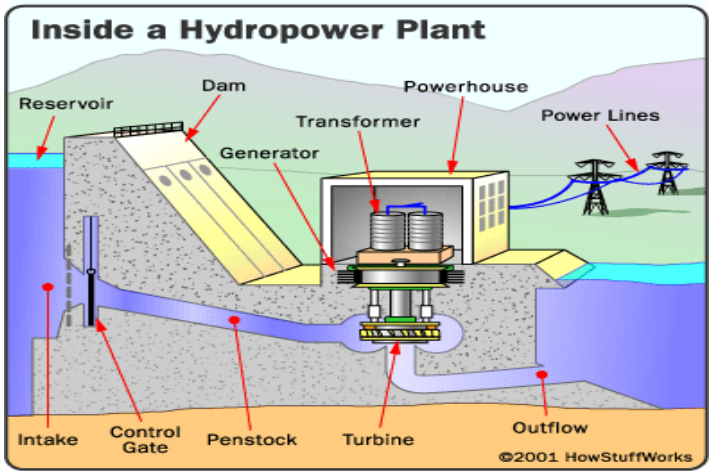


Figure 12: Water cycle inside the hydraulic power plant [40]

3.3 Hydropower Plants

3.3.1 Hydropower Plant Components

A typical hydropower plant is a system with six main components:

1. A reservoir (artificial lake) which is the main part of hydropower plant, where water can be stored. It is built at a higher level than the turbine [48].
2. A dam is a part of hydropower plant that can be opened and closed to control water flow. The dam has two functions for hydro plant:
   First, a dam increases the head or height of water. Second, it controls the flow of water; dams release water when it is needed for electricity production. For example during heavy rains, there is a special gate which is used to release excess water from the reservoir called 'spillway' [49, 50].
3. The penstock: This part connects the reservoir with the turbine propeller and runs in a downward inclined manner. When the gates of the dam are lifted, the forces of gravity make the water flow down the penstock and reach the blades of the turbine. As the water flows through the penstock, the potential energy of water stored in the dam is converted into kinetic energy [48, 49, 50].
4. A power plant where the electricity is produced. The motion of the running water turns the blades of a turbine in order to generate electricity. The turbine can be either a Pelton Wheel Model (described like a radial turbine for which the flow of its working fluid is radial to the shaft) or a Centrifugal type (where the flow of its working fluid is turned perpendicular to the axis of rotation). The turbine has a shaft connected to the generator [41, 50].
5. The generator: A shaft runs from the turbine to the generator. When the blades of the turbine rotate, the shaft turns a rotor which produces electric current in the generator.

6. Power lines: The power produced in the generator is sent to the powerhouse will send it to various power distribution stations through the power lines [50].

   Water wheels are too slow for production of electricity. Hydroelectric plants use modern turbine generators to produce electricity.

3.3.2 Types of Hydropower Plants

There are three types of hydropower facilities:

1. **Impoundmen**t

   An impoundment facility is the most common type of hydroelectric power plant. It is also typically a large hydropower system which uses a dam to store river water in a reservoir. Water released from the reservoir flows through a turbine, spinning it, which in turn activates a generator to produce electricity. That water may be released either to meet changing electricity needs or to maintain a constant reservoir level [33]. It is the most conventional hydropower plant.

2. **Diversion**

   It is another conventional hydropower facility, sometimes called run-of-river, which channels a portion of a river through a canal or penstock. It may not require the use of a dam [33].

3. **Pumped Storage**

   The pumped storage facility is specially used when the demand for electricity is low. It stores energy by pumping water from a lower reservoir to an upper reservoir. During periods of high electrical demand, the water is released back to the lower reservoir to generate electricity [33].

3.3 3 Sizes of Hydroelectric Power Plants

Hydroelectric power facilities range from large power plants that supply many consumers with electricity to small and micro plants that individuals operate for their own energy needs or to sell power to utilities [45, 48]. They are classified as:

Large Hydropower Plants: They have a capacity of more than 30 megawatts.

Small Hydropower Plants: They have a capacity of 100 KW to 30 MW.

Micro Hydropower Plants: They have a capacity of up to 100 KW.

A small or micro-hydroelectric power system can produce enough electricity for a home, farm and village.

3.3.4 Head and Flow

The amount of electricity that can be generated at hydropower is determined by two factors: **head** and **flow [**41**]**.

1. **Head** is the vertical fall of water. It is also a distance from highest level of demanded water to the part where it goes or vertical distance between the highest point of water source and the turbine (generator) [47, 48].
2. **Flow** is how much water moves through the system (the volume of water passing through a turbine in a given amount of time).

   A low head site has a head of below 10 meters. And a high head site has a head of above 20 meters.

   It is generally better to have more head than more flow since it keeps the equipment small [47, 48, 49].

3.3.5 Types of Turbines

We have two type of turbines based on head and flow of water; **reaction turbine** and **impulse turbine [**51, 52**]**.

1. Impulse Turbine: It generally, uses the velocity of the water to move the runner and discharges to atmospheric pressure. In this case, the water stream hits the bucket on the runner. Impulse turbine is suitable for high head (H) and low flow (Q) in application [51].

   Examples of Impulse turbine include the Petlon and cross flow turbines, which are shown in figures 13 and 14 respectively.



Figure 13 : Pelton Turbine [53]

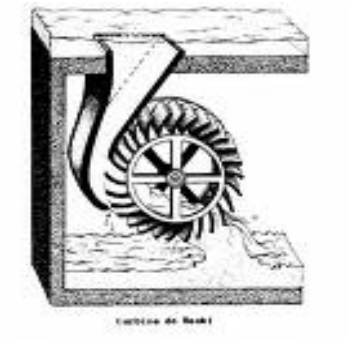


Figure 14: Cross flow turbine [54]

2. Reaction turbine: It develops power from the combined actions of pressure and moving water. The runner (a wheel which catches the water as it flows in causing the wheel to turn) is placed directly in the water stream flowing over the blades rather than striking each individually. It is suitable for low head and high flow. As we can see the choice of turbine will depend also on the head and the rate of flow [41, 44, 52].

   Examples of the reaction turbine include the Propeller turbine, with an axial flow and the Francis turbine, with a mixed flow. Both the Propeller and the Francis turbines can be mounted either horizontally or vertically.

   The Propeller turbine consists of a fixed blade and variable pitch blade (Kaplan) as shown in figure 15. This turbine consists of four runners with five blades through which water passes in a radial direction with respect to the shaft. The pitch of the blade may be fixed or movable [51]

   The Francis turbine, as shown in figure 16, consists of runners fixed with nine or more buckets (vanes), through which water enters the turbine in a radial direction with respect to the shaft, and is discharged in the axial direction. [50].

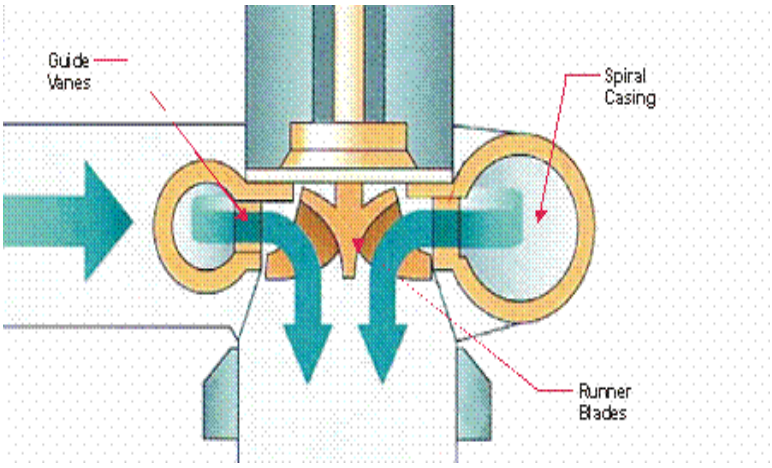


Figure 15: propeller turbine (Kaplan type) [51a]

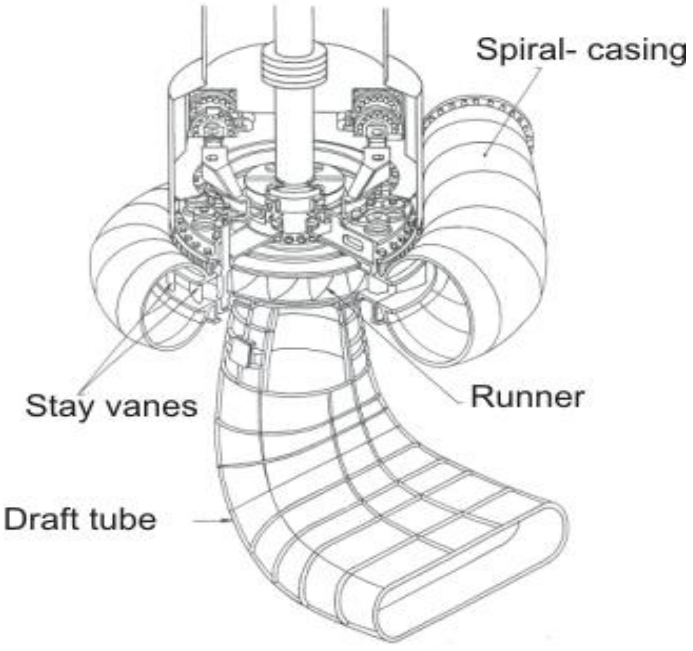


Figure 16: Francis turbine [55]

3.4 Basics Principle of Hydropower

3.4.1 Some basic concepts

In hydroelectric power plant, the potential of water due to its high location is converted into **electrical energy**.

The total power generation capacity of the hydroelectric power plants depends on the head of water and volume of water flowing towards the water turbine.

If hydro turbine is considered as a system, the force and the Bernoulli equations are applicable for the surface area of the turbine [41, 56].

- **Force equation**

  Force on control surface = Summation of Impulse and Pressure forces

$$\vec{F} = m\frac{d\vec{V}}{dt} \tag{3.1}$$

$$F = \Phi_m\ (\overrightarrow{c_1} - \overrightarrow{c_2}) + P_1\ A_1\ - P_2 A_2 \tag{3.2}$$

Where Φ_m is flow rate, c_1 is the intake jet velocity, c_2 is the outflow jet velocity, A_1 and A_2 are cross sections intake and outflow respectively.

In Bernoulli's equation, the sum of position energy, pressure energy and kinetic energy is a constant in a confined moving fluid as the fluid moves along its path. To get the power that can be generated from water in hydroelectric power plant due to its height we use the following equation [45]:

$$h + \frac{P}{\gamma} + \frac{V^2}{2g} = constant \tag{3.3}$$

where γ is equal to ρg ; ρ is density of flowing fluid; h is height of water (m); g is gravitational acceleration constant in m/s^2; P is the pressure (Pa); V is average fluid velocity (m/s).

This equation can be applied between two points (1 and 2) on a streamline (a family of curves that are instantaneously tangent to the velocity vector of the flow. These show that the direction a fluid element will travel in, at any point in time);

$$h_1 + \frac{P_1}{\gamma} + \frac{{V_1}^2}{2g} = h_2 + \frac{P_2}{\gamma} + \frac{{V_2}^2}{2g} = H \tag{3.4}$$

Considering friction loss, the equation above becomes;

$$h_1 + \frac{P_1}{\gamma} + \frac{{V_1}^2}{2g} = h_2 + \frac{P_2}{\gamma} + \frac{{V_2}^2}{2g} = h_f \tag{3.5}$$

Where h_f is the specific head loss due to friction and it depends on the type of the flow (Laminar or Turbulent) [1].

The general formula of hydro system's power output is:

$$P = \eta \rho g Q H \tag{3.6}$$

where η is the hydraulic efficiency of the turbine; Q is the volume flow rate passing through the turbine (m^3/s or l/s); H is the effective pressure head of water across the turbine (m).

In practice, hydro system's power output is calculated based on the type of turbines [41].

For a Pelton Turbine:

The force (F) acting on the bucket for flow rate, $\Phi_{m.}$

$$\vec{F} = \Phi_m 2(\vec{c} - \vec{u}) \tag{3.7}$$

where *c* and *u* are jet and turbine speed respectively.

Torque (T) generated for turbine diameter (D):

$$\vec{T} = \overrightarrow{F}\frac{D}{2} = \Phi_{\mathrm{m}} D(\vec{c} - \vec{u}) \tag{3.8}$$

Then the output power is:

$$P = \omega T = \Phi_m 2(\vec{c} - \vec{u})u \tag{3.9}$$

where $\omega = 2u/D$

We get the maximum power when turbine speed is half of the jet speed as shown below:

$$\frac{dP}{du} = 0 = c - 2u$$

$$u = \frac{1}{2}c \tag{3.10}$$

3.4.2 Efficiency

A significant factor in the comparison of different turbine types is their relative efficiencies both at their design point and at reduced flows. An important point to note is that the Pelton and Kaplan turbines retain very high efficiencies when running below design flow; in contrast the efficiency of the Cross flow and Francis turbines falls away more sharply if run at below half their normal flow. Most fixed-pitch propeller turbines perform poorly except above 80% of full flow [46, 51].

We used the first law of thermodynamics:

$$E = \Delta W + Q \tag{3.11}$$

where ΔE is change of energy of an object; W is work done on the object; Q is the heat added to the object [57].

The only way to change the energy of an object is either **to do a work on it** or add **heat on it**. Note that, having an object, doing work on its surroundings or allowing object to give off heat, are equivalent to negative values of W and Q [50].
The first law tell us that the energy involved in any transformation is **conserved**.
Then the efficiency of the system:

$$\eta = \frac{\text{Electric energy output}}{\text{potential energy}} \tag{3.12}$$

where potential energy is equal to $\left(\frac{9800\text{J}}{\text{m}^4} \times \text{VH}\right)$

Today hydropower turbines are capable of converting more than 90% of available energy into electricity, which is more efficient than any form of generation (i.e. the best fossil fuel power plant is only about 70% efficient).

Hydropower turbine generators are very efficient when compared to wind turbine generator and solar panel [44, 46, 58].

3.5 Advantages and disadvantages

(a) Advantages

The construction of micro-hydroelectric power plants in Rwanda has several advantages [38]. It diversifies production sites and improves grid stability of the network and exploits the country's hydroelectric potential (numerous rivers and streams). For examples; Rusizi, Ntaruka, Mukungwa, ect. Hydropower strengthens the energy autonomy of the country; this can help Rwanda to depend on its own energy resources and diminishes reliance on fossil fuels by developing sustainable energy (clean and renewable energies). It reduces pressure from deforestation by progressively replacing wood fuel with electricity for domestic consumption. People can reduce using biomass (wood) as the only source of energy. It reduces CO_2 emissions.

(b) Disadvantages

Dams can cause several environmental setbacks such as soil erosion, species extinction, spread of disease even though they burn no fuel. It may also affect water quality by churning up dissolved metals that may have been deposited by industry over a long period. It changes water temperature, and lowers the levels of water dissolved oxygen. It is expensive, considering the fact that it requires a lot of water,

as well as land for building dams and reservoirs and due to insufficient funds and impetus to provide equipment, such as hydro turbines generators and control systems, many projects are stuck in the planning stage.

3.6 Rwanda Situation

Rwanda is known as country of thousands Hills, but it is also a country of numerous rivers that flow down these hills which can be used to generate electricity. Currently only 9% of Rwanda's population has access to the electricity [1].

In Rwanda there are several hydropower plants. A recent hydropower atlas project has identified 333 hydro sites which have the capacity of 96 MW. For small hydropower, the technical potential is estimated to be at about 10 MW and the country hydropower potential share at Border River is about 115 MW [38].
We can give an example of Janja micro hydropower plant which has the capacity of 200KW and is implemented by the government of Rwanda.

The most electricity is produced from hydropower resources. Currently a total of 27.3 MW of electricity (Ntaruka: 11.5 MW, Mukungwa: 12.5 MW, Gihira: 1.8 MW and Gisenyi: 1.2 MW) is being produced through hydropower. A part from those ones, we have other hydropower plant under construction (i.e. 8 micro hydropower plants).

For example, by 2015 the number of people who have access to electricity is estimated to increase by 10%. Hydro power plants under construction include [38]:

3.6.1 Nyabarongo hydropower plant (27.5 MW)

This plant is located in Muhanga and Ngororero Districts. Currently the access roads are under construction. We are expecting it to start working in 2013 [4, 38].

3.6. 2 Rukarara hydropower plant (9.5 MW)

The plant is located in Nyamagabe district; the construction works are at 55% to completion. The commissioning was expected to take place in the first quarter of 2010 [38].

3.6.3 Eight (8) Micro Hydro Power Projects (MHPP)

These MHP are: Gashashi (200 kW), Janja (200 kW), Mukungwa-II (2.5 MW), Nyirabuhombohombo (500 kW), Nyabahanga (200 kW), Rugezi (2.2 MW), Nshilli-I (400 kW) and Ruhwa (200 kW). The completion date had been set for end of June 2010 but some of them still under construction [38].

Currently only 21 of 333 sites have been developed and others still under construction.

In 2006, Electrogaz decided that the power purchase agreement (PPA) tariff would only be Frw 60 per kWh (0.11$). Today electricity cost is about 0.23$ per kWh from hydropower source.

Chapter 4

Biomass

4.1 Introduction

This chapter looks at the different types of biomass energy and their basic processes of transformation. It also looks at different ways of improving the energy source, usage and also evaluates its efficiency.

4.1.1 Biomass as a Natural Energy Resource

Biomass is renewable organic (plant or animal) matter, such as wood, plants (grasses), residues from agriculture and forestry, organic components from municipality, industrial wastes and fumes from landfills [1]. The global estimation of biomass production is estimated to be 46 billion metric tons per year [59].

4.1.2 Biomass is Renewable Energy

Biomass energy is renewable and ultimately originates from solar energy origin because plants use photosynthesis to fix carbon dioxide (CO_2) and animals feed on plant material before they ultimately end up as 'waste products' (biomass resource) [1, 59]. Its resources can be replaced or grown in a short period of time.
The energy produced during the combustion of biomass is due to natural processes, where natural gases and oxygen react. The energy produced is a form of renewable energy and using this energy does not add CO_2 (except during the combustion) to the environment.

Biomass energy is an energy source that is produced from the direct burning of biomass (it reacts with oxygen in combustion and natural metabolic process; for example, Eq. 4.1), or converting it into gaseous (Methane gas) or liquid (Ethanol

(alcohol) and Biodiesel (Ester)) fuels that burn efficiently to generate electricity or heat for industrial purposes [60].

$$CH_4 + 2O_2 \rightarrow CO_2 + 2H_2O \quad (4.1)$$

Biomass energy can be used directly or indirectly. Firewood is a common example of direct use by combustion and Ethanol derived from agricultural crops such as sugar cane and methane from manure and sewage are examples of indirect use [61].

Biomass energy is mostly used in developing countries (i.e. Rwanda. Uganda, Tanzania, Burundi, etc.), and is a major component of the energy supply. The simplest way to use it as energy is to burn it to provide heat for cooking and comfort, see (Eq. 4.2) [59].

$$\text{Wood} + \text{air} + \text{heat} \rightarrow \text{ash} + \text{smoke} + \text{even more heat} \quad (4.2)$$

4.1.3 Historical background of Biomass

Biomass (plant material and animal waste) is the oldest source of renewable energy, used since ancient times in form of wood fires [14].

Prior to the industrial revolution, biomass satisfied nearly all of man's energy demands. For example, up until the 1860s, the United States used biomass, in form of wood, for nearly 91% of all the energy consumption. Although presently the majority of humankind's energy requirements are fulfilled by fossil fuel combustion, 14% of the world still utilizes biomass [59].

Until now biomass supplies more renewable electricity or bio-power than wind energy.

In Rwanda biomass energy had been used since ancient times and currently it is the main renewable energy resource that can be easily accessed.

4.2 Biomass Conversion Process

There are several ways of biomass conversion technologies available to make use of a wide variety of biomass types as a renewable energy source. Those technologies can release the energy directly, in the form of heat or electricity, or can convert it to another form of energy, such as liquid bio fuel or combustible biogas [59, 61, 62].

There are two types of biomass conversion; thermal chemical and biological conversion (i.e. Burning, alcohol fermentation, pyrolysis and anaerobic digestion).

4.2.1 Thermal Chemical conversion

1. Combustion

Combustion is a thermal conversion of organic matter with an oxidant (normally oxygen) to produce primary CO_2 and H_2O. It is very common and mostly used in order to produce heat. The energy release by direct combustion can be used to directly influence the temperature of small environment or to power turbine (steam-driven turbine) to produce electricity. This type of combustion results in air pollution and contributes to greenhouse effect. When mixing biomass with coal, this co-firing process is very efficient. Solid municipal waste is also burned to generate electricity [14, 61].

During the combustion we have the following chemical reactions:

$$C(s) + O_2\,(g) \rightarrow CO_2\,(g) \tag{4.3}$$

$$H_2\,(g) + 1/2O_2 \rightarrow H_2O \tag{4.4}$$

$$CH_4\,(g) + 2O_2\,(g) \rightarrow CO_2\,(g) + 2H_2O \tag{4.5}$$

For Combustion to take place we must have; fuel, oxygen (usually air), and a source of heat to start and maintain the process. This is known as a 'fire triangle' (see Fig. 17) and for combustion to happen this triangle must be complete [63].

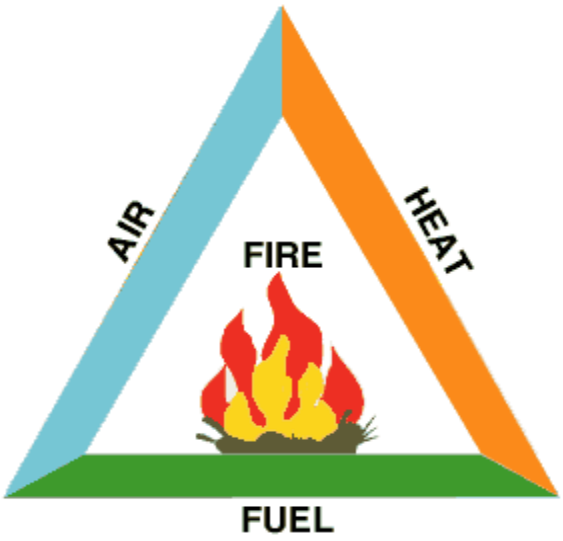


Figure 17: Fire triangle [64].

The combustion can take place into combustor such as, stoker grate, fluid bed, or a circulating fluid bed, etc.

2. Pyrolysis

Pyrolysis is a fundamental chemical reaction process which is a precursor of both gasification and combustion. It is a thermo-chemical process which converts biomass into liquid, charcoal and no condensed gases (CH_4, H_2 and CO) [59]. It involves the heating of biomass in the absence of oxygen. It occurs at 538^{o}C and allows decomposition of wood into gas and charcoal (carbon). During this process there is no production of CO_2 and it requires a high amount of energy for biomass to be heated to a very high temperature [1, 14].

Pyrolysis has the following main advantages over conventional combustion technologies:

The combined heat and power generation via biomass gasification techniques connected to gas-fired engines or gas turbines can achieve significantly higher electrical efficiencies (22 % to 37 %) compared to biomass combustion technologies with steam generation and standard turbine technology (15 % to 18 %). Using the gas produced in the fuel cell for power generation can lead to a higher overall electrical efficiency in the range of 25 % to 50 %, in small scale biomass pyrolysis plants and during partial load operation [59, 63, 65].

3. Gasification

Biomass gasification is one of biomass energy based systems which had been proven reliable and had been extensively used on transportation and farm systems during World War II [66]. This is done at elevated temperature hence, incomplete combustion of biomass results in production of combustible gases (producer gas) consisting of Carbon monoxide (CO), Hydrogen (H_2) and traces of methane (CH_4). This process takes place at temperature of about 1000^{o}C in a reactor called 'Gasifier'. Since any biomass material can undergo gasification, this process is much more preferred than ethanol production or biogas where only selected biomass materials can produce the fuel [62, 67].

Combustion is not suitable for the production of Hydrogen while pyrolysis and gasification are suitable for its production.

4.2.2 Biological conversion

Most types of biomass cannot be directly utilized and must undergo some transformations to be used as fuel. Biological processes for the conversion of biomass to fuels include ethanol fermentation by yeast or bacteria, and methane production under anaerobic conditions [65].

Biological conversion can happen through digestion and fermentation of biodegradable wastes which occurs in large digester power plants where bacteria convert wastes into gas. The produced gas is burned and drives turbines that generate

electricity. The solids that are left behind may be used as fertiliser, depending on the biomass materials used. This process is mostly used for hydrogen production and some bio fuels such as biogas, bio-ethanol, bio-buthanol and bio-diesel [1, 14, 65].

Biological conversion mostly operates at ambient temperatures and pressures. This method can use a variety of feed stocks as carbon resources.

4.2.3 Hydrogen production

Hydrogen can be produced biologically by either direct or indirect biophotolysis, biological water gasification, photo or dark fermentation.

1. **Direct Biophotolysis**

   Direct biophotolysis is biological process using micro algae or cyanobacteria photosynthetic system to convert solar energy into chemical energy in the form of hydrogen (H_2) using the [Fe-Fe]-hydrogenase and [Ni-Fe]-hydrogenase (Photosynthetic reaction) [1, 15, 63].

$$2H_2O\,(l) + \text{Light Energy} \rightarrow 2H_2\,(g) + O_2\,(g) \qquad (4.6)$$

2. **Indirect Biophotolysis: dark fermentation**

   Indirect biophotolysis consists of two stages; Photosynthesis for carbohydrate accumulation and dark fermentation of carbon reserve for hydrogen production. According to Gaudernack [59, 65], the concept of indirect biophotolysis involves the following four steps: (i) biomass production by photosynthesis, (ii) biomass concentration, (iii) aerobic dark fermentation yielding 4mol hydrogen/mol glucose in the algae cell, along with 2 mol of acetates, and (iv) conversion of 2 mol of acetates into hydrogen. In a typical indirect biophotolysis, cyanobacteria are used to produce hydrogen via the following reactions:

$$6H_2O\,(l) + 6CO_2\,(g) + \text{Light Energy} \rightarrow C_6H_{12}O_6 + 6O_2\,(g)$$

$$C_6H_{12}O_6 + 6H_2O + \text{Light Energy} \rightarrow 12H_2 + 6CO_2\,(g)$$

3. Biological water gas shift reaction

Water gas shift (WGS) reaction is used to convert carbon monoxide (CO) to carbon dioxide (CO_2) and Hydrogen H_2 through a reaction with water (H_2O) [60,67].

$$CO + H_2O \rightarrow CO_2 + H_2, \quad \Delta G^o = -20.1/\text{mol}$$

The reaction is exothermic, which means the reaction equilibrium shifts to the right and favours the formation of the H_2 and CO_2 products at lower temperatures. At higher temperatures, the equilibrium shifts to the left, limiting a complete conversion CO to H_2 [62].

4. Photo fermentation

Photo fermentation employs the degradation of organic wastes to hydrogen via hydrogen fermenting bacteria. Photosynthetic bacteria have the capacity to produce hydrogen through the action of their nitrogenise (enzyme used by some organisms to fix nitrogen gas) using solar energy and organic acids or biomass [65].

This method is not currently feasible because of its low efficiency of 10 - 20% [60].

5. Dark fermentation

Fermentation by anaerobic bacteria as well as some microalgae, such as green algae on carbohydrate-rich substrates, can produce hydrogen at 30^oC to 80^oC especially in a dark. Unlike a bio-photolysis process that produces only H_2, the products of dark fermentation are mostly H_2 and CO_2 combined with other gases, such as CH_4 or H_2S, depending on the reaction process and the substrate

used [63]. With glucose as the model substrate, maximum 4 mole of H_2 are produced per mole of glucose when the end product is acetic acid [59, 67]:

$$C_2\,H_{12}O_6\,(l) + 2H_2O\,(l) + 2CH_3COOH\,(l) \rightarrow 24H_2\,(g) + 6CO_2\,(g)$$

When the end product is butyrate, 2 moles H_2 is produced:

$$C_6\,H_{12}O_6\,(l) + 2H_2O\,(l) + 2CH_2CH_2CH_2OOH\,(l) \rightarrow 28H_2\,(g) + 12CO_2\,(g)$$

4.3 Physics behind Biomass

The majority of the processes applied in this technology are chemical and biological. However, there are some physical processes during biomass conversion for example the diffusion of reagents and the products of the combustion depending on their concentration. There are also changes in pressure and temperature.

4.4 Efficiency of Biomass Technology

Despite the fact that biomass is a renewable energy in the long term, the amount of utilisable energy in the world, is limited in the short term. Energy efficiency plays an important role on the viewpoint of cost. It is therefore important to convert biomass energy efficiently.

The aim is to determine the energy flow from biomass resources to electricity, automobile fuel and heat. The efficiency of some biomass technologies depends on moisture content.

In thermal conversion process, the biomass technology has the efficiency of 20 - 27% [1, 61].

Biogases can be used in high efficiency combined cycle plants. Combined cycle plants use both gas and steam turbines to generate electricity at a high efficiency rate of 60%.

4.5 Advantages and Disadvantages

(a) Advantages

Biomass is potentially a reliable energy resource for hydrogen production. Biomass is renewable, abundant and easy to use [59]. Over the life cycle, net CO_2 emission is nearly zero due to the photosynthesis of green plants. The thermo-chemical pyrolysis and gasification hydrogen production methods are economically viable and will become competitive with the conventional natural gas reforming method. With further development of these technologies, biomass will play an important role in the development of sustainable hydrogen economy [65].

Currently biomass is still one of the cheapest energy sources for millions of households all over the world although wider replacement of fossil fuels with biomass fuels may result higher prices in the future [61].

(b) Disadvantages

Biomass produces greenhouse gases during combustion such as CO_2 which in turn contributes to global warming [7]. Besides that experts are concerned that cultivation of some plants such as canola, corn and rapeseed for biofuel may on the long term cause lack of food. It is costly for installing technology to process and recycle wastes. Biomass is expensive and difficult to collect, harvest and store raw. Large scale crop production will use vast areas of land and water, representing major problems and crops are not present all the year. Use of abundant Biomass is preventing people from looking at alternative energy resources.

4.6 Biomass Situation in Rwanda

Firewood is by far the main source of energy for cooking in Rwanda and is being used by 84.4% of the households. The other sources of energy used for cooking include charcoal (7.2%) and other vegetation materials (6.8%). For instances in

Kigali City, approximately 65.1% of the households were found to be using charcoal and 26.6%, wood for cooking. In the capital city, barely 1.2% of household are using electricity for cooking (2002). Approximately 80%-95% of people living in the outlying areas of Kigali rely on firewood [4, 5].

The National Domestic Biogas Program (NDBP) aims at installing at least 15000 biogas digesters in rural households to provide sufficient energy for cooking and lighting. Each cubic meter (m^3) of biogas contains the equivalent of 6 kWh of calorific energy.

However, when we convert biogas to electricity, in a biogas powered electric generator, we get about 2 kWh of useable electricity, and the rest turns into heat which can also be used for heating applications. 2 kWh is enough energy to power a 100 W light bulb for 20 hours or a 2000 W hair dryer for 1 hour.

Biogas has also been used in prisons and schools where it is produced with waste from the latrines. Rwanda has even gained international recognition for its achievement, which has reduced the cost of cooking in prisons by 40% [37]. The Government is now considering the expansion of this technology to more schools and hospitals.

Households with two or more cows have the potential for small biogas plant. A significant national domestic biogas program has been launched, staff has been recruited and funds have been made available. The program is viable because the national zero grazing policy makes the cow dung available close to the household. To add on that, the one-cow-per-family program, will enable more people to actually benefit from the biogas program. So far, 350 biogas digesters have already been installed in households. These digesters are built by local craftsmen with the support of the Centre for Innovation and Technology Transfer (CITT) of the Kigali Institute of Science and Technology and Management (KIST).

Most of the digesters are made from stones and cement. There is also a pilot test phase for digesters made of fibreglass with help of Chinese engineers in Kirehe

district. By December 2011, the project is aiming to install 15,000 biogas systems for cooking and lighting [68].

Also Biogas plants using human waste are in operation in six prisons.

Chapter 5

Geothermal Energy

5.1Introduction

This chapter explores geothermal resources, technologies associated with geothermal, their mechanism (the physics behind them), purpose, efficiency and its applicability.

5.1.1 Natural Energy Resource

Geothermal energy is the natural heat stored within the earth core and visible on earth's surface in form of fumaroles, hot springs, steaming grounds and altered grounds. It comes from radioactive decay of uranium, thorium and potassium [9].

Geothermal energy is heat generated naturally in the interior of the earth, and can be used directly, as heat, or indirectly, to generate electricity [1, 14].

Geothermal resources have three important characteristics; an aquifer containing water that can be accessed by drilling, a cap rock to retain the geothermal fluid and a heat source [69].

Geothermal energy can be used to generate electricity for example by the flashed-steam method, in which high-temperature geothermal brine is used as a heat source to convert water injected from the surface into steam.

5.1.2 Geothermal is Renewable

Geothermal energy is called a renewable energy source because the water is replenished by rainfall and the heat is continuously produced deep within the earth (about 5 Km). Geothermal energy is clean energy; no fuel is burned, so there is no air pollution [70].

However, we can only use this method to generate our power in certain places where suitable hot regions are near the surface [71]. Geothermal power is an

attractive source of energy because it is naturally available, renewable and can be economically viable.

Geothermal power plant captures and uses the heat from earth to drive one or more steam turbines that turn one or more synchronous generators [72]. We can use the steam and hot water produced inside the earth to heat buildings or generate electricity.

5.1.3 Historical background of Geothermal

The first geothermal power station was built at Lardarello, in Italy 1904 see Fig. 18, and the second was at Wairekei in New Zealand [73].



Figure 18: First geothermal power plant in Lardarello in Italy 1904 [74]

Geothermal energy is tapped by over 20 countries, most notably Iceland, which gets 17% of its electricity from geothermal energy.

The largest geothermal energy plants output 300 MW (megawatts). It has been estimated that Iceland has enough geothermal energy to provide 1700 MW for over 100 years [9]. Geothermal energy is cheap and new power plants can produce electricity for about the same cost as coal plants. Despite the fact that geothermal energy is massive in total, the sun, for instance delivers 20000 times more power on the earth [72].

5.2 Sources of Geothermal

The primary source of geothermal energy is from deep within the earth where temperatures are very high to melt the surrounding rocks. This implies that geothermal energy results from the earth's natural heat flow which

1) Is highly concentrated in high-enthalpy regions at volcanically active plate margins.
2) Is sufficiently concentrated in low-enthalpy resource of sedimentary basins with shallow rock strata that conduct a low amount of heat energy
3) Is potentially concentrated enough for exploitation in certain granite areas where heat may be extracted by opening up pre-existing joints of hot dry rocks [69].

Secondary source of geothermal energy is stored heat from the sun radiation onto the land surface.

The most active geothermal resource is usually found along major plate boundaries where earthquakes and volcanic activities are predominant [1]. Most of the geothermal activity in the world occurs in an area known as the **Ring of Fire** area which rims the Pacific Ocean [79].

People around the world use geothermal energy for domestic purposes such as heat and light among others in form of electricity. This electricity is produced by by digging deep wells and pumping the heated underground water or steam to the surface. Geothermal energy can also sometimes find its way to the surface in form of: Volcanoes and fumaroles (holes where volcanic gases are released), hot springs and geysers [14].

5.2.1 Heat flow and temperature distribution within the lithosphere

The rate of increase in temperature with depth in the earth is called 'geothermal gradient'.

Heat flow is determined by combining geothermal gradient with thermal conductivity of the rock formations over which the gradient has been computed and expressed in terms of heat flowing out over unit area per time [75, 76]. Geothermal gradient is about 23ºC – 30 ºC per km of depth in most regions around the world [73].

5.2.2 Sources of heat flow

The cooling and the heat produced by radioactivity are primarily responsible of heat flow observed at the surface of the earth and the temperature distribution within it. The amount of radioactive elements present in the rocks release enough heat to account for a major portion, (around 80%) of the total heat flow observed on the earth's surface and the other 20% residual heat from planetary accretion [76]. Those radioactive elements produce a significant heat due to the decay of long lived isotopes of ^{238}U and ^{235}U, ^{232}Th and ^{40}K, meaning that they release energy during the decay as shown in the following reactions [14, 77]:

$$^{238}U = {}^{206}Pb + 8\ {}^{4}He + 51.6Mev \quad (5.1)$$

$$^{235}U = {}^{207}Pb + 7\ {}^{4}He + 46.6Mev \quad (5.2)$$

$$^{232}Th = {}^{208}Pb + 6\ {}^{4}He + 42.6Mev \quad (5.3)$$

^{40}K is very rare (abundance of 0.0119%) and decays to release energy by two process; electron capture to ^{40}Ar and beta decay to ^{40}Ca.

5.3 Types of Geothermal Plants

There are three geothermal power plant technologies being used to convert hydrothermal fluids to electricity. The conversion technologies are:

5.3.1 Dry steam system

Dry steam power plants systems were the first type of geothermal power generation plants built. In this power plant, resources produce pure steam (the hot steam is piped directly from geothermal reservoirs into a generator); the steam drives a turbine and generates power (Fig. 19) [78].

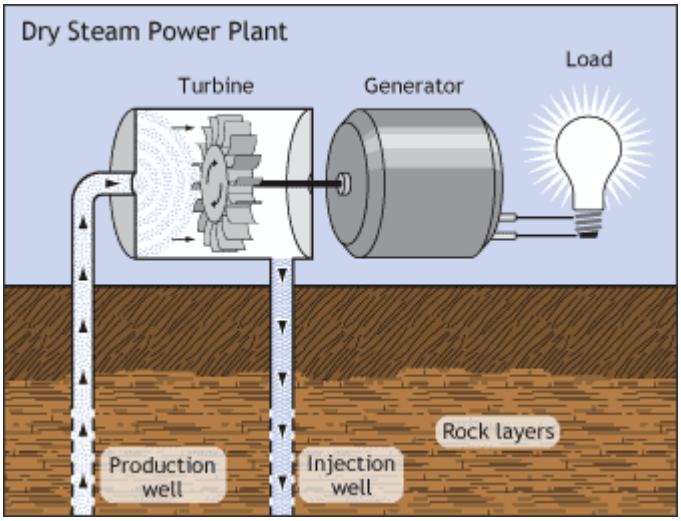


Figure 19 : Dry steam Power plant diagrams [78]

5.3.2 Flash steam plants

Flash steam plants are the most common type of geothermal power generation plants in operation today. They use resources that are typically hotter than 177°C. They use water at temperatures greater than 182°C that is pumped under high pressure to the generation equipment at the surface. Some of the water is turned into

steam which drives the turbines. When the steam cools down it condenses into water and returns to the ground (is injected back to the reservoir) see Fig. 20 [37, 78].

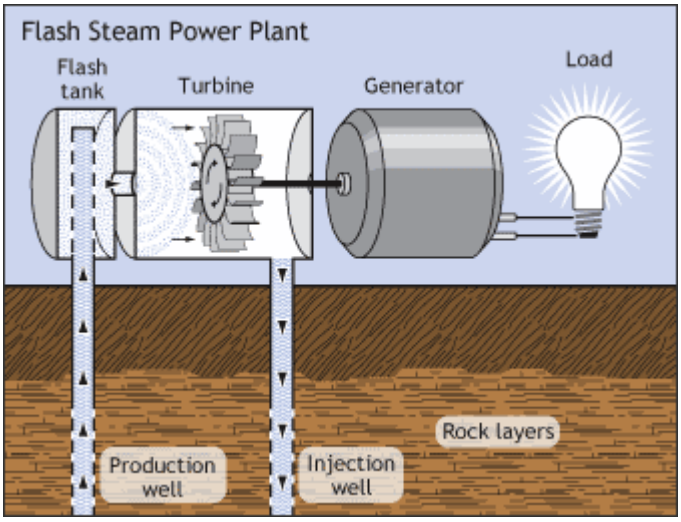


Figure 20: Flash Steam Power Plant Diagram [78]

5.3.3 Binary cycle power plants

Binary power plants were introduced in the mid-1980s and are the fastest growing generating technology currently with more than 350 MW of binary generation capacity in California, Hawaii, Nevada and Utah [78].

This rapidly expanding technology uses geothermal resources with temperatures as low as 88ºC. In this power plant geothermal water is passed through a heat exchanger, and its heat is transferred to another working fluid such as isobutene which vaporises at a lower temperature than water [76]. When this fluid is heated, it turns to steam which spins the turbine to generate power. After this, the used water is condensed and circulated back to the heat exchangers.

This type of geothermal plant has superior environmental characteristics compared to the others because the hot water (which tends to contain dissolved salts and minerals) is never exposed to the atmosphere before it is injected back into the

reservoir refer to Fig. 21 [78]. Binary cycle geothermal power generation plants differ from Dry Steam and Flash Steam systems in that the water or steam from the geothermal reservoir never comes in contact with the turbine or generator units [78].

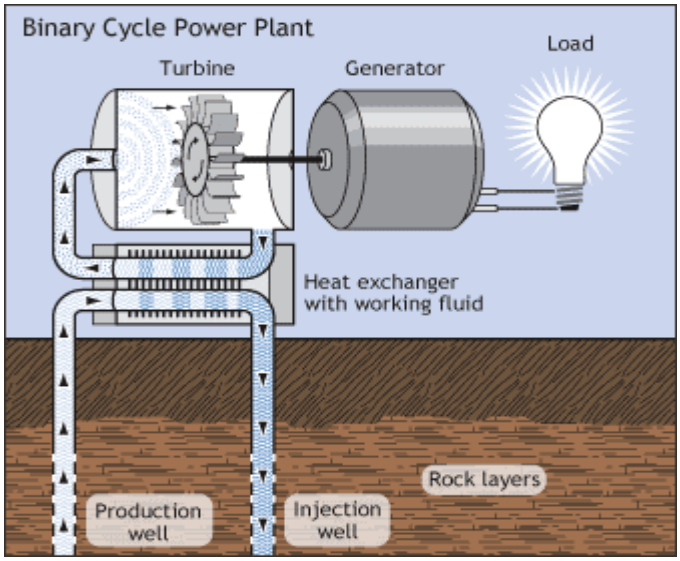


Figure 21 : Binary cycle Power Plant diagram [78]

5.4 Types of Geothermal Systems

The main conditions for a geothermal reservoir to exist are a large source of heat, a heat carrier, a porous and permeable reservoir rock and an impermeable cap rock to prevent the escape of hot reservoir fluids trough convection [9, 71]. All geothermal fields differ from one another. However, depending upon certain common characteristics, geothermal systems can be classified under the following types: vapour- dominated (dry vapour), hot water (liquid dominated), geopressured, hot dry rock and magma [78].

5.4.1 Vapour-dominated

Vapour-dominated type is the most exploited geothermal field contained at high pressures and temperature in excess of 100^{o}C [9], because of the minimum risks

that they carry for environment [71]. In this field there is production of steam associated with water and they are known as ‘wet steam fields'. (For example, Reykjavik in Iceland). There are also other geothermal fields such as Larderello (Italy) which produces superheated steam with no associated fluids (best known as vapour- dominated reservoirs). They are also known as 'dry steam fields'. The basic requirements of this type are adequate supplies of water in addition to the tree prerequisites mentioned earlier. Even if hot water and water vapour co-exist in this field, vapour phase is the continuous phase pressure regime of the reservoir [76].

The heat source of vapour-dominated geothermal fields is a young high-temperature 'magma' around 500-1000^{o}C. Approximately 90% of geothermal water has meteoric origin (originates from precipitation trough the soil and freshwater runoff) [9].

5.4.1 Hot water

In this category, water convection currents carry the heat from the deep source to a shallow reservoir. The bottom of the convective cell may be heated through conduction from hot rocks. Note that the geology of the hot water system is similar to that of groundwater system. But it differs from vapour-dominated geothermal system by the fact that the liquid phase of hot water system is continuous, pressure-determining (controlling) phase in these reservoirs. The temperature of hot water of hot water reservoirs varies from 60 to 100^{o}C and they occur at depths ranging from 1500 to 3000 m [9]. Some examples of the category are; Wairakei in New Zealand, Cerro Prieto in Mexico and Kizildere in Turkey.

In this category we have some subtypes depending on temperature, chemistry and the structure of the reservoir; systems characterised by low temperature (50-150^{o}C), the presence of partly non-meteoritic water, brine of very high salinity, natural cap rocks and the creation of their non-self-sealing cap rocks [76].

The heat recovery from liquid dominated reservoirs is higher compared to heat recovery from vapour-dominated reservoirs [71]. Comparing problems during

the production, liquid-dominated reservoirs are worse than those of vapour dominated reservoirs [70, 71].

5.4.3 Geopressured

Geopressured is a type of hydrothermal environment where hot water is almost completely sealed from exchange with the surrounding rocks. It is formed in a basin where very rapid filling with sediments takes place, resulting in higher than normal pressure of the hydrothermal water. This usually occurs in zones covered with impervious layer. It has been first identified in the deep sedimentary layers, the Gulf of Mexico at a depth between 6-8 km, at 150 - 180^{o}C and 130 MPa [9].

The geothermal gradient in the hydro pressured zones at depths ranging from 1 to 2 km varies from 20 to 40^{o}C per km.

The temperature of these systems increases with low heat conductivity and high specific heats [71].

5.4.4 Hot dry rock (HDR)

Hot dry rock is another category of geothermal resources where geothermal heat is stored in the hot and permeable rocks at shallow depths within the earth's crust without any fluid availability to store or transport the heat [71].

The only way of utilizing HDR is to extract the heat energy of the rock by water circulation along an artificial fracture between two wells [71].

5.4.5 Magma

Magma is the naturally occurring rock material (in form of hot viscous liquid), which retains fluidity. It may contain gases and particles of solid material such as crystal or fragments of solid rocks at various temperature depending upon the decomposition and pressure form 600 - 1400^{o}C [9, 71]. The heat from magma is used to boil water to generate electricity.

5.5 Physics behind Geothermal technology

According to the second law of thermodynamics (heat naturally flows from a warmer substance to a colder one), the heat from geothermal source (ground) can be removed very easily. However, in cases where the ground or water source is colder than the space to be heated, it is still possible to extract the earth's energy with the use of a heat pump [80]. We need something cold to absorb the heat like a liquid refrigerant.

Since the liquid refrigerant has a boiling point which is below 0^{o}C at normal atmospheric pressure, as it enters the evaporator, heat is taken from the ground converting the liquid to a gas.

This refrigerant, now in a gaseous state, is compressed into the condenser by use of a pump where the pressure is higher than the vapour pressure of the refrigerant and thus it becomes a liquid once more. The heat given off by the condenser is used to heat a house for instance and the refrigerant heads back to the evaporator to start the cycle all over again [80].

5.6 Advantages and disadvantage

(a) Advantages

Below are some advantages to the use of geothermal power generation:
Geothermal energy is from the earth and therefore it is clean and sustainable, it does not cause pollution and does not contribute to the green house effect since no fuel is needed to generate it [1]. It can be used as an affordable and sustainable solution to reduce dependence of fossil fuels and hence an effective way to reduce the effects of global warming and public health risks resulting from these fossils fuel.

Also, since geothermal energy is a vastly untapped renewable source of power, the use of the heat pumps allows people living in colder climates to benefit from the energy contained within the Earth [72]. Geothermal energy technology also contributes to the requirement of world energy demand; once you've built a

geothermal power station, the energy is almost free. (It may need some energy to run a pump, but this can be taken from the energy being generated which reduces dependence on oil) [15, 72].

It is considered to be sustainable because the heat extraction is small compared to the size of the heat reservoir. While individual wells may need to recover, geothermal heat is almost inexhaustible and is replenished from greater depths. The long-term sustainability of geothermal energy production has been demonstrated at the Lardarello field in Italy since 1913, at the Wairakei field in New Zealand since 1958, and at The Geysers field in California since 1960 [76].

(b) Disadvantages

The major disadvantage of geothermal energy is that it can only be exploited in a few areas on earth. As such only a few power stations can be built.

Also, hot rocks of a suitable type are needed, at a depth which can be reached by drilling. These types of rocks must be of the type that can be easily drilled through. Sometimes a geothermal site may "run out of steam", perhaps for decades. Hazardous gases and minerals may emerge underground, and can be difficult to be disposed of safely [72].

It can generate geological instability (the fracturing of hot rocks and injection of geothermal fluids can cause minor earthquakes). There is only one reported case in Basel Switzerland where this problem was experienced. Geographically, Basel city is located along an active fault line as such the city was wiped out by an earthquake that occurred naturally long ago but was later rebuilt. To produce power much later, a geothermal company in the city fractured hot rocks then injected water into the fault. This resulted in a massive earthquake leading to the station to being shut down [82].

5.7 Rwanda Situation

Rwanda has not fully explored its geothermal resources development. Traditionally Rwanda relied on two main sources of energy; biomass and hydropower. It was only recently that the Rwandan Ministry of infrastructure started to take serious steps toward the exploitation of geothermal energy resources [81].

The exploitation of geothermal in Rwanda started in 1982 with French Bureau of Geology and Mining Research (BRGM). They tried to identify all geothermal resources in the Country. Eighteen of hydrothermal springs were identified and analysed for the study. Rwanda has geothermal resources in the form of hot springs along the belt of Lake Kivu [81].

5.7.1 Rwanda geothermal potential

The potential for geothermal power generation in Rwanda is currently estimated at about 170 - 320 MW. This is proven by geothermal resources discovered in the north-west and south west regions of the country.

Rwanda hosts two prospective areas of geothermal potential [81]:

1. The Volcanoes National Park
2. The faults associated with the Western Branch of the East African Rift near the Lake Kivu.

The BRGM study found three important zones with a geothermal potential:

(a) The National Volcanoes zone in the Northern part of Kivu Lake with the eight big volcanic structures. Five of them are situated in Rwanda (Muhabura-Gahinga-Sabyinyo-Bisoke-Kalisimbi).

(b) The Cyangugu zone in the Southern part of Kivu Lake. It is situated in the Eastern part of the Graben. The hydrothermal manifestations (hot springs and the travertine deposit) are linked to this type of structure.

(c) Hot springs of Gisenyi.

5.7.2 Geothermal activities

In 2007, Geothermal Potential Assessment and Capacity Building in Rwanda, and the results showed that there was a probability of existence of medium to high temperature geothermal systems of more than 210°C on the south slopes of Kalisimbi volcano in Rwanda [73, 76].

Researchers are still working on the survey of the existence of geothermal energy in Rwanda. Rwanda is currently working with the German Federal Institute for Geosciences and Natural Resources (BGR) for the geothermal resource assessment and capacity building in the Northern part of the country [81].

Chapter 6

Wind Energy Technology

6.1 Introduction

This chapter will discuss issues relating to wind energy.

6.1.1 Natural Energy Resource

Wind is the movement of the air over the surface of the earth, from areas of high pressure to low pressure. This difference in pressure from place to place is due to the rotation of the earth and the heating effect of the sun. Wind energy ultimately comes from the sun, being produced by the heating of the earth's surface. [9].

The terms "wind energy" or "wind power" describe the process by which the wind is used to generate mechanical power or electricity. It can be exploited where the wind regime is allowed, and could thus be used in to remote areas.

Wind turbines convert the kinetic energy of the wind into mechanical power. This mechanical power can be used for specific tasks (such as grinding grain or pumping water), or a generator can convert this mechanical power into electricity to power homes, businesses and schools [83]. Over the past 10 years, offshore wind energy has become a major focus of European wind energy research and deployment.

As long as there is a temperature gradient on earth, wind will be generated. Meaning that, wind is also renewable energy source. Today, wind energy is mainly used to generate electricity.

6.1.2 Historical background of wind energy

Wind energy was one of the first non-animal sources of energy to be exploited by early civilizations. It is thought that wind was first used to propel sailing boats, but the static exploitation of wind energy by means of windmills is thought to have been going on for about 4000 years [69].

The first windmills were developed to automate the tasks of grain-grinding and water-pumping and the earliest-known design is the vertical axis system developed in Persia about 500 - 900 A.D.

In the 1970s during the "Arab Oil Crisis," much attention was given to wind energy and other forms of renewable energy. The US government did step up its involvement with wind energy, developing large multi-megawatt wind turbines for the development of grid electricity [84].

Currently, there is a growing sense that wind energy can be an important part of the US energy mix. There is a 10 MW wind plant in Northern Colorado, wind power plants dot the coast of California and over 2000 MW of new capacity were added in 2001 in the U.S. alone [84]

6.2 Types of wind Turbines

The names of different types of turbines depend on their constructional geometry and the aerodynamics of wind passing around the blades [1, 85].

Wind turbines use wind to make electricity; the wind turns the blades, which spin a shaft, which connects to an electric generator [1].

Modern wind turbines fall into two basic groups; the **horizontal-axis variety** (which rotates around the horizontal axis), like the traditional farm windmills, and the **vertical-axis design**, like the eggbeater-style Darrieus model, named after its French inventor. Most large modern wind turbines are horizontal-axis turbines. There is also the **concentrating structure,** but is not well developed yet [1, 15, 85].

The turbine has the following components: blade or rotor, a drive train, a tower and other equipments including controls, electrical cables, ground support equipment, and interconnection equipment [85].

6.2.1 Horizontal axis wind turbines (HAWTS)

There are different types of horizontal-axis turbines such as single bladed, two bladed, three bladed, multi-bladed, tip vane, upwind and downwind turbines [1].

In this type of wind turbine, we consider rotors having blades similar to airplane (propeller). The dominant driving force here is 'lift' as opposed to 'drag'. HAWTs must point into the wind to be able to harness wind energy.



Figure 22: **An example of horizontal-axis wind turbine [86]**

The blade on the rotor can be in front (upwind) or behind (downwind) of the towers. The wind veers in horizontal plane and the rotor must turn in the horizontal plane (yaw) to follow the wind without oscillations [1].

It has been found that upwind turbines need a tail or some other yawing mechanism such as electric motor drive to maintain orientation. But, downwind turbines are in principle self-orienting. The downwind turbine has its rotor on the

back side of the turbine. The nacelle is typically designed to seek the wind, thus negating the need for a separate yaw mechanism [1]. Upwind and downwind machines of rotor diameter more than 10 m use electric motor to control yaw.

Two to three bladed rotors are common for electricity generation. Three bladed rotors operate more smoothly and generally more quietly than two bladed.
A single bladed rotor has always some problems due to its asymmetry.
Multi-bladed rotors have a large starting torque in light winds and they are used for water pumping and other low frequency machine power [1].

6.2.2 Vertical axis wind turbines (VAWTS)

There are various types of vertical axis wind turbines, such as; cup anemometer, savonius rotor (sevonius rotor with twisted blades), Darrius rotor 'egg-beater' (the nearly 100 m height, 60 m diameter, 4 MW rated gigantic eggbeater EOLE), Musgrave rotor and Evans rotor.

By turning along vertical axis, a machine can accept wind from any directions without adjustment, while the horizontal axis design has to yaw first. Vertical axis wind turbine generators have gear boxes and generators at ground level.

Research is in progress to develop vertical axis machines. These have the advantage that they do not need to be orientated to face the wind, since they present the same cross section to the wind from any direction; however this is also a disadvantage as under storm conditions you cannot turn a vertical axis rotor away from the wind to reduce the wind loadings on it. There are various types of VAWTs:

The Cup anemometer rotates by the drag force. It has a shape of a cup which produces a relationship between rotational frequency and wind speed. It can be used as standard anemometer for meteorological data [1]. The Savonius rotor, also known as turbo machine. Its driving force is 'drag'. There is a complicated motion of wind through and around the two curved sheet air foils. It is mostly used for water pumping [1].

The Darrius rotor named after Frenchman Georges Jean Mary Darrius, has 2 or 3 thin curved blades with air foils section. It has the aim of rotating blades being only stressed along their length [1].

The Musgrove rotor is a vertical axis lift machine having '**H**' shaped blades and a central shaft which has been developed by a research team under Prof. Musgrave at Reading University UK. At high wind speeds the rotor feathers and turns about a horizontal point due to centrifugal force [1].

In an Evans rotor, the vertical blades change pitch about a vertical axis for control and failsafe shutdown [1].

The Savonius, Darrius and Evans rotors use lift as their driving force. The rotor for a vertical wind turbine is not usually self-starting. Movement may be initiated with the electrical induction generator used as a motor [1].



Figure 23 : An example of vertical axis [87]

The advantages of vertical axis machines include 1) it eliminates the gravity induced stress or strain cycles [1]. 2) They accept wind from all directions(any angles), 3) their components can be mounted at ground level (easy of service, lighter weight towers) and 4) they can theoretically use less materials to capture the same amount of wind [1, 85].

Their principle disadvantages are: 1) Many vertical axis machine have suffered from fatigue failures arising from many natural resonances in the structure, 2) they require support on top of turbine rotor, 3) they have poor self-starting capabilities, 4) they require the entire rotor to be removed to replace bearings, 5) they have an overall poor performance and reliability and they have never been commercially successful [1, 85].

6.2.3 Concentrators

Turbines draw power from the intercepted wind, and it may be advantageous to funnel or concentrate wind into the turbine from outside the rotor section. This can be applied on horizontal axis propeller turbines [1]. We have Blade tips and concentrating structures.

The idea of concentrating wind power is to build a structure that conducts the wind towards the turbine blades and in this way harvests more power.

6.3 Where can we put the turbines?

It has been found that wind turbines are most efficient when they are built where winds blow consistently at least 20921.472 m/h and that faster winds generate more electricity [85].

Wind turbines should be placed on top of towers that are at least 30 meters tall because wind is stronger and steadier at higher altitudes.

Nowadays, there are many different types of wind turbines with different blade shapes and different types of turbines operate most efficiently at different wind speeds. Different turbine designs operate efficiently at their design speed. Design speed ranges are from 7 Km/h up to 60 km/ h. They also come in different sizes, based on the amount of electrical power they need to generate. Small turbines may produce only enough electricity to power one home. Large turbines are often referred to as utility-scale because they generate enough power for utilities, or electric

companies, to sell. Example; the largest turbines in the U.S. produce 2.5 - 3.5 MW, enough electricity to power 750 to 1,750 homes [88].

To build a wind farm, wind speed and direction must be studied to determine where to put the turbines. As the wind power is proportional to the cube of the velocity (Eq. 6.3), it is extremely important to select windy sites. For example, if by suitable site selection is possible to obtain an average velocity 10% higher than the average for the area the power available will be almost 30% greater [85, 89].

As a rule, wind speed increases with height according to the following relationship;

$$\frac{v_1}{v_2} = \left[\frac{Z_1}{Z_2}\right]^x \tag{6.1}$$

where v_2 is the wind velocity at some reference height Z_2 and v_2 is the wind velocity at height Z_1. The constant x depends on the nature of the surface. The site must have strong, steady winds. Scientists measure the wind in an area for several years before choosing a site [4, 14].

6.4 Physics behind wind technology

The efficiency of a wind turbine depends on various factors such as; location, geographical factors, mechanisms, rotor shapes or size, ect [91]. The output can be adjusted or regulated by a constant or variable rotational speed as well as adjustable and non-adjustable blades. The power in the wind is proportional to 1) the density of air, i.e. it is lower at higher mountainous regions, but the average density in cold climates may be up to 10% higher than in tropical regions 2) the area through which the wind is passing and 3) the cube of wind velocity. Power increases a factor of 8 if wind velocity increases to double of its original.

$$E = \frac{1}{2}\, mV^2 \tag{6.2}$$

$$P = \frac{1}{2}\rho A V^3 \quad (6.3)$$

This V^3 dependence of power on velocity causes wind energy to be highly sensitive to variation in wind velocity [85].

6.4.1 Aerodynamics of blades

The Aerodynamics is the science and study of the physical laws of the behaviour of objects in an air flow and the forces that are produced by air flows [56, 85].

6.4.1.1Airfoils

Choosing the shapes of blades must be done carefully for maximum efficiency. Initially, turbines used blade shapes known as 'airfoils' based on the wings of the airplanes (Fig 24).

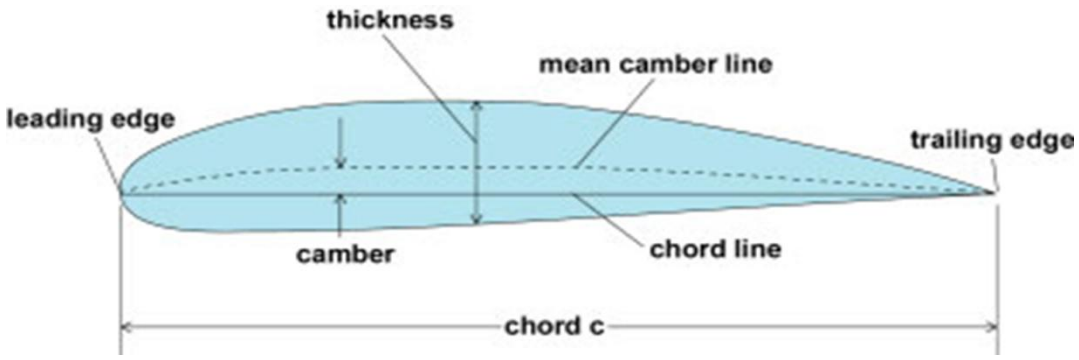


Figure 24: Airfoils [15]

Current wind turbines use airfoils but they are now specially designed for use on rotors. Airfoils used the concept of lift as opposed to drag, to harness the wind's motion [91].

6. 4.2 Drag and lift

a) Drag

It has been found that an object placed in wind, experiences a force which can be quite large. For example; trees blow down in strong wind [15, 85]. This acting force depends on different factors such as: velocity *v*, the density of the air ρ, the area of the object at the right angles to the wind direction and its shape. The drag force is parallel to the direction of motion. It is usually expressed in terms of a dimensionless quantity, the drag coefficient $C_{D,}$ as follows:

$$C_D = \frac{dragforce}{{}^1/_2 \rho v^2 \times area} \tag{6.4}$$

b) Lift

Bernoulli's Principle can be used to calculate the **lift force** on an **airfoil** if you know the behaviour of the fluid or gas flow in the area of the foil. For example, if the air flowing past the top surface of an aircraft wing is moving faster than the air flowing past the bottom surface then Bernoulli's principle implies that the pressure on the surfaces of the wing will be lower above than below. This pressure difference results in an upwards lift force. Lift force is perpendicular to the direction of the motion. As the drag force, this one also is expressed into dimensionless coefficient as follow:

$$C_L = \frac{liftforce}{{}^1/_2 \rho v^2 \times area} \tag{6.5}$$

Whenever the distribution of speed past the top and bottom surfaces of a wing is known, the lift forces can be calculated (to a good approximation) using Bernoulli's equation bellow. Bernoulli's principle does not explain why the air flows faster past the top of the wing and slower past the underside [56, 85].

Many explanations for the creation of lift (on airfoils, propeller blades, etc) can be found; but some of these explanations can be misleading, and some are false. This has been a source of heated discussion over the years. In particular, there has been debate

about whether lift is best explained by Bernoulli's principle or Newton's laws of motion. Nowadays, modern writings agree that Bernoulli's principle (see eq. 6.6) and Newton's laws are both relevant and correct [56].

$$\frac{v^2}{g} + gz + \left(\frac{\gamma}{\gamma-1}\right)\frac{P}{\rho} = \text{constant (along the streamline)} \quad (6.6)$$

Where p is the pressure, ρ is the density, v is the flow speed, γ is the ratio of the specific heats of the fluid, g is the acceleration due to gravity, and z is the elevation of the point above a reference plane. This equation is used to calculate the entropy (specific value that measures how much energy is released in systems where it settles into the lowest potential energy) generation [91].

6.5 Efficiency and Capacity of Winds Machines

6.5.1 Efficiency of wind machines

Some energy is always lost or wasted when one form of energy is converted to another. This lost energy is usually in the form of heat, which is dissipated into the air and cannot be used again, economically [89].

Wind machines are just as efficient as coal power plants. A wind machine converts 30 - 40% of the wind's kinetic energy into electricity. A coal-fired power plant converts about 30 - 35% of the chemical energy in coal into usable electricity.

Horizontal axis wind turbines are far more efficient than vertical axis wind turbines [94]. HAWTS's efficiency is about 50% and 10% for VAWTs. The best VAWTs can reach 15%.

6.5.2 What is the capacity of wind machine?

A power plant with a 100% capacity rating would run all day, every day at full power. There would be no down time for repairs or refuelling, an impossible goal

for any plant. Coal plants typically have a 75% capacity rating since they can run day or night, during any season of the year [85, 87]

Wind power plants are different from power plants that burn fuel. Wind plants depend on the availability of wind, as well as the speed of the wind. A wind turbine at a typical wind farm operates 65 – 80% of the time, but usually at less than full capacity, because the wind speed is not at optimum levels. Therefore, its capacity factor is 30-35% [87, 89].

6.6 Advantages and Disadvantages

(a) Advantages

Wind energy is friendly to the surrounding environment as no fuel is burnt to generate electricity from wind energy.

Wind turbines take up less space than the average power station. Windmills only occupy a few square meters for the base; this allows the land around the turbine to be used for many purposes, for example agriculture.

Wind turbines are a great resource to generate energy in remote locations, such as mountain communities and remote countryside. Wind turbines can be a range of different sizes in order to support varying population levels. Another advantage of wind energy is that when combined with solar electricity, this energy source is great for developed and developing countries to provide a steadier, reliable supply of electricity [91].

Wind energy can be a cheaper alternative source of energy to solar power [92]. There is growing number of people that install ‘do-it-yourself’ windmills on their lands to generate enough electricity for their homes, ranches, and farms. Windmills of course have long history and tradition of use it, and anyone living in those places should consider using this renewable source of energy. An example about the cost of wind; it has declined from 0.40$/kWh from 25 years ago to less than 0.05$ in 2010.

(b) Disadvantages

The main disadvantage of wind power is wind unreliability factor. In many areas, wind strength is too low to support a wind turbine or wind farm, and this is where one must look for viable alternatives.

Wind turbine construction can be very expensive and dangerous to the surrounding wildlife during the build process.

The noise pollution is also a major disadvantage to people living close to commercial wind turbines [93].

Protests and petitions usually confront any proposed wind farm development. People feel the countryside not be spoilt by wind farms.

6.7 Rwanda Situation

In Rwanda, wind energy has not yet been fully exploited due to a lack of detailed and reliable information on wind regimes and potential exploitation sites. In order to improve the diversity of renewable resources, the Government has initiated the assessment of wind potential in Rwanda [4].

Studies on wind regimes are being undertaken to determine wind power potential in Rwanda. The first step in exploring the potential is the development of a wind atlas (map of how wind flows). This atlas aims to identify windy sites and the estimated exploitable wind energy capacity throughout the country. This requires detailed meteorological surveys and the election of wind potential measurement instruments in promising sites [1, 94].

The necessary studies for the development of the wind atlas started in September 2009 with support from the Belgian Government, but so far it has made little impact.

In 1999, lifeline radios (radios which use wind energy to work) to give hope to post genocide orphans were introduced. They made them feel safe during the night. Two years later these became more popular.

In August 2010 the radios were replaced by the prime (multi-band radio), which has a powerful rechargeable battery pack and a DC input which can be plugged into either a wall socket or a car batter [36].

Chapter 7

Conclusion for Part1

In this dissertation we explored five different renewable energy resources (Solar, hydropower, biomass, geothermal and wind) looking at their applicability in Rwanda. And we made the following observations and conclusions:

1. In solar energy, the simplest way to harness energy from the sun is to use photovoltaic cells which have a special technology that captures the sun's energy and converts it into electricity. The cost of electricity from the sun, trough photovoltaic, has dropped from 1$/kWh (1980) to nearly 0.2$/kWh today (2010). In Rwanda, solar energy is used for two purposes: production of electricity trough solar photovoltaic's systems and direct heating using solar water heaters. A number of public institutions are using solar panels. Solar panels are still expensive ($120) for the majority of people. The other challenge of solar energy technology is its low efficiency (15%). Other technologies such as CSP still need more studies (cost, affordability and durability) in order to satisfy the needs of Rwanda population.

2. Beside hydroelectric energy which is the main source of electricity in Rwanda there are some other energy sources that harness water to get electricity such as wave and tidal power which are not applicable in Rwanda.

3. Biomass is a renewable resource with high potential, and the most used in Rwanda. This source of energy has been exploited and we are trying to improve its applicability by introducing biogas digesters, improved stoves in order to improve its efficiency. Once people in rural area will have access to

this improved energy technology, the number of people using firewood will be reduced. For example the introduction of improved stoves will increase from 80 -100% in urban areas and 50 - 80% in rural areas. This will reduce the use of fuel wood by 35%. Once we have enough gas, people will no longer use electricity for cooking and hopeful the cost of electricity will reduce. The equipments materials for biomass technology are not expensive and some of them can be found for free (briquettes).

4. Geothermal energy uses the heat from deep inside the earth to produce electricity. Various methods have been developed to do this, and the most common method is harnessing the steam that naturally comes out of fissures on the ground. Geothermal energy can only be used in certain regions, reducing its applicability. This technology still investigated in Rwanda.
5. Wind power uses the same principle found in hydroelectric dams to convert the wind kinetic energy to electricity.

   There are lots of windy areas across the globe, and in many parts of the world people are trying to harness wind energy as much as possible, though efficiency of this energy source still remains a big problem, largely because of inconsistency of wind blowing. In Rwanda they did not set yet the atlas map of wind places, it still in process of study. And we have hope that it will contribute a lot to the energy demand.

   In Rwanda, a wind map has not been established yet, but work is in progress. Once the information regarding windy areas is available, this technology may be reviewed.

   There are certain drawbacks in using renewable energy. For instance the solar power is significantly less effective in cloudy weather and the wind power is highly ineffective to use during calm days. But combining couple of renewable energy sources can hide these drawbacks.

The following Pie chart shows us the proportions of various energy sources used in Rwanda:

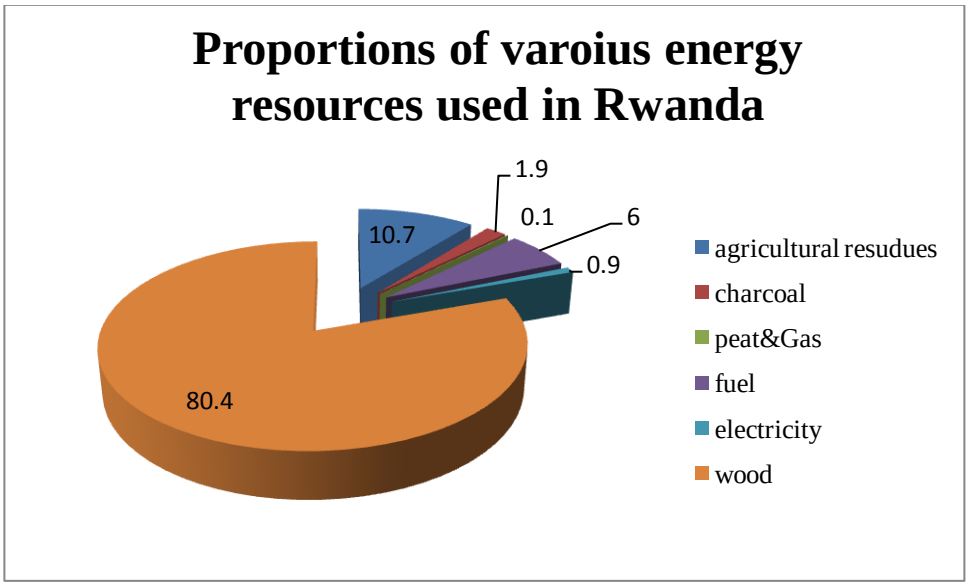


Figure 25: Proportions of various energy resources in Rwanda [5]

As we said a big part of Rwanda population depends on wood energy, and we really hope that to introduce new and renewable energy technologies will help more.

Based on our survey on five renewable energy used in Rwanda, we came up with the following assumptions: solar, biomass and hydropower are being used and we can improve their technologies. Geothermal and wind are under study for future use. The attention should be pay on geothermal energy because Rwanda is one of the only African countries with potential prospects for geothermal resource utilisation.

At the moment, we can't draw a chart showing the distribution of renewable energy resources studied in research because some of them still under constructions (e.g. geothermal and wind energy). A father study should be done for more numerical support.

In conclusion, the most applicable renewable energy sources at the moment are likely to be biomass and solar, since both resources are abundantly available. Hydropower is already in great use in Rwanda. Wind energy maps are insufficiently investigated to come to a conclusion about the usefulness of using wind energy, while geothermal energy is restricted by its location.

In this section, we found out that Rwanda has renewable energy resources (solar, biomass, hydropower, geothermal and wind) which can contribute to the reduction of the energy crisis for the country by implementing efficient renewable energy technologies, which are important to the economic and financial situation of the country.

It is more likely that a combination of renewable energies should be found, and that each area will have its own strengths and weaknesses

PART II

Chapter 8

Efficiency Comparison of a Solar Trough Receiver using a Hot Mirror and Selective Coating

This part concerns itself with a project on solar energy. It looks at a solar trough system with the receiver pipe enclosed in a glass cover under vacuum, where the dominant radiation losses from the receiver are reduced by the use of a 'hot mirror' on the glass cover instead of selective coating on the receiver pipe. Results for a general heat transfer model and comparison of the performance of selective coating with a hot mirror using simulations are presented. It is seen that a hot mirror is a viable alternative, and certainly allows high temperatures of the working fluid.

8.1 Introduction

Solar energy has been identified as a strong candidate for use as an alternative energy source. Numerous ways of extracting useful energy from the sun have been investigated (refer to chapter 2). These ranges from domestic applications such as flat-plate collectors, cookers, solar panels, and pool heating systems to those of industrial size including power-towers, solar troughs, solar panels arrays and de-salination plants, amongst others.

8.1.1 Historical background for a solar trough plant

Luz international constructed the first solar trough plants in California in 1984 and the last in 1991. Nine such plants were built; Solar Energy Generating Systems (SEGS I-VII) at Kramer junction and SEGSVIII-IX at Harper lake and Barstow respectively. Their peak capacity is 354 MW and today they generate enough electricity to meet the need of about 500,000 people [28, 35].

This study mainly concerns with efficiently converting solar energy into the desired energy form (thermal, electric, etc.). Efficiency loses during energy conversions and operation can be minimised using different technologies. The basic idea in this chapter is to investigate the theoretical performance of an alternative to selective coating, the "hot mirror".

8.2 Solar Trough Plant

A solar trough is a medium to high temperature solar energy technology (100^{o}C to 350^{o} C) and is among the most-studied solar systems [95].

Such systems consist of a parabolic curved trough shaped reflectors which focus the sun's energy onto a receiver pipe (absorber tube) running at the focus of the reflectors, through which a 'working fluid' circulates (Fig. 25).

The trough is parabolic in one direction and straight in another. The geometric properties of a parabola are such that any light beam moving vertically downwards parallel to the optical axis in the concavity of the parabola (i.e. parallel to the axis of symmetry) will reflected off the parabola and move directly towards the focus, where the receiver is located. The collectors are aligned on and east-west axis and the trough is rotated to follow the sun to maximize the suns energy input to the receiver tube.

Due to their parabolic shapes, mirrors produce a focal line by concentrating the sun's radiation at 30-60 times its normal intensity on the receiver pipe which in turn heats the fluid moving along inside it [1, 28, 35].

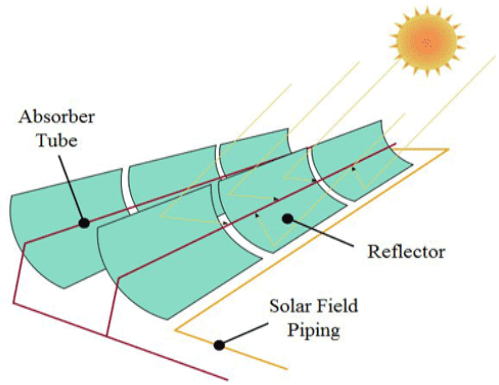


Figure 26: Solar Trough plant layout taken [96]

The working fluid is then circulated to a power station where it is converted to electricity. Generally, the receiver unit must be designed in such way that it loses as little heat as possible via radiation, convection and conduction to its surroundings [35].

8.2.1 Solar Trough Receiver with selective coating

8.2.1.1 What is a selective coating?

The selective coating is a dielectric material which absorbs well in the visible region of spectrum (i.e. sunlight) but emits very poorly in the Infra-Red region, which is the radiation that is lost from the receiver pipe [10, 101, 102]. For example; Pbs films which have a high absorption ($\alpha = 0.92$) in the visible spectrum (390 – 750 nm) and small thermal emittance (ε (100ºC) = 0.12) [103]. Hence the dominant heat loss mechanism at high temperature (radiation) can be diminished (Fig. 26). It collects heat energy more efficiently than ordinary black paints which emit a significant

amount of the energy they absorb. This solar coating allows manufacturers of solar collector panels to achieve selectivity with the economy and ease of application of paint. The coating also resists out gassing, a major cause of internal fogging of collector covers by up to 400^{o}C. The coating is designed for spray application and can be applied directly to clean metal surfaces and dries up after about 15 minutes. It is also available in spray cans, and provides a convenient way to touch up electroplated collector panels which may have incurred damage during manufacture, shipping or installation [97]

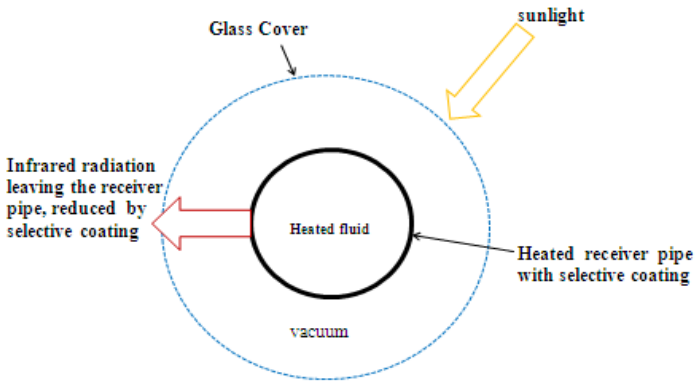


Figure 27: **Cross section of receiver unit with selective coating**

The receiver (as shown in Fig. 26) typically consists of a glass cover, encapsulating a metal receiver pipe with a vacuum in between. The vacuum minimizes convective loses from the heated receiver pipe to the surroundings [28]. Conduction loses are reduced by minimizing the contact between the receiver pipe and the glass sleeve [98]. Thermal radiation loses are reduced by the use of a selective coating applied to the receiver pipe [98, 99]. All aspects of the receiver units are topics of on-going research, such as optical, thermal and chemical properties of all materials concerned, the vacuum integrity, thermal expansion, as well as which

working fluid should be used, and many others [98]. We will concentrate on the possibility of a substitute for the selective coating.

8.2.1.2 Advantages of selective coating

A selective coating on the receiver pipe will render the system more efficient in terms of the fraction of solar energy absorbed by the working fluid, heating it.

Numerous articles have been published on selective coatings on the receiver pipes and their properties [1, 11]. Some have mainly focussed on improving the optical properties such that the selective coating becomes more efficient at withholding heat, while others seek to improve its thermal stability.
Data from experimental facilities such as SEGS, and computer simulations provide valuable insight to this effect. The aim of research on selective coatings is to create a stable, efficient coating over a wide temperature range (0^{o}C to 1000^{o}C).

8.2.1.3 Disadvantages of selective coating

The main weakness of commercial selective coatings is that they deteriorate thermally at temperatures around 680^{o}K (400^{o}C) [1, 16, 98, 99, 102], thereby restricting the maximum temperature to which the receiver pipe can be heated, and hence the Carnot or Rankine efficiency of the subsequent heat to electrical conversion [98].

8.2.2 Solar Trough Receiver with hot mirror

8.2.2.1 Hot mirror

A “hot mirror” refers to a dielectric coating that is designed to reflect the IR region of the spectrum and to transmit the visible. In our model, it is applied to the inside of the glass cover. The hot mirror on the glass cover will then reflect IR radiation emitted from the receiver pipe back onto itself, thereby reducing the amount of thermal radiation leaving the receiver unit (Fig. 27). The net effect is similar to that

of the selective coating. Hot mirror is ideal for reducing heat projectors; it reflects 90% in near infrared and Infrared. Hot mirror transmit 80% of visible light. For example $SnO_{2:\ F}$ shows 90% optical transmission at solar maximum (550 nm). High infrared reflectivity is indicating that, the thin film is a good heat mirror with low sheet resistance [100].

To our best knowledge, a hot mirror system has not been studied in this context. We could also find no reference to the possibility of a hybrid system, where different types of technologies are used at different temperature ranges, within this context, as in this part.

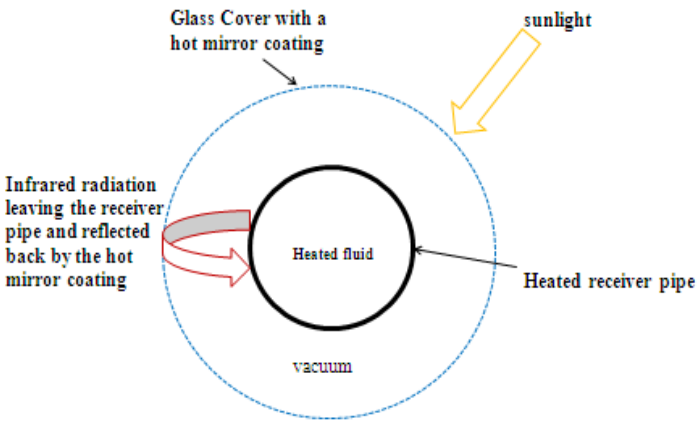


Figure 28: Cross section of proposed receiver unit with hot mirror Coating

8.2.2.2 Advantages of Hot mirror

By using a hot mirror, heat levels are limited with minimum impact on the overall system performance.

For our system, the hot mirror is applied to the glass cover, which is cooler than the receiver pipe during operation (by around 200K). It is therefore possible to sustain higher temperatures in the receiver pipe using a hot mirror instead of a selective coating on the receiver pipe. This additional temperature increase is transferred to the working fluid, and subsequently to the steam power station, where it will improve thermal efficiency [98, 101].

8.2.2.3 Disadvantages of hot mirror

The hot mirror coating also breaks down thermally around 680K [16, 103]. In essence, therefore, we are addressing the problem of the temperature ceiling (~680K) in existing systems, since use of a hot mirror sidesteps the problem of thermal decomposition of the selective coating and thereby allows for a higher temperature of the working fluid [16].

Chapter 9

Analysis of the receiver unit

We want the receiver to absorb the sun's visible radiation while losing as little as possible of the radiation emitted by the receiver, in the IR region. Below is a diagram of a conventionally used receiver with selective coating.

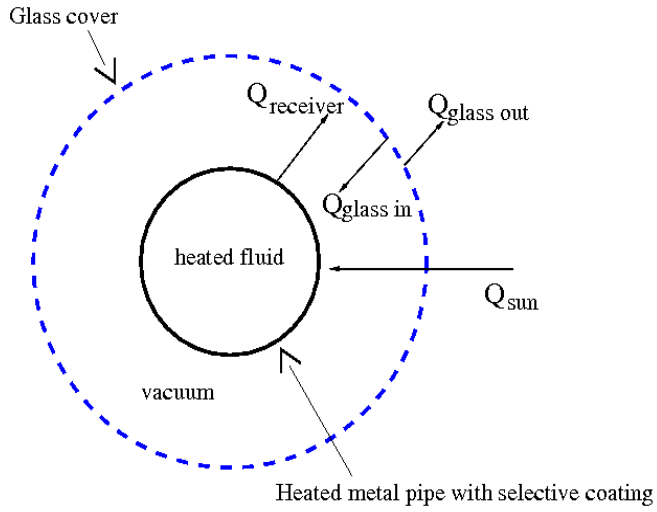


Figure 29: Interchanges of energy in a system using selecting coating

In figure 28 Q_{sun} is the amount of radiation coming from the primary mirror arriving at the receiver, $Q_{receiver}$ is thermal radiation leaving the receiver (black body radiation and reflected radiation), $Q_{glass\text{-}in}$ is the total radiation originating from the glass cover back onto the receiver. This contains thermal radiation due to the hot glass cover as well as reflected radiation, and $Q_{glass\text{-}out}$ is total radiation leaving the

glass cover, including thermal radiation from the glass and transmitted radiation from the receiver.

9.1 Basic formulations for receiver unit

We calculated the dominant radiation heat transfer mechanism between the receiver pipe and the glass cover, dividing the radiation into visible and IR. We further included the heat transfer into the working fluid and convection losses to the outside from the glass cover, see Fig. 29. The resulting equations are functions of the absorption/emission coefficients of the glass cover and receiver pipe in the visible and IR (well defined in section 9.3). By adjusting these coefficients, we simulated a selective coating and hot mirror system.

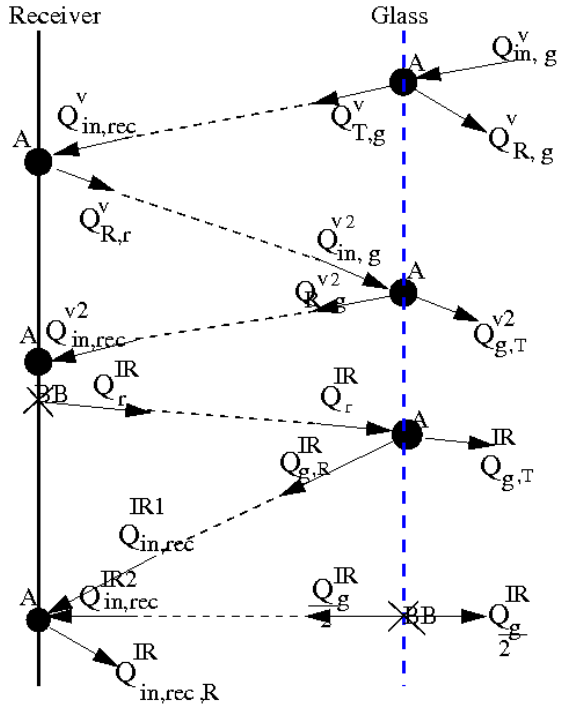


Figure 30: Radiation types falling on our system surfaces. At every node there is a chance for reflection, transmission and absorption. The shot-dashed lines connecting nodes refer mainly to the fact that output of one becomes input of the next, e.g. $Q^{v}_{in,rec} = Q^{v}_{T,g}$.

9.2 Calculations and Analysis

Our model describes the heat transfers via radiation between the glass cover, the receiver pipe and the outside, as well as the conductive heat transfer into the working fluid and convective losses to the surroundings. The relevant equations are presented below.

The equation for radiative heat transfer is

$$Q = \varepsilon\sigma A(T_2^4 - T_1^4) \tag{9. 1}$$

with ε the emissivity of the material, σ being the Stephan-Boltzmann constant , A surface area and T_1, T_2 being the temperatures of the outside and the material respectively.

The equation for convective loss was taken to be

$$Q_{conv} = hvA_g(T_g - T_0) \tag{9. 2}$$

where $hv = a_c + b_w.u$; with a_c the convection factor; b_w the wind factor and u the wind speed , T_o is the ambient temperature (293^o K) [1, 16].

The equation describing the heat transfer from the receiver pipe into the liquid is

$$Q_{LC} = \frac{KA_r}{L\left(1+\frac{KA_r.K1}{L}\right)}(T_r - T_L) \tag{9. 3}$$

with $K_1 = \frac{1}{h_f \pi D_p} - \frac{1}{c_b}$

where K *is* the thermal conductivity of the material; A_r is receiver area; T_r is receiver temperature; T_L is liquid temperature; L thickness of the receiver; h_f is heat transfer between wall and fluid coefficient; $D_p$is pipe diameter and c_b the bond thermal conductance [95].

9.3 Heat Transfer Mechanism

9.3.1 Heat Loss Analysis

Radiation falling on a surface interacts with it via the mechanisms of reflection (r), transmission (t) and absorption (a = 1 – r – t) in relative proportion [5, 34], where, 'r' and 't' are the reflection and transmission coefficients respectively (fig. 30). In each case, the superscript refers to whether the term of interest applies to visible (v) or IR (IR) and the subscript refers to its physical location, being either on the glass cover (g) or the receiver pipe (r).

The physical mechanism we describe mathematically is this: the (visible) solar radiation from the parabolic mirrors is incident on the glass cover with power $Q_{visible}$ denoted Q^v. A fraction of this radiation is transmitted with transmission coefficient, t_g^v, some is reflected with reflection coefficient r_g^v and the remainder $(1 - t_g^v - r_g^v)$, is absorbed which heats the glass cover, making it emit in the IR (Fig. 30)

The transmitted visible light is incident on the receiver pipe. Again, this radiation is reflected, transmitted and absorbed. In this case, transmission on the receiver is negligible, since virtually no visible light passes through the metal of the receiver pipe. The reflected visible light from the receiver pipe interacts again with the glass cover via the three mechanisms. This infinite series of interactions can be added together [16].

The visible light absorbed by the receiver pipe heats it and causes it to emit IR radiation with power $Q_{receiver}^{IR}$ denotedQ_r^{IR} and some emission coefficient, ε_r. This radiation strikes the inside glass cover where a fraction of it is reflected as

$Q_{Reflected,glass}^{IR}$ (The fraction depends of the reflection coefficient of IR on glass, r_g^{IR}), some is transmitted as $Q_{Trasmitted,glass}^{IR}$ with a fraction t_g^{IR} and the remainder is absorbed, further heating the glass cover.

The heated glass cover radiates in the IR with power , Q_g^{IR} with an emission coefficient, ε_g, both to the inside (where it is again partially absorbed by the receiver pipe) and outside of the glass cover (where it is lost to the surroundings).

On the outside of the glass cover we must also account for the convective losses to the surroundings, Q_{conv}. Further, a term describing the heat flow into the liquid (Q_{LC}), depending on the temperature gradient between the inside of the receiver pipe and the liquid, is included.

9.3.2 Derivation of receiver and Glass cover equations

Using conservation of energy, we derived the following equations (see Appendix A) for the heat incident on and emitted by the glass cover and the receiver pipe. In order to derive glass cover and receiver equations, Fig. 30 can be subdivided into 3 parts: Visible radiation, IR radiation into and from the glass cover, and IR radiation from and into receiver (see Fig. 31, 32 and 33).

The total visible radiation falling into receiver is

$$Q_{tot}^{v} = Q_{T,g}^{v} + Q_{R,g}^{v2} \tag{9.4}$$

The total IR radiation incident on the receiver is

$$Q_{g,tot}^{IR} = Q_{R,g}^{IR} + \frac{Q_g^{IR}}{2} \tag{9.5}$$

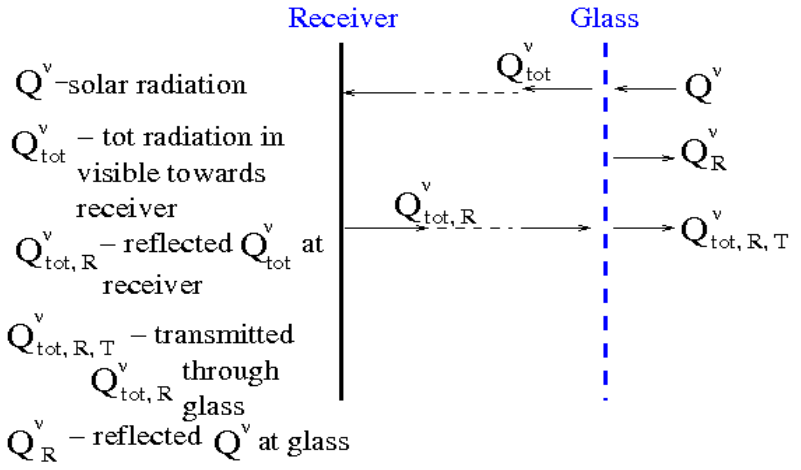


Figure 31: Visible radiation for glass cover and receiver

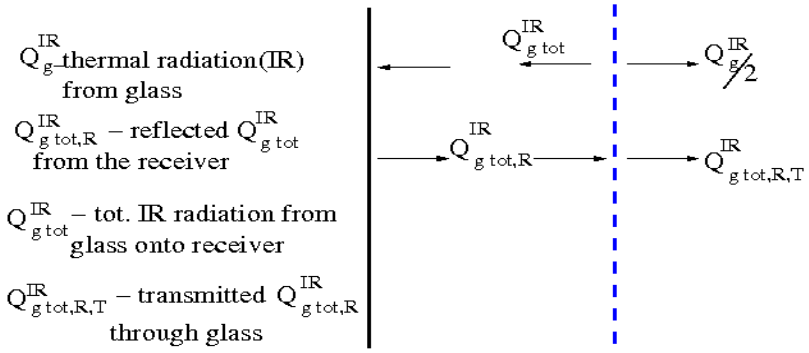


Figure 32: IR radiation into and from glass cover

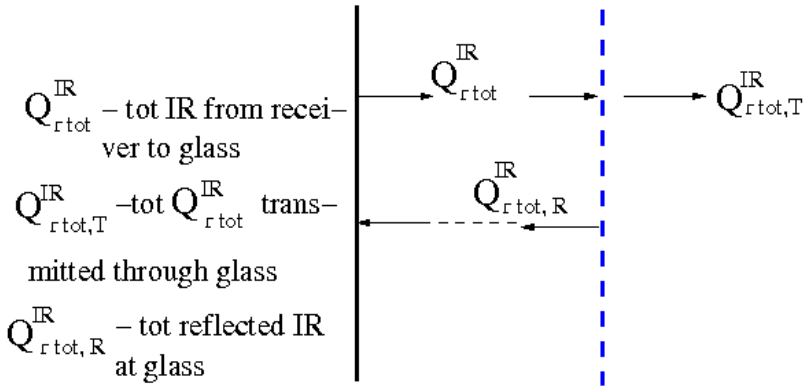


Figure 33: IR radiation into and from receiver

9.3.2.1 Derivation of glass cover equation

Referring to Figures 31, 32, 33, convection loss from glass cover to the surroundings (Q_{conv}) and the conservation of energy law, we know that all radiation falling onto the glass cover must be radiated out. We can therefore write the equation as

$$Q^{v} + Q^{v}_{tot,R} + Q^{IR}_{g,tot,R} + Q^{IR}_{r,tot} = Q^{v}_{R} + Q^{v}_{tot} + Q^{v}_{tot,R,T} + Q^{IR}_{g,tot,R,T} + Q^{IR}_{g2} + Q^{IR}_{r,tot,T} + Q^{IR}_{r,tot,R} + Q_{conv} \quad (9.6)$$

By rearranging and putting the terms together (see appendix A), the equation for the glass cover has the following form;

$$AQ^{v} + BQ^{IR}_{r} + CQ^{IR}_{g} - Q_{conv} = 0 \quad (9.7)$$

9.3.2.2 Derivation of receiver pipe Equation

As we did for the glass cover, radiation falling onto the receiver must be radiated out we included the heat goes into the fluid inside the pipe (Q_{LC}).

$$Q^{v}_{tot} + Q^{IR}_{r,tot,R} + Q^{IR}_{g,tot} = Q^{v}_{tot,R} + Q^{IR}_{g,tot,R} + Q^{IR}_{r,tot} + Q_{LC} \quad (9.8)$$

By rearranging and putting the terms together (see appendix A), the equation for the receiver pipe has the following form;

$$DQ^{v} + EQ^{IR}_{r} + FQ^{IR}_{g} - Q_{LC} = 0 \quad (9.9)$$

9.3.2.3 Assumptions made for our study

A simple model of this type captures the dominant heat movement effects of the system. We did not specifically consider convection and conduction interactions

inside the receiver unit, since they are sub-leading mechanisms of heat transfer at high temperatures and can also be assumed to remain similar in both systems.

A more realistic, but complex, model can be created if some or all of the following major approximations are addressed. The model is nevertheless suitable to answer the main questions of this chapter.

The approximations used in this calculation are first, the strict division of the radiation into visible and IR bands. Coatings have different behaviours of interactions within these regions, and an average constant for absorption and transmission was assumed. This average was sought to be close to the value near the dominant wavelength, found from Wien's law [1, 16].

Secondly, the calculation was performed on a two-dimensional cross section of the glass cover and receiver pipe. We thought it to be justified to extend the model to three dimensions because the temperature along the receiver pipe varies slowly enough, so that the radiation loss along the pipe from one cross sectional element is similar to the radiation gained by its neighbour.

The heating of the receiver unit was assumed to be uniform. We did not take a temperature gradient along the circumference of the glass cover or receiver pipe into account, as it was assumed that the material involved was a good conductor of heat.

Furthermore, we assumed the glass cover and the receiver to be close enough together so that the majority of the radiation leaving either one is absorbed by the other. This is certainly the case for the radiation leaving the receiver pipe. It is clear that unless they are infinitesimally close to each other, some small fraction of the radiation leaving the glass cover will be lost by not striking the receiver pipe. This lost fraction will however be partially absorbed by the glass cover again, remaining within the system, so we are somewhat justified in this approximation.

We did not include any heat transfer effects into the working fluid due to the type of flow it displays, laminar or turbulent. We also did not include the above

mentioned sub-leading heat transfer mechanisms, such as convection and conduction inside the receiver.

We proceeded as follows:

We added all the incoming and outgoing contributions in the visible and IR regions for both the glass cover and the receiver pipe, using Eq. 9.1. We then substituted for the amount of heat being transferred to the liquid using Eq. 9.3, and the heat lost from the glass cover to the surrounding by convection using Eq. 9.2. This yield the two coupled equations for the unknown temperatures of the glass cover T_g and the receiver pipe T_r, shown below,

$$AQ^v + BA_r\varepsilon_r\sigma T_r^4 + CA_g\varepsilon_g\sigma T_g^4 - \varepsilon v A_g(T_g - T_0) = 0 \tag{9.10}$$

$$DQ^v + EA_r\varepsilon_r\sigma T_r^4 + FA_g\varepsilon_g\sigma T_g^4 - \frac{KA_r}{L\left(1+\frac{KA_rK1}{L}\right)}(T_r - T_L) = 0 \tag{9.11}$$

Where A_r and A_g is the unit area of the receiver pipe and glass cover respectively, which are active in their heat transfer.

The equations are solved for T_g and T_r using a numerical program, which we wrote (see Appendix B).

The constants A to F (see derivation in appendix A) depend on the various reflection and transmission coefficients as follows:

$$A = \frac{1 - r_g^v - t_g^v + r_r^v(r_g^v(r_g^v - 1) + t_g^v(1 - t_g^v))}{1 - r_g^v r_r^v} \quad , \quad B = \frac{1 - t_g^{IR} - r_g^{IR}}{1 - r_g^{IR} r_r^{IR}}$$

$$C = \frac{r_r^{IR}(1 - t_g^{IR})}{1 - r_r^{IR} r_g^{IR}} - 1 \quad , \quad D = \frac{t_g^v(1 - r_r^v)}{1 - r_g^v r_r^v}$$

$$E = \frac{r_g^{IR} - 1}{1 - r_r^{IR} r_g^{IR}}, \qquad F = \frac{1 - r_r^{IR}}{2(1 - r_g^{IR} r_r^{IR})}$$

where the coefficients have their usual meaning, defined above.

The parameters A to F are interpreted as giving the amount of radiation (visible or IR) absorbed by a given surface of interest. At equilibrium temperature, the amount of heat absorbed by any surface is equal to the amount of heat released. In equation 9.7, the glass cover loses heat mainly via IR radiation, making C negative. In equation 9.9, E is expected to be negative for a similar reason. The last terms in both equations represents heat loss via convection to the surrounding by the glass cover (Eq. 9.10), and heat loss to the working fluid via conduction (Eq. 9.11). Both depend on the local temperature difference linearly.

These results have been tested in numerous limits of coefficients and provided the expected results argued on purely physical grounds.

The equations above can be used to obtain the equilibrium temperatures of both the receiver pipe and the glass cover at any point along the length of receiver unit for any given working fluid temperature. From that, all relevant heat that flows into the system can be calculated, notably the heat flow into the working fluid and the total heat loss to the surroundings. From these results, efficiency comparisons can be undertaken and questions regarding thermal decomposition answered.

9.3.2.4 Computer Simulation

We have written a program which simulates the behaviour of a solar trough system (see appendix). Solar radiation is incident on a section of the receiver unit, where it undergoes the interactions described above leading to equations (Eq. 9.10 and Eq. 9.11). The program solves these equations (Eq. 9.10 and Eq. 9.11) simultaneously for the equilibrium temperature of the glass cover and receiver pipe.

From this, all equilibrium heat-flows had been calculated. The initial working fluid temperature was known and the final temperature as it exits the pipe section was computed and used as initial input for the following section.

Quantities derived from the program include the equilibrium temperatures of the glass cover, the receiver pipe and the working fluid at incremental points along its length, and all heat flows related to them. Efficiencies are also computed.

For the simulations, we used a visual basic program coupled with an excel worksheet. We further checked the results against an independent program in Math CAD.

9.4 Results and Discussion

9.4.1 Data used

Since finite sections of length are considered, the temperatures obtained are averages over that section. It was found that since the temperature variation was small along the pipe, the results were not very sensitive to the choice of section length when smaller than 0.5 m (we used 0.25m in the simulation).

Errors introduced by the program were mainly due to this finite length approximation. Yet since we wanted to compare performance of a hot mirror to a selective coating, the errors would be similar in both cases and the comparison was still taken to be valid for the aims of this study.

We used the following parameters to simulate the case of the selective coating and the hot mirror (see Table. 3) [16, 95, 98, 99, 101, 102].

Table 3: Typical values of Reflection, transmission and absorption coefficient for Selective coating and Hot mirror in Infrared and visible region.

	Selective coating						Hot mirror					
	t_g	t_r	r_g	r_r	a_g	a_r	t_g	t_r	r_g	r_r	a_g	a_r
Visible radiation (V)	0.9	0	0.04	0.04	0.06	0.96	0.9	0	0.04	0.04	0.06	0.96
Infrared radiation (IR)	0.25	0	0.2	0.8	0.55	0.2	0.07	0	0.7	0.2	0.23	0.8

These values are typical for the type of coating considered, but there is a whole range of values for different types of selective coating and hot mirror available. These different values can be used to study to optimum performance for each system. The transmission (t_g) and reflection (r_g) in the visible for the glass cover was taken as 0.9 and 0.04 in both cases. Transmission of the receiver pipe (t_r) was set to zero in both cases for visible and IR.

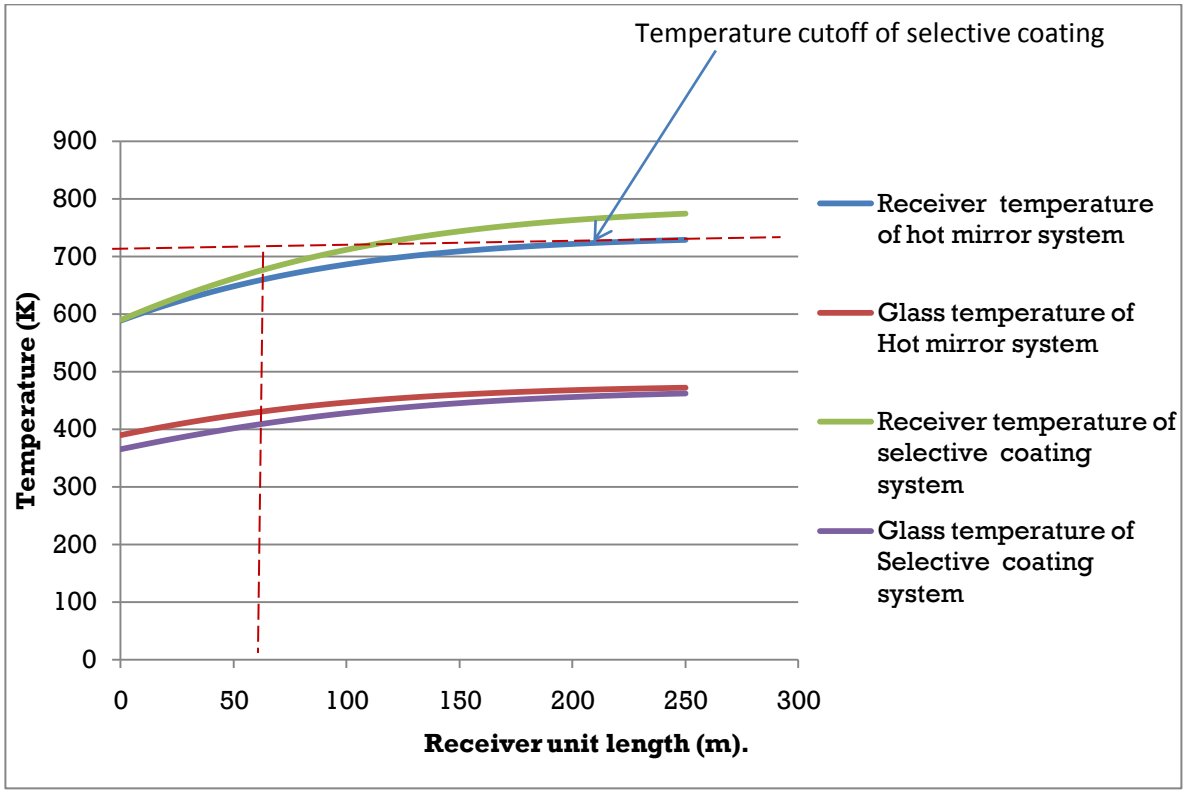
The selective coating was modelled by setting the reflection of the receiver pipe ($r_r = 0.04$) visible to a small value (it absorbs well in the visible) and reflection in IR ($r_r = 0.8$) to a high value (it absorbs poorly in IR, hence it emits poorly). The glass cover characteristics are within a conventional range [104].

The hot mirror system was modelled by making the reflection coefficient in the IR large ($r_g = 0.7$). The receiver pipe had characteristics close to a darkened steel pipe without selective coating [16, 104].

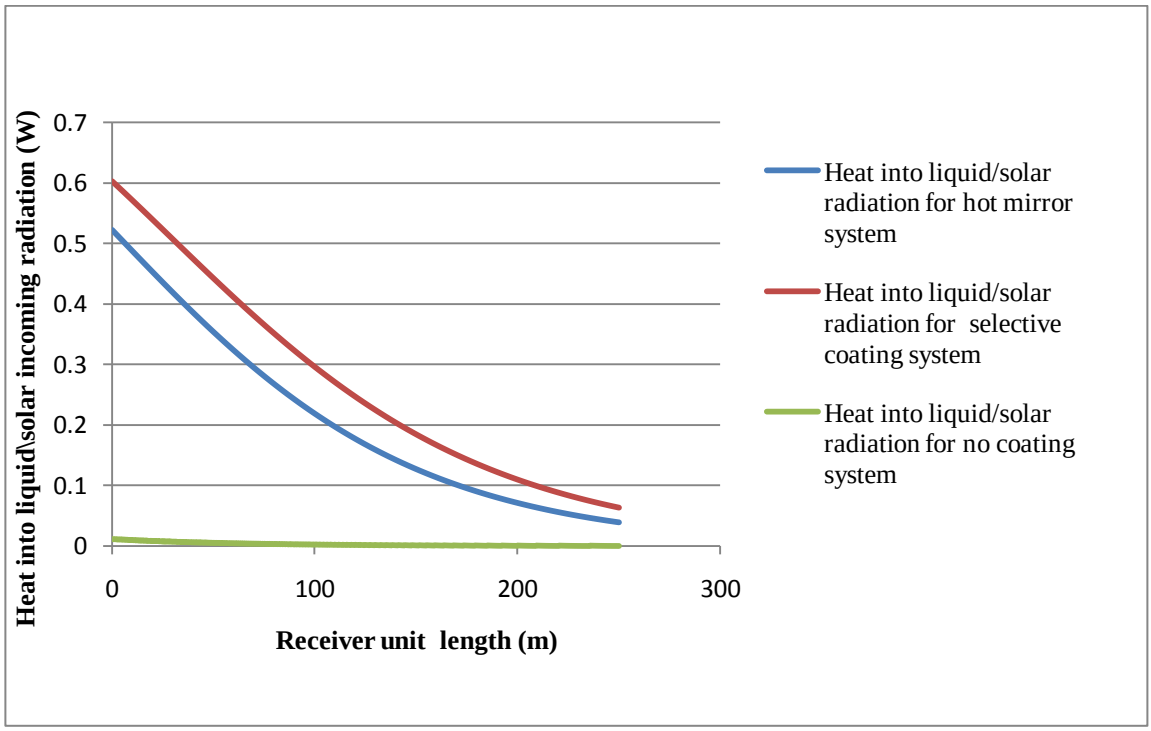
Results of the simulations are shown in the next section.

9.4.2 Results

Results shown below are graphs for the temperatures of glass cover and the receiver pipe for both the selective coating and hot mirror system as a function of length of the solar trough system (Graph. 1). Results for the efficiency of heat going into the working fluid (compared to the total incident solar radiation) are shown for selective coating, hot mirror and a system without either (Graph. 2).



Graph 1: Comparison between selective coating and hot mirror temperature of glass cover and hot mirror. Although the graph for selective coating is shown along the antire length of the receiver unit, it is understood that this graph terminates at the dotted vertical line, due to thermal decomposition.



Graph 2: Heat flow into working fluid/Solar incoming radiation versus receiver unit length.

9.4.3 Discussion

The simulation was started at a temperature close to where failure of the selective coating is expected (600K). Relative efficiencies of selective coating and hot mirror can be compared in this region, and the question of applicability of the hot mirror answered.

Looking at the graph 1, it is seen first that for the chosen parameters of selective coating and hot mirror, the selective coating performs slightly better in the sense that the receiver pipe increases to a similar temperature over a short distance. This implies a higher heat transfer for selective coating into the working fluid compared to the hot mirror at the same length, since the temperature gradient between

the pipe and liquid is larger. As seen in graph 2. Hence the selective coating should be used at temperatures where it is stable (below 680K). After this critical temperature, a substitution to the hot mirror system is advisable. The glass cover temperature is seen to be much lower than the receiver pipe temperature (around 200K), and this allows the glass cover to be coated with a hot mirror, since the hot mirror coating can operate at these temperatures. This will allow the working fluid to be heated to more elevated temperatures, making the overall system more efficient. It should be noted that our choice of values for the hot mirror coating properties was on the conservative side, and it can perform better in terms of IR reflection, elevating the stagnation temperature even higher. This is a detailed engineering concern and can be studied elsewhere.

Graph 2 indicates the efficiency of heat moving into the working fluid (heat into working fluid, $Q_{LC)}$ / (total incident solar radiation, Q_v). It is seen that both the selective coating and the hot mirror perform much better in terms of working fluid heat transfer than a system without either, making both suitable for efficiency increase of a solar trough plant.

Chapter 10

Conclusion on Part 2

We investigated the general performance of a hot mirror system when compared to a selective coating system in terms of efficiency of heat transfer into the working fluid and the possibility of using a hot mirror system to replace the currently used selective coating system at temperatures beyond which a selective coating system fails (~400^{o}C).

A set of heat transfer equations was derived, modelling the thermal behaviour of a solar trough receiver unit. Radiative heat transfer within the receiver unit was considered, as well as convective losses to the outside, and heat transfer into the liquid. A code was written using the equations, and this was the main source of our results.

First, it was seen that for our chosen parameters for hot mirror and selective coating, the hot mirror system performed slightly poorer in terms of heat transfer into the working fluid, but much better than a system with no coatings. An optimized hot mirror system may be a candidate to replace a selective coating system in a temperature range for which the hot mirror is useful.

Second, it was seen that the glass cover temperature was sufficiently low for a hot mirror system to remain operational beyond temperatures currently available to a commercial selective coating system. This allows the construction of solar trough systems with longer receiver pipes of two types: selective coating should be used in the temperature region where it is appropriate, and a hot mirror system at higher temperatures. This will allow the working fluid to reach a greater temperature, and

hence better overall plant performance. For this purpose, it would be well worth investigating the hot mirror receiver system further.

The weakness of the hot mirror is that it performs slightly poorer in terms of heat transfer into the liquid, at least for our choice of parameters. The reflectivity of a hot mirror changes significantly with wavelength even in the IR region. Generally shorter IR is reflected better, making the hot mirror system useful at higher temperatures. Further, it is necessary for a solar trough plant to switch between selective coatings and hot mirror at some length of the receiver pipe using two technologies. Also, depending on what type of hot mirror is used, the glass cover may nevertheless reach quite high temperatures.We have not addressed detailed questions such as cost effectiveness or a detailed design for a receiver unit with hot mirror coating. The main purpose of this chapter was to highlight the possibility of an alternative system to selective coatings.

In conclusion, a hybrid system between selective coating and hot mirror is likely to improve the overall efficiency of the solar trough plant as it performs better than either a system with selective coating or hot mirror alone.

Appendix A

A.1 Derivation of Receiver unit equations

In order to deriver Glass cover and receiver equation fig 30 has been spited into 3 different parts as shown in Fig. 31, Fig. 32 and Fig. 33: Visible radiation, IR radiation into and from the glass cover, and IR radiation from and into receiver

The total visible radiation falling into the receiver

$$Q_{tot}^{v} = Q_{T,g}^{v} + Q_{R,g}^{v2} \quad \text{(A.1)}$$

where

$Q_{T,g}^{v}$ is visible radiation transmitted by glass cover and $Q_{R,g}^{v2}$ is visible radiation reflected by glass cover .

Total IR radiation falling into receiver

$$Q_{g,tot}^{IR} = Q_{R,g}^{IR} + Q_{g2}^{IR2} \quad \text{(A.2)}$$

where

$Q_{R,g}^{IR}$ is IR radiation reflected by glass cover and Q_{g2}^{IR2} is IR radiation radiated by the glass cover on no coated side.

A.2 Derivation of equation of glass cover

Referring to figures 31, 32, and 33 and the conservation of energy law, we know that all radiation falling onto the glass cover must be radiated out. We can therefore write the equation as

Radiation coming in = radiation going out.

$$Q^v + Q^v_{tot,R} + Q^{IR}_{g,tot,R} + Q^{IR}_{r,tot} =$$
$$Q^v_R + Q^v_{tot} + Q^v_{tot,R,T} + Q^{IR}_{g,tot,R,T} + Q^{IR}_{g2} + Q^{IR}_{r,tot,T} + Q^{IR}_{r,tot,R} \quad \text{(A.3)}$$

where

Q^v is visible radiation coming in from the sun, $Q^v_{tot,R}$ is reflected total visible radiation at receiver, $Q^{IR}_{g,tot,R}$ is reflected IR radiation from glass cover into receiver, $Q^{IR}_{r,tot}$ is total IR from receiver to glass, Q^v_R is reflected visible radiation at glass cover, $Q^v_{tot,R,T}$ is transmitted reflected visible radiation at receiver through glass cover, $Q^{IR}_{r,tot,T}$ is transmitted reflected IR radiation at receiver through glass cover and $Q^{IR}_{r,tot,R}$ is total reflected IR at glass cover.

$$Q^v + Q^v_{tot,R} + Q^{IR}_{g,tot,R} + Q^{IR}_{r,tot} - Q^v_R - Q^v_{tot} - Q^v_{tot,R,T} - Q^{IR}_{g,tot,R,T} - Q^{IR}_{g2} - Q^{IR}_{g,tot} - Qr,tot,T \quad IR - Qr,tot \quad ,RIR=0$$

(A. 4)

Where

$$Q^v_R = r^v_g Q^v, \quad Q^v_{tot,R.T} = r^v_r t^v_g Q^v_{tot}, \quad Q^{IR}_{g,tot,R,T} = r^{IR}_r t^{IR}_g Q^{IR}_{g,tot}$$

$$Q^v_{tot,R} = r^v_r Q^v_{tot}, \; Q^{IR}_{g,tot,R} = r^{IR}_r Q^{IR}_{g,tot}, \; Q^{IR}_{r,tot,T} = t^{IR}_g Q^{IR}_{r,tot} \text{ and } Q^{IR}_{r,tot,R} = r^{IR}_g Q^{IR}_{r,tot}$$

Equation (A.4) becomes

$$Q^v - r^v_g Q^v + r^v_r Q^v_{tot} - Q^v_{tot} - r^v_r t^v_g Q^v_{tot} + r^{IR}_r Q^{IR}_{g,tot} - Q^{IR}_{g2} - Q^{IR}_{g,tot} -$$
$$r^{IR}_r t^{IR}_g Q^{IR}_{g,tot} + Q^{IR}_{r,tot} - t^{IR}_g Q^{IR}_{r,tot} - r^{IR}_g Q^{IR}_{r,tot} = 0 \quad \text{(A. 5)}$$

By rearranging and putting the terms together we have:

$$Q^v\left(1 - r^v_g\right) + Q^v_{tot}\left(r^v_r - r^v_r t^v_g - 1\right) - Q^{IR}_{g2} + Q^{IR}_{g,tot}\left(r^{IR}_r - r^{IR}_r t^{IR}_g - 1\right) +$$
$$Q^{IR}_{r,tot}\left(1 - r^{IR}_r - t^{IR}_g\right) = 0 \quad \text{(A. 6)}$$

We know that

$Q_{tot}^{v} = t_g^v Q^v + r_r^v r_g^v Q_{tot}^{v}$,

$Q_{tot}^{v}\left(1 - r_r^v r_g^v\right) = t_g^v Q^v$,

$Q_{tot}^{v} = \frac{t_g^v Q^v}{1 - r_r^v r_g^v}$.

Let us call $\frac{t_g^v}{1 - r_r^v r_g^v} = t$

Then $Q_{tot}^{v} = tQ^v$

For $\boldsymbol{Q_{g,tot}^{IR}}$

$Q_{g,tot}^{IR} = Q_{g,tot,R}^{IR} + Q_{g1}^{IR}$,

$Q_{g,tot}^{IR} = r_r^{IR} r_g^{IR} Q_{g,tot}^{IR} + Q_{g1}^{IR}$,

$Q_{g,tot}^{IR}(1 - r_r^{IR} r_g^{IR}) = Q_{g1}^{IR}$,

$Q_{g,tot}^{IR} = \frac{Q_{g1}^{IR}}{1 - r_r^{IR} r_g^{IR}}$,

Let us call $\frac{1}{1 - r_r^{IR} r_g^{IR}}$ =r

Then $Q_{g,tot}^{IR} = rQ_{g1}^{IR}$.

For $\boldsymbol{Q_{r,tot}^{IR}}$

$Q_{r,tot}^{IR} = Q_{r,tot,R}^{IR} + Q_r^{IR}$, $Q_{r,tot}^{IR} = r_r^{IR} r_g^{IR} Q_{r,tot}^{IR} + Q_r^{IR}$, $Q_{r,tot}^{IR}(1 - r_r^{IR} r_g^{IR}) = Q_r^{IR}$ and

$Q_{r,tot}^{IR} = \frac{Q_r^{IR}}{1 - r_r^{IR} r_g^{IR}}$,

Therefore, $Q_{r,tot}^{IR} = bQ_r^{IR}$

And equation (A.5) takes the following form:

$$Q^v\left(1-r_g^v\right)+tQ^v\left(r_r^v-r_r^v t_g^v-1\right)-Q_{g2}^{IR}+rQ_{g1}^{IR}\left(r_r^{IR}-r_r^{IR}t_g^{IR}-1\right)+$$
$$rQ_r^{IR}\left(1-r_r^{IR}-t_g^{IR}\right)=0 \quad \text{(A.7)}$$

Putting the terms together we have (A.7) becomes:

$$Q^v\left(1-r_g^v+tr_r^v-tr_r^v t_g^v-t\right)+Q_{g1}^{IR}\left(rr_r^{IR}-rr_r^{IR}t_g^{IR}-r\right)-Q_{g2}^{IR}+Q_r^{IR}\left(r-\right.$$
$$rrrIR-rtgIR=0 \quad \text{(A.8)}$$

The coefficient of Q^v is:

$$A=\frac{1-r_g^v-t_g^v+r_r^v\left(r_g^v\left(r_g^v-1\right)+t_g^v\left(1-t_g^v\right)\right.}{1-r_g^v r_r^v}$$

The coefficient of Q_r^{IR} is:

$$B=\frac{1-r_r^{IR}-t_g^{IR}}{1-r_r^{IR}r_g^{IR}}$$

The coefficient of Q_{g1}^{IR} is:

$$C=\frac{-1+r_r^{IR}\left(1-t_g^{IR}\right)}{1-r_r^{IR}r_g^{IR}}$$

Note that

$$Q_g^{IR}=CQ_{g1}^{IR}-Q_{g2}^{IR}$$

Therefore equation for the glass cover is:

$$AQ^v+BQ_r^{IR}+Q_g^{IR}=0 \quad \text{(A. 9)}$$

A.2 Derivation of receiver equation

As we did for the glass cover, radiation falling onto the receiver must be radiated out.

$$Q_{tot}^{v} + Q_{r,tot,R}^{IR} + Q_{g,tot}^{IR} = Q_{tot,R}^{v} + Q_{g,tot,R}^{IR} + Q_{r,tot}^{IR} \quad \text{(A.10)}$$

where

$Q_{g,tot}^{IR}$ is total IR radiation from glass cover into receiver and $Q_{g,tot,R}^{IR}$ is reflected IR radiation from glass cover by the receiver.

$$Q_{tot}^{v} - r_r^{v} Q_{tot}^{v} + Q_{g,tot}^{IR} + r_g^{IR} Q_{r,tot}^{IR} - r_r^{IR} Q_{g,tot}^{IR} - Q_{r,tot}^{IR} = 0 \quad \text{(A. 11)}$$

By rearranging (A. 9) we have:

$$Q_{tot}^{v}(1 - r_r^{v}) + Q_{g,tot}^{IR}(1 - r_r^{IR}) + Q_{r,tot}^{IR}\left(r_g^{IR} - 1\right) = 0$$

$$aQ^{v}(1 - r_r^{v}) + bQ_{g1}^{IR}(1 - r_r^{IR}) + bQ_r^{IR}\left(r_g^{IR} - 1\right) = 0 \quad \text{(A.12)}$$

Coefficient of Q^v

$$a(1 - r_r^{v}) = \frac{t_g^{v}}{1 - r_r^{v} r_g^{v}}(1 - r_r^{v})$$

$$D = \frac{(1 - r_r^{v}) t_g^{v}}{1 - r_r^{v} r_g^{v}}$$

Coefficient of Q_r^{IR} is:

$$\left(r_g^{IR} - 1\right) b = \frac{\left(r_g^{IR} - 1\right)}{1 - r_r^{IR} r_g^{IR}}$$

$$E = \frac{\left(r_g^{IR} - 1\right)}{1 - r_r^{IR} r_g^{IR}}$$

Coefficient of Q_{g1}^{IR} is

$$b\left(r_g^{IR}-1\right)=\frac{\left(r_g^{IR}-1\right)}{1-r_r^{IR}r_g^{IR}}$$

$$F=\frac{\left(r_g^{IR}-1\right)}{1-r_r^{IR}r_g^{IR}}$$

Therefore (A.10) becomes our receiver equation:

$$DQ^v+EQ_r^{IR}+FQ_{g1}^{IR}=0 \qquad \text{(A. 13)}$$

For both receiver and glass cover we have

$$AQ^v+BQ_r^{IR}+Q_g^{IR}=0$$

$$DQ^v+EQ_r^{IR}+FQ_{g1}^{IR}=0$$

A.3 Interpretation of receiver unit equations

Let us describe the parameters Q in terms of their temperatures:

$$Q_r^{IR}=A_r\mathcal{E}_r\sigma T_r^4 \qquad \text{(A. 14)}$$

$$Q_g^{IR}=(C\mathcal{E}_{g1}-\mathcal{E}_{g2})\sigma A_g T_g^4 \qquad \text{(A. 15)}$$

$$Q_{g1}^{IR}=A_g\mathcal{E}_{g1}\sigma T_g^4 \qquad \text{(A.16)}$$

$$Q_{g2}^{IR}=A_g\mathcal{E}_{g1}\sigma T_g^4 \qquad \text{(A.17)}$$

We consider also the convection loss from glass cover to the surroundings:

$$Q_{conv}=hvA_g\left(T_g-T_0\right) \qquad \text{(A.18)}$$

There is also a heat transfer from receiver pipe into the liquid in side it:

$$Q_{LC}=\frac{KA_r}{L\left(1+\frac{KA_r.K1}{L}\right)}(T_r-T_L) \qquad \text{(A.19)}$$

Putting (A.14), (A.15), (A.16), (A.17), (A.18) and (A.19) into (A.9) and (A.13) we get

$$AQ^v + BA_r\varepsilon_r\sigma T_r^4 + CA_g\varepsilon_g\sigma T_g^4 - \varepsilon v A_g(T_g - T_0) = 0 \quad \text{(A.20)}$$

$$DQ^v + EA_r\varepsilon_r\sigma T_r^4 + FA_g\varepsilon_g\sigma T_g^4 - \frac{KA_r}{L\left(1+\frac{KA_rK1}{L}\right)}(T_r - T_L) = 0 \quad \text{(A. 21)}$$

Appendix B

B. Computer program

The following program has been written using a macro for Microsoft excels.

```
Sub hotmirror ()

Dim a

Dim b

 Dim c

Dim d

Dim e

Dim eqn As Double

Dim x

Dim sigma

sigma = 5.67 * 10 ^ -8

Dim QLC

Worksheets("Sheet1").Range("A20:z370").Clear

Cells(1, 2) = "Incoming solar radiation"

Cells(2, 2) = "material thermal conductivity"

Cells(3, 2) = "receiver thickness"

Cells(4, 2) = "pipe diameter"

Cells(5, 2) = "wind speed"

Cells(6, 2) = "liquid flow rate"

Cells(7, 2) = "specific heat capacity liquid"

Cells(8, 2) = "outer receiver radius"

Cells(9, 2) = " outer glass cover radius"

Cells(10, 2) = "emmissivity glass cover (IR)"

Cells(11, 2) = "emmissivity receiver (IR)"

Cells(12, 2) = "wind speed"
```

Cells(13, 2) = "wind factor"

Cells(14, 2) = "convection factor"

Cells(15, 2) = "bond thermal conductance"

Cells(16, 2) = "wall/fluid transfer coeff"

Cells(17, 2) = "outside temp"

Cells(18, 2) = "length segment"

Cells(1, 5) = "VISIBLE"

Cells(2, 5) = "glass"

Cells(3, 5) = "glass"

Cells(4, 5) = "receiver"

Cells(5, 5) = "receiver"

Cells(6, 5) = "INFRARED"

Cells(7, 5) = "glass"

Cells(8, 5) = "glass"

Cells(9, 5) = "receiver"

Cells(10, 5) = "receiver"

Cells(2, 6) = "transmission"

Cells(3, 6) = "reflection"

Cells(4, 6) = "transmission"

Cells(5, 6) = "reflection"

Cells(7, 6) = "transmission"

Cells(8, 6) = "reflection"

Cells(9, 6) = "transmission"

Cells(10, 6) = "reflection"

Cells(2, 9) = "A"

Cells(2, 10) = "=(1-g3-g2+g5*(g3*(g3-1)+g2*(1-g2)))/(1-g3*g5)"

Cells(3, 9) = "B"

Cells(3, 10) = "=(1-g8-g7)/(1-g10*g8)"

Cells(4, 9) = "C"

Cells(4, 10) = "=-1+(g10*(1-g7))/(1-g10*g8)"

Cells(6, 9) = "D"

Cells(6, 10) = "=g2*(1-g5)/(1-g5*g3)"

Cells(7, 9) = "E"

Cells(7, 10) = "=(g8-1)/(1-g10*g8)"

Cells(8, 9) = "F"

Cells(8, 10) = "=0.5*(1-g10)/(1-g10*g8)"

Cells(10, 9) = "heat conv (hv)"

Cells(10, 10) = "=c14+c13*c12"

Cells(11, 9) = "K1"

Cells(11, 10) = "=1/(1/(c16*3.1415*(c4-2*c3)*c18)+1/(c15))"

Cells(12, 9) = "liquid temp"

Cells(13, 9) = "receiver area"

Cells(13, 10) = "=2*3.1415*c8*c18"

Cells(14, 9) = "glass cover area"

Cells(14, 10) = "=2*3.1415*c9*c18"

Cells(16, 9) = "Mirror height"

Cells(16, 10) = "1"

Cells(17, 9) = "mirror reflectiveness"

Cells(17, 10) = "0.9"

Cells(18, 9) = "effective incoming radiation"

Cells(18, 10) = "=c1*j16*j17*c18"

Cells(2, 12) = "a1"

Cells(2, 13) = "=j2*j18+j10*j14*c17"

m2 = Cells(2, 13)

Cells(3, 12) = "b1"

Cells(3, 13) = "=j3*j13*c11*5.67 * 10 ^ -8"

m3 = Cells(3, 13)

Cells(4, 12) = "c1"

Cells(4, 13) = "= j4*2*j14*c10*5.67 *10 ^ -8"

m4 = Cells(4, 13)

```
Cells(5, 12) = "d1"

Cells(5, 13) = "=-j10*j14"

m5 = Cells(5, 13)

Cells(7, 12) = "a2"

Cells(7, 13) = "=j6*j18+c2*j12*j13/(c3+c2*j13/j11)"

m7 = Cells(7, 13)

Cells(8, 12) = "b2"

Cells(8, 13) = "=j7*j13*c11*5.67 * 10 ^ -8"

m8 = Cells(8, 13)

Cells(9, 12) = "c2"

Cells(9, 13) = "=5.67 * 10 ^ -8*j8*j14*c10"

m9 = Cells(9, 13)

Cells(10, 12) = "d2"

Cells(10, 13) = "=-c2*j13/(c3+c2*j13/j11)"

m10 = Cells(10, 13)

Cells(12, 12) = "max temp"

Cells(12, 13) = "=j18/(c2*j13/(c3+c2*j13/j11))+j12"


eqn = 1

'plots the initial temp of the liquid in the cell

Cells(21, 3) = Cells(12, 10)

Cells(21 + y, 2) = "=j6*j18+c2*c21*j13/(c3+c2*j13/j11)"

'calculates the current value for a2, which is the only thing that changes from value to value

Cells(21 + y, 1) = Cells(6, 10) * Cells(18, 10) + Cells(2, 3) * Cells(21, 3) * Cells(13, 10) / (Cells(3, 3) + Cells(2,
3) * Cells(13, 10) / Cells(11, 10))

'CALCULATION ROUTINE STARTS **************************

For y = 1 To 1000

e = Cells(19 + y, 5)

x = e + 1

Cells(20, 3) = "T(liq_ini)"

Cells(20, 4) = "T(liq_fin)"
```

```
Cells(20, 5) = "T(rec)"

Cells(20, 6) = "T(glass)"

Cells(20, 7) = "QLC"

Cells(20 + y, 3) = Cells(19 + y, 4)

If y = 1 Then x = 599: Cells(21, 3) = Cells(12, 10)

'MINIMISATION PROCEEDURE START ++++++++++++++++++++++++++++

While Abs(eqn) > 0.5

x = x - 0.01

'Cells(20 + y + 1, 7) = ((m10 * x + m8 * x ^ 4 + m7) / -m9)

'RECEIVER TEMP

'**************************************

eqn = (m3 - m4 * m8 / m9) * x ^ 4 - m4 * m10 * x / m9 + (m2 - m4 * m7 / m9) + m5 * ((m10 * x + m8 * x ^ 4
+ m7) / -m9) ^ (1 / 4)     'equation goes here

'**************************************

'GLASS COVER TEMP

'**************************************

gct = ((m10 * x + m8 * x ^ 4 + m7) / -m9) ^ (1 / 4)

'**************************************


'how far away from convergence is it?

Cells(20 + y, 10) = eqn

'what is the current trial temp for receiver?

Cells(20 + y, 5) = x

'what is the corresponding temp for glass cover?

Cells(20 + y, 6) = gct

'how much heat is transferred to the liquid?

QLC = Cells(2, 3) * Cells(13, 10) * (x - Cells(20 + y, 3)) / (Cells(3, 3) + Cells(2, 3) * Cells(13, 10) / Cells(11,
10))

'Cells(20 + 3, 7) = Cells(2, 3)

'Cells(20 + 4, 7) = (x - Cells(20 + y, 3))

'Cells(20 + 5, 7) = Cells(13, 10)

'Cells(20 + 6, 7) = (Cells(3, 3) + Cells(2, 3) * Cells(13, 10) / Cells(11, 10))
```

'CHECK OF HEATS ++++

Cells(20, 12) = "A.Qv"

Cells(20 + y, 12) = "=j2*c1*j16*c18*j17"

Cells(20, 13) = "B.QRECir"

Cells(20 + y, 13) = "=j3*j13*(1-g9-g10)*5.67 * 10 ^ -8"

Cells(20 + y, 13) = Cells(20 + y, 13) * (Cells(20 + y, 5) ^ 4)

Cells(20, 14) = "C.QGLAir"

Cells(20 + y, 14) = "=j4*j14*(1-g7-g8)*5.67 * 10 ^ -8"

Cells(20 + y, 14) = Cells(20 + y, 14) * (Cells(20 + y, 6) ^ 4)

Cells(20, 15) = "QGLAconv"

Cells(20 + y, 15) = Cells(10, 10) * Cells(14, 10) * (Cells(17, 3) - Cells(20 + y, 6))

Cells(20, 17) = "D.Qv"

Cells(20 + y, 17) = "=j6*c1*j16*c18*j17"

Cells(20, 18) = "E.QRECir"

Cells(20 + y, 18) = "=j7*j13*(1-g9-g10)*5.67 * 10 ^ -8"

Cells(20 + y, 18) = Cells(20 + y, 18) * (Cells(20 + y, 5) ^ 4)

Cells(20, 19) = "F.QGLAir"

Cells(20 + y, 19) = "=j8*j14*(1-g7-g8)*5.67 * 10 ^ -8"

Cells(20 + y, 19) = Cells(20 + y, 19) * (Cells(20 + y, 6) ^ 4)

Cells(20, 20) = "QLC"

Cells(20 + y, 20) = -Cells(2, 3) * Cells(13, 10) * (x - Cells(20 + y, 3)) / (Cells(3, 3) + Cells(2, 3) * Cells(13, 10) / Cells(11, 10))

'PUT ALL THE HEATS HERE ie BQir, CQgIR etc

'CHECK OF HEATS END +++++

Cells(20 + y, 7) = QLC

Cells(20 + y, 8) = (x - Cells(20 + y, 3))

'what is the final exit temp of the liquid?

FLTEMP = QLC / (Cells(6, 3) * Cells(7, 3)) + Cells(20 + y, 3)

Cells(20 + y, 4) = FLTEMP

Wend

'MINIMISATION PROCEEDURE END ++++++++++++++++++++++++++++

'calculates the current value for a2, which is the only thing that changes from value to value

Cells(21 + y, 1) = Cells(6, 10) * Cells(18, 10) + Cells(2, 3) * Cells(20 + y, 4) * Cells(13, 10) / (Cells(3, 3) + Cells(2, 3) * Cells(13, 10) / Cells(11, 10))

m7 = Cells(6, 10) * Cells(18, 10) + Cells(2, 3) * Cells(20 + y, 4) * Cells(13, 10) / (Cells(3, 3) + Cells(2, 3) * Cells(13, 10) / Cells(11, 10))

eqn = 1

Next

End Sub

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