# TECHNO-ECONOMIC COMPARISON AND ENVIRONMENTAL IMPACT ASSESSMENT OF A HYBRID PHOTOVOLTAIC THERMAL SOLAR SYSTEM AND A THERMOSIPHON SOLAR THERMAL HOT WATER SYSTEM WITH ELECTRIC BACK UP ELEMENT, UNDER WINDHOEK, NAMIBIAN CONDITIONS

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# Abstract

Lack of accessible data on technical and economic evaluation of thermosiphon solar water heater (TS-SWH) and hybrid photovoltaic thermal (PVT) water heaters under Namibian conditions is limiting options available to decision makers on locally economic and opportune systems. This study compares the technical, economic aspects, and environmental impacts of TS-SWH and PVT water heaters. The TS-SWH installed in Otjomuise suburb, in Windhoek, were compared to PVT studied by others, in the UK and India. TS-SWH data was collected by Namibia Energy Institute using measuring instruments coupled to the systems. Both TS-SWH and PVT systems have the same technical make up, but the PVT system has solar PV cells on its collector. The findings of this study are that global radiation plays a major role in the operation of both solar water heaters and has influence on other parameters. TS-SWH of 1.2 $m^2$ collector area results in about 6.3t of avoided $CO_2$ as opposed to the PVT of the same aperture area that results in about 12.8t of avoided $CO_2$ over their life span of 20 years, by interpolation of results by Herrando et al (1). PVT systems are cost effective, they cover domestic hot water demand completely and generate electricity simultaneously, in comparison to TS-SWH of same aperture area. TS-SWH has shown a solar fraction of 100%, specific solar energy yield of 470 $kWh/m^2$ annually and return on investment of 7.7 years, in comparison, a PVT system has solar fraction is of about 68.6%, payback period of more than 20 years (2), a better energy yield of about 515 $kWh/m^2$ annually and cogeneration efficiency of 66% (3). Installation of PVT systems for both domestic and commercial use country wide is recommended to reduce electricity demand and environmental impacts arising from generation of electricity from conventional methods. A study of PVT systems installed in Namibia and analysis of all year round data for TS-SWH is recommended for more reliable comparisons.

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# List of abbreviations and Acronyms

$CO_2$- Carbon dioxide

E.V.A- Ethylene Vinyl Acetate

LCS- Life Cycle Savings

P.V.C- Poly Vinyl Chloride

PV- Photovoltaic

PVT- Photo Voltaic thermal

TS-SWH- Thermosiphon Solar Water Heaters

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*Meme* Laina Shipingana for the foundation laid, it is for the education you instilled in me in my early years, that I can write documents of this kind. I am because you are.

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*Thank you. Gracias. Tangi Unene!*

# Dedications

This thesis is dedicated to my niece (Naango), and nephew (Aluendo), as a motivation for them to publish papers like this one in future.

# Declarations

I, Laina Tulimegameno Shipingana, hereby declare that this study is my own work and is a true reflection of my research, and that this work, or any part thereof has not been submitted for a degree at any other institution.

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# CHAPTER 1: INTRODUCTION

## 1.1 Background of the Study

Solar energy has numerous benefits in comparison to coal, oil and nuclear energy, and thus has grown into one of the greatest potentials for clean energy in the world. Solar energy does not produce harmful gases or pollute the environment, and no geographical and resource constraints, hence could be used easily everywhere, without harm as long as sunlight is available (4).

The idea of harnessing solar energy by means of collectors was recorded at 212 BC, when the Greek scientist/physician Archimedes by means of concave metallic mirror set the Roman fleet on fire (5). Now, water heating using solar energy is one of the most successful and feasible applications of solar energy, among other applications (3).

About 40-50% of electricity used in the residential sector is for hot water preparation in Southern Africa (6). The use of solar water heaters can decrease the electricity demand in the residential sector, hospitals, boarding schools and student residences, and in the tourism industry. Solar water heating has potential to reduce electricity consumption and subsequently lower the environmental effects such as those due to $CO_2$ emissions caused by fossil fuel power plants (7-8) since 75% of the hot water needed at homes can be obtained using solar energy to heat the water, instead of using electricity or gas (4).

A conventional solar water heater, thermosiphon or pumped system, consists of a collector to collect solar energy and transfer the heat to water, and an insulated storage tank to store hot water. The solar water heater with an electric backup element saves about 50% of electricity (7). Thermosiphon systems heat water or a heat transfer fluid and use natural convection to transport heated water or fluid from the collector to storage hence there is no need for pumps and controls to transfer the water heated by solar energy (7). On the other hand, hybrid Photovoltaic Thermal (PVT) hot water systems combine the basic principle of the PV panel and solar thermal collectors to generate both electricity and thermal output from the same collector area (8-9). The PVT hybrid system consists of a photovoltaic (PV) panel with heat exchanger and fins fixed at the back, and a water storage tank. This type of system allows the PV panel to operate at a lower temperature, because the cold water runs beneath the heat exchanger hence cooling down the solar cells, and thus allowing the solar cells to generate at higher photovoltaic efficiency. The PVT hybrid system generates electricity, and at the same time heats water (8,10).

Numerous studies have been done around the world on different types of solar water heaters (2,11), however not under Namibian conditions. The study becomes necessary due to this gap.

## 1.2 Statement of the Problem

There is no accessible information and/or data about the technical, economic and environmental performance and impacts comparisons of thermosiphon solar water heating systems and hybrid photovoltaic thermal solar water heating systems under Namibian conditions. Thus, the lack of reliable data limits the options available to decision makers regarding the implementation of such systems in a sustainable manner.

Thermosiphon hot water systems with electric back up elements have been in use in Namibia over the years. Data on the performance of thermosiphon systems, with electric back-up elements, has been collected by the Namibia Energy Institute using the measuring instruments coupled the systems, for a period of more than one year, but such data has not been fully analyzed. These systems cannot be used to produce hot water and electricity simultaneously. In comparison, hybrid photovoltaic thermal solar water heaters can heat water and generate electricity (8,10). The research is investigating the possibility of adopting the concept and to assess the merits and demerits of the option under the Namibian conditions.

## 1.3 Objectives of the Study

This study aims to compare the technical, economic and environmental performance of the hybrid photovoltaic thermal solar system and the thermosiphon solar water heating system, and to recommend if the photovoltaic thermal solar system should be used widely in Namibia. The specific objectives include the following:

a) To describe the technical makeup, and function of the thermosiphon solar water heating system, and of the hybrid photovoltaic thermal solar system;
b) To analyze the performance parameters of the two systems;
c) To analyze the factors that affect the performance of the systems;
d) To carry out a comparative economic analysis of the two systems;
e) To determine the environmental impacts and benefits involved, if widespread use is adopted;

## 1.4 Significance of the Study

Analyzing the technical aspects, economic and environmental benefits of the hybrid PVT systems against those of the thermosiphon (TS-SWH) systems used in Namibia, is crucial in understanding better these systems, and thus, aid in recommending whether the hybrid PVT system is the suitable system for Namibian conditions.

## 1.5 Limitation of the Study

Due to limited resources the University of Namibia could not procure PVT system and TS-SWH for study purposes. In absence of primary data for the PVT systems, secondary data is relied upon and used, in contrast to primary data for the thermosiphon systems, therefore, comparing primary data to secondary data may give rise to biased conclusions. Moreover, the data for the TS-SWH was collected by means of a data logger (electronic device), hence discrepancies in data was detected in some days; such data/days were not considered.

## 1.6 Delimitation of the Study

The study focuses only on the techno - economic analysis and environmental impacts of hybrid photovoltaic thermal solar systems and the thermosiphon solar water heating systems with electric element for back up under Namibian conditions, hence some portions or findings of the study may not be generalized outside Namibia or to systems different from the ones mentioned above.

# CHAPTER 2: LITERATURE REVIEW

This chapter highlights and compares the technical structures of the TS-SWH and hybrid PVT systems, their performance parameters and factors that affect the same, as well as economic and environmental impact analysis parameters for both systems.

The evaluation of hot water systems is based on the typical weather data on one hand, and on the second law of thermodynamics on the other, hence the evaluation of a PVT system should be extended to geographical comparison all year round (12). The electrical efficiency of the PVT systems varies during the course of the day (12-13) since the incident solar radiation intensity varies during the day due to the rotation of earth on its axis, the angle of inclination of the sun's rays, the length of the day, the transparency of the atmosphere and the configuration of land in terms of its aspect (14).

By simultaneously generating both electricity and heat (temperatures lower than 200°C), the PVT systems maximize the solar energy extracted per unit of collector area and have the added benefit of increasing the photovoltaic electrical output by reducing the PV operating temperature (13). This is one benefit of the PVT systems that independent PV, and thermal systems do not have. Herrando et al. (1), however argues that other studies have concluded that the electrical output of some PVT systems is lower because of the higher operating temperatures and optical losses due to additional glazing. Therefore, the question remains whether the electrical output is higher in PVT systems or not.

Economic analyses, comparing different water heating systems have been carried out (2,11), with the conclusion that solar thermal systems have better cost-effective benefits than the traditional systems. PVT systems have greater chances of succeeding because of the economic viability of these systems, however an in-depth comparison of thermosiphon systems and the photovoltaic thermal hybrid systems has not been done, especially for Namibian conditions.

Due to its desirable environmental and safety aspects, it is widely believed that solar energy should be utilized instead of other alternative energy forms (15). Different hot water systems' global warming impacts can be reasonably assessed through evaluating the amount of $CO_2$ produced while manufacturing the hot water systems, and while the systems operate (2). This is very important because if the aim is to replace conventional sources of energy with renewable ones, there is a need to evaluate how improved these sources are in terms of pollution and global warming potential so that the situation is not made worse. In this case the total energy produced over the lifetime of the systems, at zero emission rates during operation, are then compared with the $CO_2$ that would have been produced if conventional sources were used to produce the same amount of energy.

The installation and operation of, renewable energy systems is distinguished in three categories: energy saving, generation of new working posts, and the decrease in environmental pollution. The decrease in environmental pollution is achieved by the reduction of Carbon dioxide emission, due to the substitution of conventional fuels, and it is relatively simple to measure the financial impact of these effects when they affect the tradable goods, however it gets more complicated when it comes to non-tradable goods like human health and ecosystems (16).

Additional thermal output provided by the PVT systems makes them cost effective compared to separate PV and thermal units of the same aperture surface area. Hence it is important to quantify the energy savings associated with the hot water systems.

The electrical and thermal performance of PVT systems and that of separate PV modules and solar thermal collectors have been compared by numerous studies (1). An important finding is that the performance of these systems is highly dependent on the geographical location despite the choice of the configuration, hence concurring with Chow (12). PVT systems have considerably higher electrical efficiencies, however PVT collectors can be less efficient than conventional solar thermal collectors in extracting heat, due to the reduced conductivity of the absorber and limitations imposed by the presence of the PV module. The overall energy efficiency of a hybrid PVT system is better than the efficiencies of separate, conventional solar water-heating collectors, and PV modules (1).

Kalogirou et al.(2) in their experiment emphasized that whether the PV module is made from c-Si, pc-Si or a-Si cells, the cost of the thermal unit remains the same, however the ratio of the added cost of the thermal unit per PV module cost is almost twice in the case where a-Si modules are used rather than the c-si or pc-si PV ones. In addition, a-si PV modules present lower electrical efficiency although the total energy output (electrical and thermal) is almost equal to that of c-si or pc-si PV modules (2). For the a-Si PV modules, their lower electrical efficiency results in slightly higher PV module temperature as compared to pc-Si PV modules. Although the c-si cells have higher efficiency than other forms of silicon cells, they are expensive and sometimes present absorption problems, hence the pc-si cells are suitable.

Riffat et al (17) indicate that currently extensive researches are been carried out in the UK, India and all over the world on how to improve the performance of PV/T, and simultaneously reducing the cost, Moreover further researches on optimizing the air channel geometry of PV/T systems need to be carried out. Further emphasizing that different models and configurations of PVT systems give rise to different results, hence the difference in results in experiments carried out in Cyprus, India, and Greece.

## 2.1. Classification of Solar Water Heaters

Solar water heaters are classified into passive, and active, types. A passive system depends on natural convection (thermosiphon effect) to circulate water, while the active system requires a control pump, or check valve, hence forced circulation (18-19). The Integrated Collector Storage (ICS), also referred to as the batch beater system, has a tank which acts as a solar collector and a storage tank at the same time. These types of heaters are normally made from a thin tank with the side containing the glass facing the sun during the day (20).

Active systems or forced circulation systems can be further classified as direct (open loop) or indirect (closed loop) (19-20). Direct solar water systems do not possess a heat exchanger while the indirect ones are fitted with heat exchangers, either inside or outside the storage tank. In a direct system, the service water flows directly between the collector and the water storage tank, however in an indirect system, an anti-freeze or other heat transfer /working fluid, such as distilled water, or an organic fluid, flows through the solar collector. A heat exchanger is utilized to transfer the heat from the collector to the service water in the storage tank. Many are times the indirect system performs better than the direct one. The indirect system is less climate-selective and more suitable for use in regions experiencing cooler temperatures (21-22). The passive systems are discussed further under section 2.2.1.

## 2.2. Thermosiphon Solar Water Heaters (TS-SWH)

### 2.2.1. Components of a Thermosiphon Solar Water Heating (TS-SWH) System

As highlighted in section 2.1, the solar water heating systems are further classified as active or passive, hence the thermosiphon systems are also classified as closed or open loop (20). In a closed-loop system the heat transfer fluid (water or anti-freeze solution) flows through the system without mixing with the water in the water storage tank(20,23). These systems are suitable for colder climates and places with hard water because the anti-freeze solution prohibits the system from freezing and the system forbids scales formation inside the collector's pipes. Closed-loop system functions in both forced circulation and thermosiphon systems. The Open-loop systems however function like closed loop systems except that the heat transfer fluid is not used, the hot water coming from the collector mixes with the water in the storage tank. Unlike closed loop system, the open loop systems are suitable for warm climates, or in regions where the water is not very hard or acidic, as the water can freeze in colder climates and possibly destroy the system, corrode, or block the system's tubes. Open loop systems are mostly used in a thermosiphon mode (20).

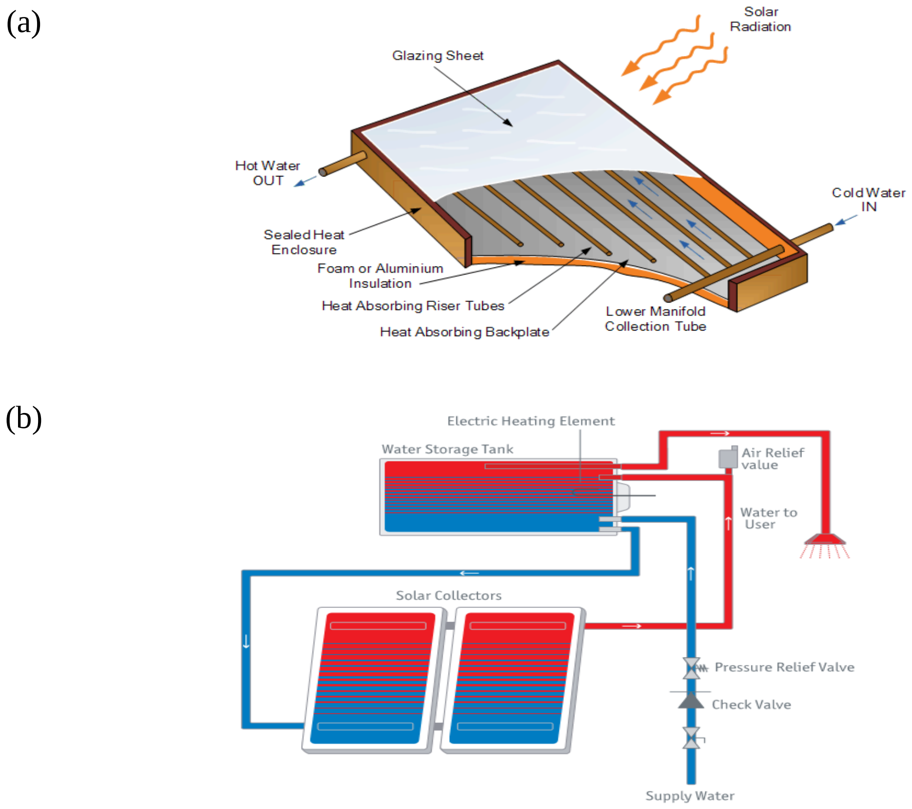


Figure 1 (a) Configuration of a flat plate thermal collector (20) (b) Schematic of a thermosiphon open loop system (18).

The parts and components of a typical thermosiphon systems are discussed below.

A **solar collector**: this is basically a heat exchanger that converts solar radiation to heat. Heat is transferred to the working fluid flowing through the collector (14,24).

Three basic types of solar collectors used in solar water heating systems, include **flat-plate, evacuated-tube, and parabolic collectors** (21,23).

A flat-plate collector is mainly a panel-shaped box housing tubes filled with fluid mounted on an absorber which is dark in color. This collector is suitable for both residential and non-residential use. In an evacuated-tube collector the tubes that are holding the fluid to be heated are side-by-side. Every tube is encircled by an outermost tube made from glass hence a vacuum between the inner and outer tubes offers a good insulation and reduces heat loss. This collector works at high temperatures and high efficiency employing both direct and diffuse light (21).

A parabolic-trough collector comprises a u-shaped trough with fluid filled tubes and a long U-shaped mirror that directs the sun onto the center of the U-trough. This system is highly efficient and typically tracks the sun and requires only direct sunlight-not diffuse. They are commonly used in non-residential or institutional applications i.e. prisons and hospitals (21).

The **Absorber plate or collector plate**: an absorber plate is part of the collector and it is made of copper or aluminum, mild steel or galvanized iron, and is in close contact with the pipes carrying the fluid to be heated. Copper is the best among these materials because it has high thermal conductivity, however aluminum is preferred because it’s cheaper compared to copper (25-26). The absorber successfully converts the solar radiation to heat. The surface of the absorber is usually coated panted in order to maximize the energy harness. The coating is therefore tailored with a high absorption coefficient. For outstanding performance, the absorber should also have a low emission coefficient. Absorber covers/paints that have both high absorptivity and low reflectance are called selective absorbers (27).

**Collector casing** is usually made from black mild steel, because it is cheap and light, in order to hold different components of a solar collector together. Sometimes aluminum sheet stock or extruded sections, galvanized and painted steel, molded or extruded plastic parts, or composite wood products are used for collector casing

(25,27). The casing of the collector must provide the required mechanical strength to preserve the absorber and the insulation in order to minimize heat loss to the ambient. The casing must resist wind and snow loads that are experienced at the site where the collector is installed. It also must be watertight enough to resist the penetration of the rainwater. These characteristics must be ensured over the entire lifespan of the system.

A **Transparent cover** on the collector is necessary in order to help provide the ‘greenhouse’ effect that is crucial in heating up the water. The transparent cover reduces the convection losses from the absorber, while simultaneously permitting the highest amount of radiation to get to the absorber This material need to be of high transmittance to ultra violet and visible, but low transmittance to infra-red radiation in order to trap the heat radiated by the absorber plate (25,27). Just like the collector casing, this cover needs to as well present mechanical strength in order to shield the absorber from the environment. Tempered glass with low iron content is usually used to minimize the breakage from impacts (27).

**Insulation,** Insulation is employed in the collector and hot water storage tank to reduce heat loss in order to increase the efficiency. Common insulation materials normally used for collector and tank include glass wool, sawdust, wood shavings mineral fiber, ceramic fiber, plastic foams and styro-foam The insulation provides low heat conductivity, some mechanical strength, and temperature and fire resistance (25,27).

**Frame / stand**, mild steel with high flexural strength is used for the frame or stand (25).

**Pipe**, galvanized steel is used to make pipes that hold water because of its rigidity and resistance to corrosion (25). Plastic pipes such as P.V.C can also be used for the piping system because of its rigidity and its resistance to corrosion; this is very important because it can hold the water and keep it clean to be used domestically (25).

**Water Storage Tank**: the tank to hold the water is made of galvanized mild steel with the inside properly insulated to prevent heat loss (25). A backup electric heating element may be inserted in the tank, to supplement the energy needed to heat water, if the system cannot supply enough hot water, especially during periods of no, or reduced sunshine.

### 2.2.2. Principles of Operation of the Flat Plate TS-SWH System

When solar radiation strikes the transparent cover and passes through to the absorber plate where it is absorbed as heat, the flat-plate collector becomes very hot. The water, contained in the riser and header pipes attached to the plate, absorbs the heat by conduction, hence it expands and becomes less dense than the cold water in the storage tank. Hot water is pushed through the collector and rises by natural convection to the top part of the water storage tank while the cold water descends to the bottom by gravity pull (thermosiphon principle). Therefore, there is circulation. The circulation continues as hot water goes out, while cold water comes in (25-26,28).

### 2.2.3. Advantages of TS-SWH System

The TS-SWH System is preferred because of its simplicity since it is easy to install and operate; it comes at a low cost; it requires no electrical power or fuel supply to operate; it does not require a controller or pump; it can withstand mild sub-zero temperature; it is reliable and long-lasting since there are no moving parts; it is scalable, several collectors can be assembled in parallel to increase hot water supply; it provides heated water of about 70 °C or within that range (25).

### 2.2.4. Disadvantages of TS-SWH System

The TS-SWH Systems may not be desired because of the following reasons: they may not withstand mains pressure; they cannot give higher temperature water; are affected by weather conditions; very useful only during the dry season and can be more practicable and useful in the sunny regions (25), such as Namibia. This system every so often cannot supply hot water at the preferred temperatures in the morning (18). This is when the electric backup element may be needed.

## 2.3. Hybrid Photovoltaic Thermal (PVT) System

### 2.3.1. Components of a Hybrid Photovoltaic Thermal (PVT) System

Hybrid PVT Systems concurrently generate electricity, and heat water or air. Solar cells absorb energy corresponding the energy bandgap of the materials of cells, any remaining energy is converted to heat, so they heat up during operation. A heat transfer fluid removes heat from the absorber and PV cells during the operation. The collected heat can be used to preheat water (29), or to drive the thermosiphon effect, if the collector is appropriately connected to a hot water storage tank. A typical PVT collector is shown in figure 2.

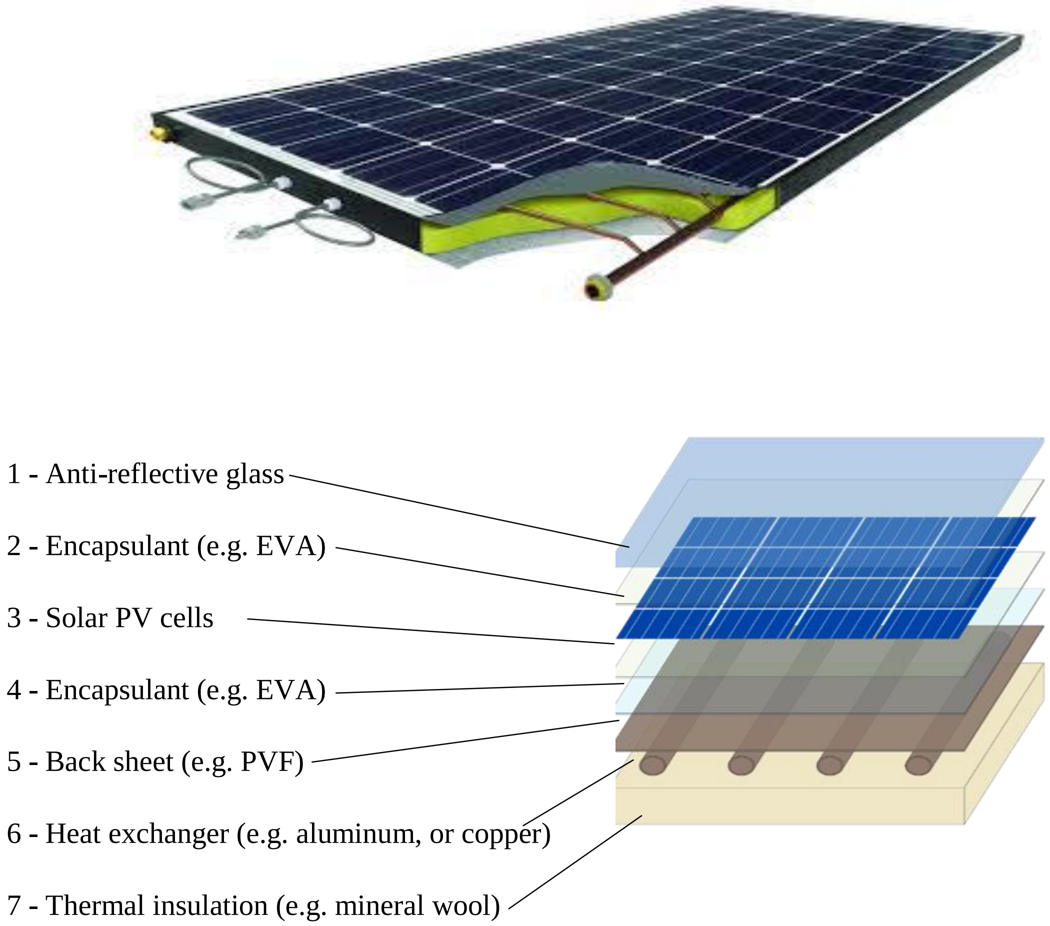


Figure 2 The photovoltaic/thermal solar collector (30) and a schematic cross section of an uncovered PVT collector with sheet and tube type heat exchanger and rear insulation (31)

The parts and components of the PVT system are as follows:

**Collectors** are categorized as water, air or combined air and water, depending on the working fluid (9,17), while TS-SWH collectors PVT collectors can also be classified as can be designed as flat-plate or concentrating (23).

A collector unit is made up of a **transparent cover** (glass), an air gap, a mono-crystalline (c-Si) **PV module**, an **EVA** encapsulating film, an **absorber–exchanger** which changes the solar radiation to heat and it is then absorbed by the collector fluid, and a **layer of insulation** material at the bottommost. The backside/underside and side insulation layers serve to reduce heat losses, and at the same time improving structural strength (1).

Figures 3 (a) and (b) show the parts and components of PVT solar collector and layout of the entire PVT system, respectively.

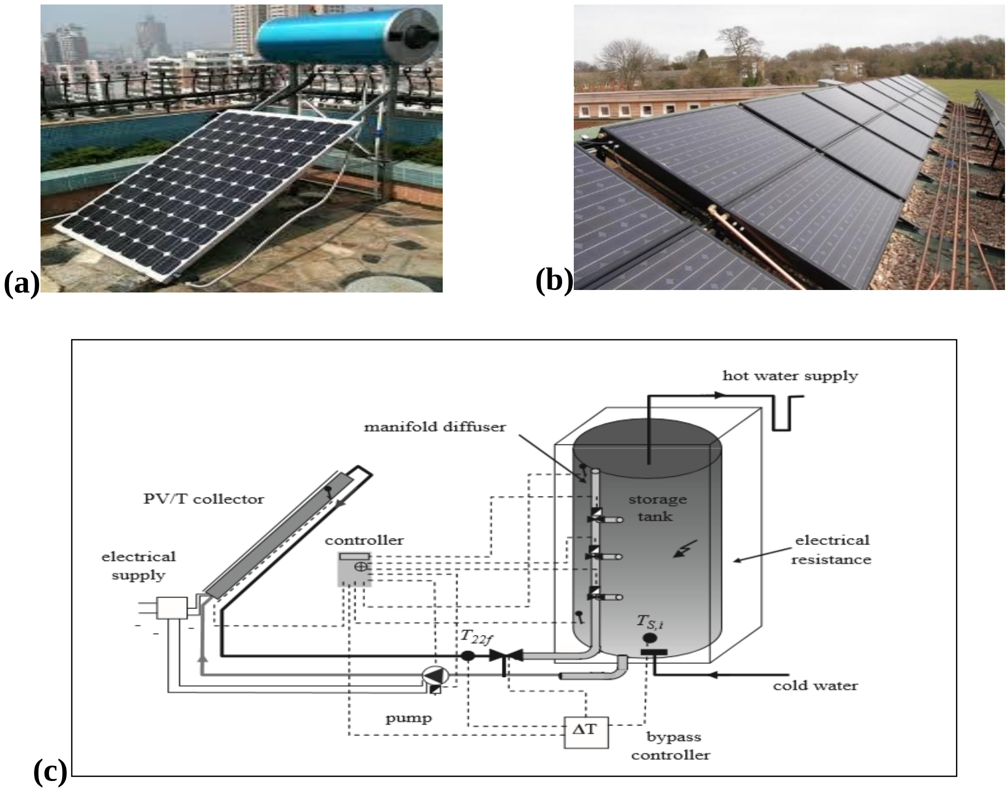


Figure 3 (a) Thermosiphon PVT system (32) (b) Typical installation of collectors on a roof(30); (c) Layout of a pumped PVT system installation (29).

The absorber–exchanger consists of a sheet-and-tube heat exchanger in which water circulates in parallel pipes from the header inlet pipe to an outlet pipe on the upper side of the collector that collects the warm water. The transparent cover is a single glass sheet with a thickness of 3.2mm (1,29). The absorber – exchanger in the copolymer material must honor these limitations: UV protected, high thermal conductivity, water-resistant and glycol resistant, good thermal range of utilization (–10 to +150 ˚C), good mechanical strength and chemically stable (29).

### 2.3.2. Principle of operation of the PVT system

By convection, the thermal energy collected by the PV module is transmitted to the absorber for further heating of the absorber. When the water underneath the absorber gets heated it moves in the upward direction. The collector is connected to an insulated storage tank. In forced circulation, a water pump connected to the PV module is required to circulate the water between collectors and storage tank (29).

In a new model of a dual-flow PVT-liquid collector, the incoming water flow to the collector flows directly beneath the PV laminate while the outgoing water flows directly above the PV-laminate. Some researchers have reversed the water flow, water inlet to the collector flows over the PV and the water exit underneath the PV. This model has an additional insulating air layer in the middle of the PV and the lower channel. The last option with a water channel underneath the cells instead of a sheet-and-tube construction was found to have raised the annual yield of the PVT system by 2% (29).

### 2.3.3. Main advantages of Photovoltaic Thermal Solar Collector

- The PVT system generates both heat and electricity from the same surface area, as opposed to separate, individual side-by-side PV panels and solar thermal collectors, hence has an economical order compared to a combination of separate thermal and photovoltaic panels (1,29).
- Since the space on the roof of a house is often limited, the area covered by hybrid solar collector produces more electrical and thermal energy than a corresponding area half covered with standard PV panels and half with a conventional thermal collector.
- Electrical generation is increased because the average temperature of operation for a hybrid collector being generally lower than for a standard PV module.
- A hybrid collector is aesthetically pleasing, provides architectural uniformity on a roof in contrast to an association of two separate solar collectors (1,29).

## 2.4. Performance Parameters of the TS-SWH and PVT Systems

Two specific PVT system parameters of particular interest are the **extent and specific area layout/coverage** and the **mode of the fluid circulation** (1,33).

One of the actual performance parameters of the PVT system is the **number of covers** (glazing), an extra cover of glass on the collector may diminish heat loss, and however, it results in escalation of reflective losses. Another parameter is the **mass flow rate**: a rise in mass flow rate results in an increase in heat transfer coefficient, therefore resulting in a decrease in the PV panel temperature, thus increasing the efficiency. However, an increase in duct depth results in a decrease in efficiency (17,33).

The **absorber plate parameters** include the tube spacing (W), tube diameters (D) and fin thickness. The outlet temperature of the fluid decreases as the W/D ratio increases. The total efficiency of the system depends on the fin size; however, the electrical efficiency is not significantly affected by the fin size. Moreover, it is pointless to increase the cost of the system by reducing the ratio W/D if the aim is to cool the PV cells (17).

Performance parameters are Pumping **Energy; Specific Yield** which is energy delivered per collector area**; System Efficiency -** energy delivered per incident radiation; **Solar Fraction -** the ratio of energy delivered over the energy demand**; Collector Area;** and **Losses due to Snow and Dirt** (34)**.**

Approaches such as the use of selective coating on the surfaces, increased number of glass covers, optimization of tube diameter and spacing, tracking of the sun etc. have been developed in order to improve the thermal performance of SWH and reduce its initial cost (18).

The strategy to improve the thermal performance can be the enhancement of heat transfer from the copper pipes to the flowing water. Heat loss is reduced when transferring the heat to the water since the average temperature of the absorber surface reduces(18). There are studies done on natural and forced laminar flow through tubes of various types of heat exchangers and SWH with different typed of heat transfer enhancement devices; these includes the use of mechanical aids, surface vibration, electrostatic fields and jet impingementation, which requires external power supply. The use of inserts and swirl flow devices, coiled tubes are some of the passive method (use of surfaces or geometrical modifications to the flow channel) of enhancement used.

For more than a century the swirl flow devices such as the twisted tape and wire coil inserts have been used in industrial heat exchangers to improve the heat transfer. A twisted tape is placed in a tube to reduce the diameter of the passage, and the heat transfer enhancement is due to the secondary flow generated by the tape, which creates swirl. The resulting mixing of fluids improves the temperature gradient leading to an increase in the heat transfer rate (18).

The heat energy output, for most solar water heating systems, is linear with the surface area of the absorber plate, and therefore it is important to note that a collector with less absorber area will result in lesser heat output (4), because with a larger collector area the fluid will have a prolonged contact with the absorber, hence high chance of collecting heat. Similarly, larger coverage areas results in increased electricity production (4).

## 2.5. Factors that Affect the Performance Parameters of the Systems

Several factors affecting the overall energy output (both electrical and thermal) of the PVT systems are the configuration design and heat extraction arrangement; solar irradiance; ambient temperature and wind speed; and operating temperature of a number of other components (1, 33, 35**,** 14).

The overall amount of heat energy that a solar water heater can supply is dependent on the amount of solar radiation received by the collector on each day. The amount of heat energy delivered by the sun is relatively high, about 7 kWh/m$^2$/day in areas around the equator. Additionally, the average amount of solar radiation varies from location to location even within the same latitude due to differences in weather patterns (25).

The performance and the efficiency of solar water heating systems is dependent of the region's solar energy resource because the amount of solar energy available for heating water varies by geographical location. Solar resource of the site is measured by the solar radiation intensity; however, the cloud cover and latitude must as well be considered during the purchasing decision of the system. The flat plate collectors are tilted at an angle equal to the latitude in order to receive the greatest amount of sunlight. The latitude of the site will affect the solar radiation collected; hence it is crucial to tilt panels according to the latitude of the installation site. During the shorter days of winter, the sun tends to travel/ lean far south when the sun follows a southern path in the sky. Therefore, the solar collectors should face true south in the northern hemisphere (27), and should face north for sites in the southern hemisphere, because the opposite is true for the countries in the southern hemisphere.

The output of a solar energy system is in proportion to the intensity of the solar radiation, but its efficiency is also dependent of the temperature therefore, the energy delivered by the solar water heating systems depends on the environmental conditions, i.e. global radiation and temperature. However, as the solar collector gets hotter and more heat is lost to the ambient environment, the efficiency of the system may decrease (27).

The clouds reduce the solar radiation that reaches the earth's surface by reflecting part of it back into the space and absorbing another part. In addition, multiple reflections disperse another part of the radiation into diffuse radiation. Diffuse irradiation that reaches the earth's surface is made up of the irradiation coming from angles different from the solar incidence angle or the actual sun position. Therefore, cloud cover reduces the total amount of global radiation, and it also changes the relation between beam and diffuse radiation due to scattering. Since cloud cover is different every season, the effects are hence dependent on the season. Depending on the location, the diffuse fraction of the total annual global radiation can be greater than 50% (27).

Apart from solar irradiance, cell temperature is another factor which affect the performance of a PV module. However, the amount of energy delivered by a PV module is also dependent on other factors such as (36):

**Mismatch losses** that results when PV modules with distinct current and voltage ratings are interconnected, they provide an overall power output less than the power achieved by adding the power output provided each module.

**Shading losses:** when PV modules are shaded by objects such as buildings, trees in the vicinity, shading loss occurs since a reduction in solar irradiance as a result of partial or complete shading will affect the performance of the PV module

**Soiling losses**: loss in power that comes as a result of covering of the surface of the PV module by snow, dirt, dust and other particles. The accumulated dust over time aggravates the soiling effect. Losses may also occur in cables, wires and diodes used in the PV module connections (36).Therefore, these losses influence the performance of the PV modules of the hybrid PVT system, therefore affecting the electrical and overall output of the system.

The increase in the packing factor (the fraction of absorber plate area covered with solar cell) leads to the increase of both electrical and thermal improvement and results in an increased output (4).

Heat is also lost from any solar water heating system in forms of heat transfer: radiation, convection and conduction. The radiation losses take place on the absorber plate because of the plate temperature. The conduction heat losses take place at the sides and the back of the collector plate, while the convection heat losses take place at the absorber plate and the glazing cover. The convection losses  can be reduced by creating a vacuum space between the absorber plate and the glazing cover as well as by optimizing the spacing between them The heat losses from the glazing cover to the ambient are due to radiative and convective exchanges which are affected by the wind velocity, ground, surrounding condition and by long wave radiation from the sky (37).

The major cause of heat loss for roof-mounted solar collectors is wind instigated convection (38-39). Hence for a typical day the thermal gains between solar collectors at different locations over the same roof could vary up to 21% due to wind speed. More especially the Parabolic trough solar collectors systems are more prone to being affected by strong winds because they are usually located in an open terrain and strong winds could affect their stability and optical performance, as well as the heat exchange between the solar receiver and the ambient air (39). There is however, a positive correlation or linear relationship between wind speed and their efficiency in photovoltaic modules (40). This is to say that the efficiency of the PV modules increases linearly with an increase in wind speed.

There are different indices used to assess and compare the performance of solar thermal systems, however the most essential ones are solar fraction (SF), specific solar energy yield (SE), and solar system efficiency (SN). (27,41):

**Solar fraction (SF)**

Solar fraction is the commonly used performance index. Solar fraction identifies the fractional amount of the building heating energy demand is supplied by the solar thermal system.

Therefore, the solar fraction is determined as follows:

$$SF = \frac{Q_{solar}}{Q_{boiler}+Q_{solar}} \times 100\% \qquad [1]$$

where:

$SF$ solar fraction [%]

$Q_{Solar}$ annual energy produced by collector loop [kWh/a]

$Q_{Boiler}$ annual heat input of the auxiliary heating system [kWh/a].

**Specific solar energy yield (SE)**

The specific solar energy yield is often said to be the important parameter for measuring the potential of a solar energy system. This is the measure of the amount of energy supplied to the storage tank unit from 1 $m^2$ of collector surface area annually is known as the specific solar energy yield. The specific energy yield is then determined as follows:

$$SE = \frac{Q_{solar}}{A_{collector\_REF}} \qquad [2]$$

where:

$SE$ = specific annual solar energy yield [kWh/m$^2$]

$Q_{Solar}$ = annual energy produced by collector loop [kWh/a]

$A_{collector\_REF}$ = collector area on which the solar yield [m$^2$].

The size of the system, the solar fraction and the system losses need to be considered for a correct interpretation of the specific energy yield of the system (27).

The energetic performance of the solar water system may also be measured using the following indices (38, 41):

- Energy Yield Ratio (EYR) -the ratio of the life cycles primary energy output of the domestic solar water heating system to the lifecycle embodied energy.
- Energy Payback Period (EPBT)- the time required to recover the initial primary energy embodied in the domestic solar water heating system by the net annual primary energy savings due to the use of the solar water heating system.

These measures have been used to evaluate the energy feasibility of domestic solar water heating system.

### Efficiency of TS-WH

The total efficiency of the TS-SWH is an important parameter which should be reviewed for the performance of these solar water heater. This efficiency is therefore determined as follows (42-44):

$$n = \frac{M \times C_p \times (T_f - T_i)}{A_C \times I} \% \qquad [3]$$

where, M is the water mass in the water tank [kg]; $C_p$ is the water specific heat [ J/kg·K]; $T_f$ and $T_i$ are the final and initial water temperature in the water tank [K]respectively; $A_c$ is the Area of collector [$m^2$], and I is the incident solar radiation (accumulation of solar irradiation of the whole day) [W/$m^2$]

however, the heat absorbed by the solar collector is determined as (42):

$$Q_c = M \times C_p \times (T_f - T_i) \qquad [4]$$

The heat absorbed by the collector is equal to the heat gain by water in a collector loop.

When the heat loss coefficient for a riser pipe, and the diameter and length of the riser are not known, the heat loss from the pipe can be estimated as to be 20% of the overall heat conveyed by the water at the collector outlet. If radiation intensity is less than the intensity at sunrise, then this heat loss is assumed to be 10% of the overall heat carried by the water at the collector outlet (42).

Moreover, when the heat loss coefficient for down comer, and its diameter and length of are not known the heat loss from the pipe is assumed to be 15% of the total heat conveyed by the water at the outlet of storage tank. Additionally, If the intensity of the radiation is less than the intensity at sunrise, heat loss is estimated to be 30% of the total heat conveyed by the water at the outlet of storage tank (42).Increase in radiation intensity and collector outlet temperature has led to an increase in the overall efficiency (42).

### Efficiency of PVT

The combination of both PV (electricity) and thermal (heat energy) components of the PVT system makes up its overall performance also known as the cogeneration efficiency ($n_0$) (3,38).

Thus, the thermal gain of the system is given as (38):

$$E_{th} = M_w\ C_P\ \Delta T \qquad [5]$$

where $M_w$ is the water mass flow rate (kg/s), $C_p$ is the specific heat capacity of water (kJ/kg ◦C) and ΔT (◦C) is the temperature difference of the collector water inlet and outlet temperatures

The thermal efficiency of the PVT is then determined as (38):

$$n_{th} = \frac{100 \times E_{th}}{A_m \times G_p}\% \qquad [6]$$

While the PV module efficiency is calculated as(38):

$$n_{pv} = \frac{100 \times E_{dc}}{A_m \times G_p}\% \qquad [7]$$

Where, $A_m$ is the module total surface area ($m^2$) and $G_p$ is the in-plane solar irradiance ($kW/m^2$). $E_{dc}$ is the DC power from the module in kW. Depending on the available data and desire level of resolution. The instantaneous, hourly, daily, monthly and annual efficiencies can be calculated, based on ones need (38).

The cogeneration efficiency is therefore the sum of thermal efficiency and pv module efficiency (3).

### 2.6. Economic Analysis of the Solar Thermal Systems

Investors typically consider making an investment only if it is profitable. Hence an evaluation of the investment in order to calculate the expected cash flows. The attractiveness of residential solar energy systems is treated as a financial investment and depends on the following parameters: the initial cost of system, maintenance costs, the lifespan of the system, the amount and form of energy used, the concordance between solar energy captured and load, the cost of the energy consumed using conventional energy and awarded grants. Investment valuation methods may include: net present value savings to investment ratio, payback periods, internal rate of return in accordance with possible maximum lifespan period of the system (9,45-46).

Many attempts have been done to offer clearer visibility on the economics of solar energy systems. The low temperature options for water and space heating in buildings are satisfactorily established to move into the phase of commercial use, however it is too difficult to assess the cost of all solar options since there are various encouraging concepts, yet to be taken to the investigational and verification stages (47).

Solar systems are commonly regarded as having high initial cost, and low operating cost (47-48). Therefore, the primary economic problem is comparing an initial known investment with estimated future operating cost. The major factors in solar processes economics are investments in purchasing and installing solar energy equipment. These comprise of the delivered cost of equipment such as collectors, storage units, blowers, pipes, ducts, heat exchangers, glazing, insulation, and all other crucial elements for a unit system installation. This installed cost of solar equipment (CS) can be estimated by (47);

$$CS = Total\ area\ dependent\ cost\ (CA)\ \times\ Collector\ area(AC) + \\ Total\ cost\ of\ equipment\ independent\ of\ collector\ Area\ (CE) \qquad [8]$$

### 2.6.1. Life Cycle Analysis

Both initial cost and annual operating costs are considered for the entire life of the solar energy system in the life cycle analysis. These include the initial purchase cost of the system, operating costs for fuel and electricity required for the pumps, interest charges on money borrowed, maintenance costs, and taxes paid, if applicable. The return at the expiration of the life of the system when the components are sold as scrap metal for recycling is called the salvage value.

### 2.6.2. Financial Savings

Financial savings are determined as per the following equation (41):

$$Total\ Financial\ Savings = Electricity\ Units\ Saved\ \times\ Cost\ of\ Electricity\ per\ Unit \qquad [9]$$

Or can be calculated as the difference between the cost of conventional and solar energy systems (47):

$$Solar\ savings = Cost\ of\ conventional\ energy - Cost\ of\ solar\ energy \qquad [10]$$

Else,

$$Solar\ savings = Fue\ savings + Extra\ mortgage\ payment + extra\ maintenance\ cost + extra\ insurance + extra\ parasitic\ energy\ cost + extra\ property\ tax + income\ tax\ savings \qquad [11]$$

The price of solar energy is greater than the price of fossil fuels, but it is costs less than electricity. The cost can be calculated directly by (47),

$$Solar\ energy\ cost = \frac{Solar\ system\ cost\ during\ system\ life\ time}{Total\ energy\ gain\ during\ the\ life\ time \times Solar\ heating\ fraction} \qquad [12]$$

Here the solar heating fraction refers to the ratio of energy provided by the solar technology and the total energy required by the hot water heating load. The solar radiant energy is free, however the equipment essential to convert it to a useful form such as thermal or electrical energy is not. A cost must be therefore assigned to solar thermal or solar-electrical energy, which reveals the conversion equipment’s cost, allocated on the number of kWh delivered by solar energy (47).

The return on investment is therefore (28, 47),

$$Return\ on\ Investment = \frac{Total\ Cost\ of\ System}{Annual\ Financial\ Savings} \qquad [13]$$

This is also known as the payback period, the time needed to get back the money paid to install the solar energy system, from the fuel savings gained due to of the use of the system, or the time required for the collective fuel savings to be equivalent to the entire initial investment. It also means the time after which the solar system has obtained the exact amount of energy that was needed for its production (ecological amortization time).

### 2.6.3. Present Value

A cash flow (F), occurring (n), years from time of installation can be reduced to its present value (P) by (47):

$$P = \frac{F}{(1+d)^n} \tag{14}$$

Where $d$ is the market discount rate.

An amount of money or cash flow is worth less than its present-day value in the future and must be discounted.

### 2.6.4. Mortgage Payment

A mortgage payment is the yearly amount of money needed to cover the funds borrowed at the beginning to erect the system. This comprises of payment of interest and principal. An estimate of the yearly mortgage payment can be obtained by dividing the amount borrowed by the present worth factor (PWF). The PWF can be approximated by using the inflation rate, equal to zero (equal payments) and with the market discount rate equal to the mortgage interest rate.

The PWF can be obtained from tables or calculated by the following equation (47):

$$PWF_{nL,0,dm} = \frac{1}{dm}\left[1 - \left(\frac{1}{1+dm}\right)^{nL}\right] \quad [15]$$

Where, dm – mortgage interest rate (%) and

$n_L$- number of years of equal installment for the loan

## Pay Back Period

The economical meaning is the amortization period of the solar energy system (capital repayment time). It is the time needed to get back the money paid to install the solar energy system, from the fuel savings gained due to of the use of the system, or the time required for the collective fuel savings to be equivalent to the entire initial investment. It also means the time after which the solar system has obtained the exact amount of energy that was needed for its production (ecological amortization time). The pay-back is then: (47);

$$N = \frac{\log\left(\frac{E-M}{a-b}\right) - \log\left(\frac{E-M}{a-b} - C\right)}{\log\left(\frac{1+a}{1+b}\right)} \quad [16]$$

Where, $a$- compound interest rate per annum, $A$- Absorber area (m$^2$),

$b$- inflation rate in energy and maintenance per annum,

$C$- cost of the heater, $E$- energy savings per year,

$M$- maintenance cost per annum, and $N$- payback period.

**Annual Fuel Cost (AFC) Determination**

The energy required for the production of the daily hot water needs (EDHN) of a typical family is estimated according to the following equation (47):

$$\mathrm{EDHN} = \mathrm{AFS} * \mathrm{ADHP} * \mathrm{C_p} \times \mathrm{DT} \qquad [17]$$

Where, AFS- average family size;

ADHP- average daily hot water needs of a person, (liter/person/day);

$C_p$ - specific heat capacity of water, (kJ/kg ˚K);

DT- temperature difference, (˚K).

**Annual Cost**

In general the annual cost (AC) of a system can be expressed as the following equation, taking the concept of time value of money into consideration (47):

$$\mathrm{AC} = \mathrm{IC} \times \mathrm{CRF} + \mathrm{AFC} + \mathrm{AMC} - \mathrm{SV} \times \mathrm{SFF} \qquad [18]$$

Where, IC- initial cost of the system, CRF- capital recovery factor,

AFC- annual fuel cost, AMC- annual maintenance cost,

SFF- sinking fund factor,

SV- salvage value at the end of the assumed operation life of the system.

The capital recovery factor (CRF) and the sinking fund factor (SFF) can be expressed as the follows:

$$CRF = \frac{i \times (i+1)^N}{[(i+1)^N - 1]} \qquad [19]$$

And

$$SFF = \frac{i}{[(i+1)^N - 1]} \qquad [20]$$

Where, $N$ - operation time of the system in consideration (year), and

$i$- annual discount rate on loans.

Assuming linear depreciation of the system with time, then the salvage value at time $N$ could be expressed as (47):

$$SV(N) = IC - \frac{D}{N} \qquad [21]$$

$$D = \frac{IC}{N_{max}} \qquad [21a]$$

Where, $N_{\max}$ - time after which the system is entirely discarded, (year);

$D$ - Depreciation rate (N$/year).

The cost of one unit of useful energy ($C$) delivered by a system can be computed as the follows (47):

$$C = \frac{AC}{ADUE} \qquad [22]$$

Where $ADUE$ is the annual delivered useful energy in kJ/year

Besides this, annual maintenance cost of solar energy system can also be considered for annual cost for the $N^{th}$ year, and evaluated by (47);

$$AMC = \alpha N \qquad [23]$$

Where α - proportionality constant, N$/year).

Using the above equations one can approximate all the financial terms related with purchasing, installing, maintaining as well as savings for solar energy systems.

## 2.7. Environmental Impacts and Benefits if Widespread Use of SWH is Adopted

Several environmental analyses and legal control instruments focused on conventional contaminants such as sulfur dioxide ($SO_2$), nitrogen oxides ($NO_x$), particulates, and carbon monoxide (CO) a few years ago. However, lately the environmental anxiety has stretched to the control of harmful air contaminants, which are typically toxic chemical substances, dangerous even in insignificant amounts, as well as to other globally significant pollutants such as $CO_2$ (49). Carbon dioxide is the main product of combustion of fossil fuels (the $CO_2$ emitted is directly related to the carbon content of fuels), although, methane ($CH_4$) and nitrous oxide ($N_2O$) are as well predominant greenhouse gases from fossil fuels combustion for energy and heat production. SF6 is also produced but in smaller quantities, that are sometimes negligible (3,45). Additionally, developments in industrial processes and structures have led to new environmental problems. $CO_2$ as a greenhouse gas plays a great role in global warming, as studies have shown that it is responsible for about two-thirds of the enhanced greenhouse effect. A significant contribution to the $CO_2$ emitted to the atmosphere is attributed to fossil fuel combustion (49).

Generally, it is agreed that a secure supply of energy is necessary, although not a sufficient condition for development within a society. Additionally, it is essential that a sustainable supply of energy and an effective and efficient exploitation of energy resources are secure for a sustainable development within a society. There is a close link between renewable sources of energy and sustainable development, since a supply should be readily available in the long term at a reasonable cost, sustainable, and able to be consumed for all the required tasks without causing negative social impacts (49).

The most significant benefit of renewable energy systems is the reduction in environmental pollution which is achieved by the decrease of air emissions because of the replacement of electricity and conventional fuels. It is worth noting that the amount of the environmental impact and consequently the social pollution cost largely depend on the geographical location of the emission sources. This is however dissimilar to the conventional air pollutants whereby the social cost of $CO_2$ does not differ with the geographical features of the source, since each unit of $CO_2$ adds equally to the climate change thread and the resulting cost (49).

Beyond studying the performance of a PVT system, a further goal should be an assessment of the possible emissions savings associated with the installation of such a system in comparison to the emissions associated with the use of conventional means to meet the hot water demand. This is based on the typical current practices of buying the electricity from the grid, and using a boiler, heat pump or electrical heater With regards to electricity, the emission saving results due to the difference between the emissions related to the purchase of all electricity from the grid ($Em_{cE}$) and the emissions incurred after a PVT unit is installed ($Em_{PVTE}$), while the hot water saving arises from the reduction in the required primary fuel for heating, from the conventional levels ($Em_{cHW}$) to the lower auxiliary heating levels needed by the PVT system ($Em_{aux}$) when auxiliary heating is required/used (1),

$$Em_{CE}(\%) = \frac{Em_{CE} - Em_{PVTE}}{Em_{CE}} . 100\% \qquad [24]$$

$$Em_{SHW}(\%) = \frac{Em_{CHW} - Em_{aux}}{Em_{CHW}} . 100\% \qquad [25]$$

In order to undertake this assessment, the $CO_2$ equivalent emissions associated with grid electricity and natural gas burning are required. The values assigned to these parameters are: 0.5246kg $CO_2$(e)/kW$_e$h for electricity and 0.1836kg $CO_2$(e)/kW$_{th}$h for natural gas (1)**.**

The pollution created during the manufacturing process of solar collectors is determined by calculating the energy invested in the production and assembly (embodied energy) of the collectors and other components of the systems and estimating the pollution produced by this energy (3,41).

The total embodied energy required to produce a complete flat-plate collector (all components materials) is determined using the energy required for the primary and intermediate stages (26,41). By estimating the direct and indirect energy embodied in the system during the entire process of manufacturing of the finished good and in maintenance over its useful lifetime, the life cycle embodied energy of the solar water heating system is known (41).

The energy embodied in the components ($E_{mat}$) of the solar water heater is estimated using the following equation (41):

$$EE_{Mat} = \sum_{i=}^{n} \delta_i m_i \qquad [26]$$

Hence the life cycle embodied energy ($E_{lc}$) can, therefore, be expressed as (41):

$$E_{lc} = E_{direct} + \sum_{i=1}^{n} \delta_i m_i + \sum_{i=1}^{n} \left\lceil \frac{UL_{dshw}}{FR_i} - 1 \right\rceil [\delta_i m_i] \qquad [27]$$

where

$m_i$ is the mass/volume of the $i^{th}$ component of the solar water heating system,

$\delta_i$ is the energy intensity (in MJ per unit mass or MJ per unit volume as applicable) of the material of the $i^{th}$ component

n is the total number of components in the system.

$E_{direct}$ is the direct energy input in the manufacturing of the domestic solar water heating system is i.e. welding, drilling, cutting, rolling etc.

$UL_{dswh}$ is the expected useful life of the domestic solar water heating system

$FR_i$ is the frequency of replacement of the $i^{th}$ component.

## 2.8. Summary

The chapter has reviewed the classification of the TS-SWHT and hybrid PVT systems, and discussed the main components of the two systems, advantages and disadvantages of both systems, their performance parameters and factors that affect them, economic and environmental impact analysis parameters for both systems.

# CHAPTER 3: RESEARCH METHODS

This chapter discusses the research methodology used in the study, which includes the research design, procedures, data collection and analysis methods.

## 3.1. Research Design

An exploratory study approach was used in order to compare and gain insights on the Technical composition, performances, economic and environmental benefits associated with the two hot water systems. To be specific, the study included extensive literature review of technical composition of the TS-SWH and hybrid PVT system, analyzed and compared the performance parameters of the thermosiphon water heaters with flat plate collectors installed in the (National Housing Enterprise) NHE houses in Otjomuise, middle income suburb in Windhoek by means of graphs/charts and compared against those of the PVT systems in literature, e.g., studied by Herrando et al (1); Tiwari et al (50); and Kalogirou et al (2).

Environmental impacts of the two systems in terms of greenhouse gasses ($CO_2$) avoided were determined as per Herrando et al (1) and Arif (41) equations, while the economic implications in terms of payback periods and financial savings associated with the two systems were evaluated as per Saxena's equations (47).

The data used for the thermosiphon solar water heaters belongs to the Namibia Energy Institute (NEI), who has been monitoring the systems, hence they collected data for several years for analysis purposes. NEI has various solar water systems installed in Windhoek and other areas, however the data for Otjomuise NHE houses has not been analyzed until this study.

The data was collected by means of measuring instruments such as the pyrometer and thermometers, some instruments are sheltered in the Stevenson screen while others are coupled to these systems, respectively. The measuring instruments are connected to a 'data box/ logger' that records the information in an excel sheet. However, as highlighted earlier, there was no primary data for the PVT is available, hence secondary data was relied upon for both technical and economic analysis. The secondary data (performance parameters) obtained by Herrando et al (1); Tiwari et al (50) and Kalogirou et al (2) in their studies of the flat plate hybrid photovoltaic thermal systems is appropriate, because of similarities in components and dimensions of the systems are similar to those of the thermosiphon systems in question, hence making the comparison just. Additionally, the weather conditions of these studies are, to some extent, like those of similar to Namibia. Metrological reports indicate that Windhoek has an average ambient temperature of 29 ºC/ 16 ºC in summer and 22 ºC/ 7 ºC in winter and an average rainfall of 7 days in summer and none in winter, while the highest average wind speed is recorded in October (12.6 km/h) and lowest in March of 9.3km/h.

By studying all these aspects a fair comparison of both systems in question was achieved, and a recommendation on whether the hybrid PVT systems should be used widely in Namibia could be given.

### 3.1.1. Thermosiphon Solar Water Heaters (TS-SWH) Descriptions

The Description of thermosiphon solar water heater installed at the NHE home A in Otjomuise, Windhoek has the following description:

Application: domestic hot water

Date of installation: December 2015

**System**

System/ mode of fluid circulation: indirect thermosiphon system

Back up heating: Electricity 2 kW element

Manufacturer (collector and storage tank): ASSOS, Greece

**Hydraulic Scheme**

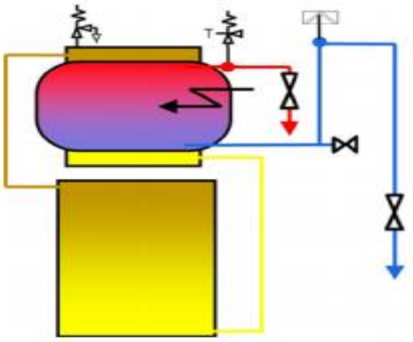


Figure 4 Hydraulic scheme of the thermosiphon system installed at house A (13)

The rest of the remaining TS-SWH descriptions are shown in Table 1 below

Table 1 Description of the TS-SWH installed at NHE house A in Otjomuise, Windhoek

| **Component** | **Description/ size** |
|---|---|
| **Collector** | |
| Number of collectors | 1 |
| Collector type | flat plate collector |
| Collector area | Collector area: 1.2 $m^2$ (1.26 kW) |
| Absorber material | copper |
| Absorber coating | selective coating |

| | |
|---|---|
| Collector inclination | 30˚ |
| Type of installation | on roof- elevated |
| Azimuth | North West |
| Flow rate in the collector loop | low flow 30 kg/h |
| **Hot water storage** | |
| Tank capacity | 160 L |
| Tank type | pressurized tank |
| Tank material | enameled- steel |
| Insulation of tank | 40-60 mm of polyurethane foam |
| **Piping** | |
| Piping type | copper (tank to tap) |
| Other components such as the safety valves, vacuum breaker and pressure reducing valves are installed in their respective positions. | |
| The backup element comes with a breaker in the distribution board for manual switching on and off of the element. | |

### 3.1.2. Hybrid Photovoltaic Thermal (PVT) System Descriptions

Since there are no PVT systems installed in Namibia, The PVT systems chosen have the descriptions matching those of the thermosiphon system above, or close enough in order to realize for a fair comparison.

For an unbiased comparison, a thermosiphonic operating PVT system was assumed since this is possible for smaller systems (12).

The descriptions of the c-Si PVT unit studied by (7) are shown in the table below:

Table 2 Descriptions of the c-Si PVT unit studied by Herrando et al (1)

| **Component** | **Description /size** |
|---|---|
| Collector area | 1.5 $m^2$ |
| Collector slope | latitude 36˚ -facing South |
| Storage capacity | 150 L |
| Auxiliary heating capacity | 3kW |
| Hot water demand | 122 L (4 persons) |
| Glazing | Tempered glass |

### 3.2. Procedures

In order to recommend if the hybrid PVT system should be used widely in Namibia,

the system descriptions, components and other details of the thermosiphon systems such as investments, sizes, locations, and orientations were obtained from NEI and compared to hybrid PVT systems from reviewed literature including those studied by Herrando et al (1); Tiwari et al (50); and Kalogirou et al (2). The performance parameters, such as temperature of the hot water in comparison to the external factors that influence them such as radiation and ambient temperature of the thermosiphon systems collected by the NEI were analyzed by means of plotting charts/graphs in the excel program and compared to those of the PVT systems analyzed and studied by Herrando et al (1); Tiwari et al (50); and Kalogirou et al (2)

The environmental impacts of the two systems in terms of greenhouse gasses ($CO_2$) emitted by the two systems were determined as per Herrando et al (1) and Arif (41) equations, while the economic implications in terms of payback periods and financial savings associated with the two systems were evaluated as per Saxena's equations (47).

### 3.3. Data analysis

Both quantitative and qualitative research techniques were used for analysis of performance parameters and factors that affect the performance parameters of the systems. Primary data, for the installed thermosiphon systems, was compared to the secondary data obtained for PVT, using an excel sheet to plot charts, hence studying, and technically analyzing, the effects of external factors on the performances of the system. Conclusions addressing economic analysis were drawn based on the savings (energetic and monetary) associated with the systems, whilst those of the environmental impacts based on the reduction in green houses gases grounded on the $CO_2$ avoided by the systems in comparison to the emissions from the conventional systems, hence achieving the comparison of the two systems and recommending if the hybrid PVT system should be installed widely in Namibia.

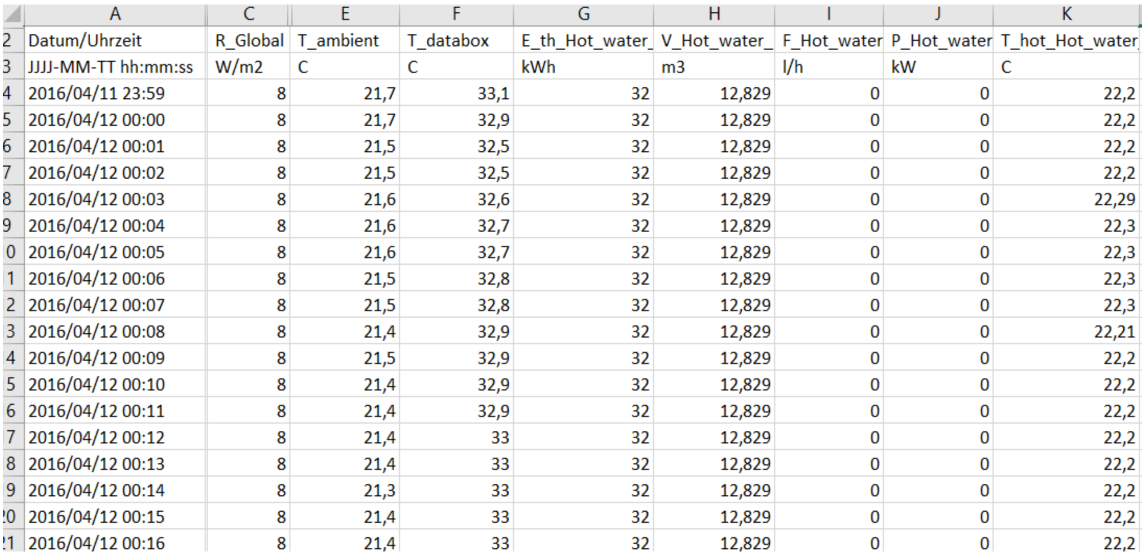
#### 3.3.1. Data collected for the TS-SWH

The data collected for the thermosiphon system is as follows:

House A was occupied by three [3] people.

The data was recorded for every minute, every day for the whole month. A typical excel sheet of the house's hot water demand profile is as shown in Table 3, below

Table 3 Sample of data collected for the TS-SWH installed at NHE house A in Otjomuise



|  | A | C | E | F | G | H | I | J | K |
|---|---|---|---|---|---|---|---|---|---|
| 2 | Datum/Uhrzeit | R_Global | T_ambient | T_databox | E_th_Hot_water_ | V_Hot_water_ | F_Hot_water | P_Hot_water | T_hot_Hot_water |
| 3 | JJJJ-MM-TT hh:mm:ss | W/m2 | C | C | kWh | m3 | l/h | kW | C |
| 4 | 2016/04/11 23:59 | 8 | 21,7 | 33,1 | 32 | 12,829 | 0 | 0 | 22,2 |
| 5 | 2016/04/12 00:00 | 8 | 21,7 | 32,9 | 32 | 12,829 | 0 | 0 | 22,2 |
| 6 | 2016/04/12 00:01 | 8 | 21,5 | 32,5 | 32 | 12,829 | 0 | 0 | 22,2 |
| 7 | 2016/04/12 00:02 | 8 | 21,5 | 32,5 | 32 | 12,829 | 0 | 0 | 22,2 |
| 8 | 2016/04/12 00:03 | 8 | 21,6 | 32,6 | 32 | 12,829 | 0 | 0 | 22,29 |
| 9 | 2016/04/12 00:04 | 8 | 21,6 | 32,7 | 32 | 12,829 | 0 | 0 | 22,3 |
| 0 | 2016/04/12 00:05 | 8 | 21,6 | 32,7 | 32 | 12,829 | 0 | 0 | 22,3 |
| 1 | 2016/04/12 00:06 | 8 | 21,5 | 32,8 | 32 | 12,829 | 0 | 0 | 22,3 |
| 2 | 2016/04/12 00:07 | 8 | 21,5 | 32,8 | 32 | 12,829 | 0 | 0 | 22,3 |
| 3 | 2016/04/12 00:08 | 8 | 21,4 | 32,9 | 32 | 12,829 | 0 | 0 | 22,21 |
| 4 | 2016/04/12 00:09 | 8 | 21,5 | 32,9 | 32 | 12,829 | 0 | 0 | 22,2 |
| 5 | 2016/04/12 00:10 | 8 | 21,4 | 32,9 | 32 | 12,829 | 0 | 0 | 22,2 |
| 6 | 2016/04/12 00:11 | 8 | 21,4 | 32,9 | 32 | 12,829 | 0 | 0 | 22,2 |
| 7 | 2016/04/12 00:12 | 8 | 21,4 | 33 | 32 | 12,829 | 0 | 0 | 22,2 |
| 8 | 2016/04/12 00:13 | 8 | 21,4 | 33 | 32 | 12,829 | 0 | 0 | 22,2 |
| 9 | 2016/04/12 00:14 | 8 | 21,3 | 33 | 32 | 12,829 | 0 | 0 | 22,2 |
| 0 | 2016/04/12 00:15 | 8 | 21,4 | 33 | 32 | 12,829 | 0 | 0 | 22,2 |
| 1 | 2016/04/12 00:16 | 8 | 21,4 | 33 | 32 | 12,829 | 0 | 0 | 22,2 |

Where:

| | |
|---|---|
| Datum/Uhrzeit: | date/ time |
| Fehlerzähler: | error counter |
| R_Global: | Global radiation (W/m$^2$) |
| AI_Reserve0: | not known |
| T_$_{\text{Ambient}}$: | Ambient temperature (˚C) |
| T_$_{\text{Data Box}}$: | Temperature of the data box (˚C) |
| E_$_{\text{th_Solar_}}$NHE A: | Cumulative solar thermal energy incident on the collector in (kWh) |
| V_$_{\text{Solar_}}$NHE A: | Cumulative volume of working fluid passing through the collector (m$^3$) |
| F_$_{\text{Solar_}}$NHE A: | Flow of working fluid in the collector (l/h) |
| P_$_{\text{Solar_}}$NHE A: | Solar Power incident on the collector in (kW) |
| T_$_{\text{Hot_Solar_}}$NHE A: | Temperature at the outlet of the collector in (˚C) |

T_$_{\text{Cold_Solar}}$_NHE A: Temperature at the collector inlet in (˚C)

E_$_{\text{th_Hot_Water}}$_NHE A: Cumulative thermal Energy of the hot water in (kWh)

V_$_{\text{Hot_Water}}$_NHE A: Cumulative Volume of hot water used ($m^3$)

F_$_{\text{Hot_Water}}$_ NHE A: Flow of hot water (l/h)

P_$_{\text{Hot_Water}}$_NHE A: Power associated (saved when solar is used) with hot water in (kW)

T_$_{\text{Hot_Hot_Water}}$_NHE A: Temperature of hot water exiting the storage tank (˚C)

T$_{\text{_Cold_Hot_Water}}$_NHE A: Temperature of cold-water inlet to storage tank (˚C)

E_$_{\text{el_ehe}}$_ NHE A: Cumulative Energy used by the electric element in (kWh)

P_$_{\text{el\_ehe\_}}$ NHE A: Power consumed by the electric element in (kW)

E_$_{\text{el_main}}$_ NHE A: Electrical Energy of the mains in (kWh)

P_$_{\text{el_main}}$_ NHE A: Power of the electricity mains in (kW)

## 3.4. Research Ethics

The study did not harm plants, animals nor humans in any way, no harmful substances with negative impact on the environment have been used. Ethical clearance certificate from the University of Namibia’s Research Ethics Committee, and Research Permission from Center of Postgraduate Studies was obtained before inception of the study.

## 3.5. Summary

This chapter discussed the exploratory study approach intended to be used in the analysis and comparison of the data for the TSWH and hybrid PVT systems. The means of data was collection, a data logger coupled to the system; the use of excel program to analyze data as well as reviewing of literature for attainment of secondary data, analysis and comparison of the same.

# CHAPTER 4: RESULTS

This chapter discusses comparisons of the TS-SWH and PVT systems based on the data collected on the TS-SWH system and data obtained for the PVT systems from literature. Main parameters used in technical analysis are temperatures of cold and hot water, collector temperatures, while the major factors affecting these parameters are global radiation and ambient temperatures. The energetic performance measures are solar fraction, specific energy yield, energy payback period and efficiency. The economic viability is measured in payback periods while the environmental impact with the avoided $CO_2$ emissions.

## 4.1. Performance of TS-SWH systems

All the parameters of the solar water heater were plotted against time. Global solar radiation was assumed to be key input (33). For comparison, the graphs of Temperature (˚C) and Radiation (W/m$^2$), on a typical sunny day, are shown in figure 6 below.

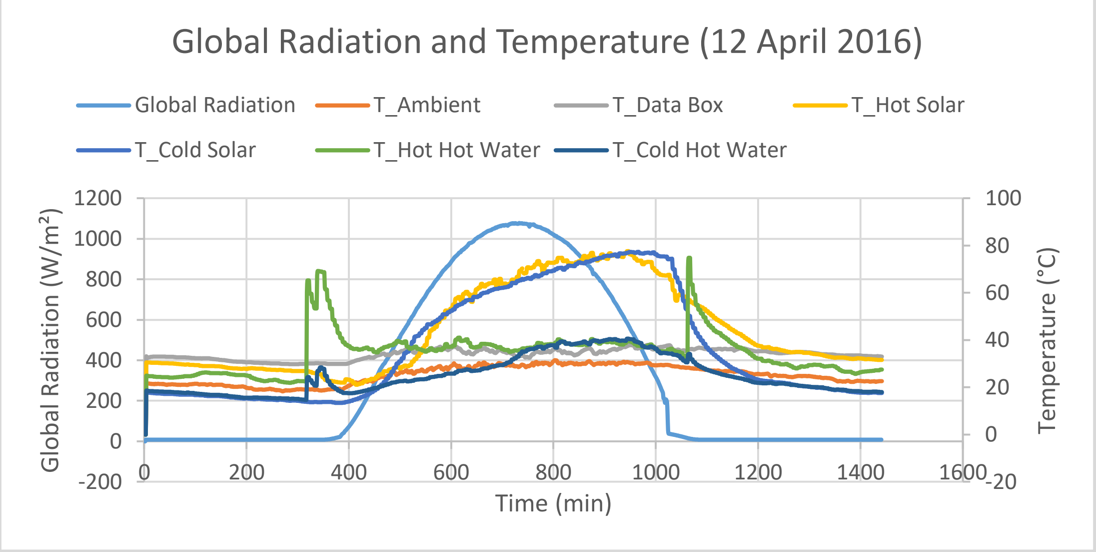


Figure 5 Global radiation and temperatures associated with the TS-SWH installed at House A and time for 12 in April 2016, Windhoek Namibia

The global radiation as well as all the temperatures associated with the solar water heater are graphed against time, as seen in the figure 6 above. These are $T\_{\text{Ambient}}$ - ambient temperature; $T\_{\text{Data Box}}$ -temperature of the data box; $T\_{\text{Hot Solar}}$- temperature of the water at the collector outlet; $T\_{\text{Cold Solar}}$-temperature of the water at the collector inlet; $T\_{\text{Hot Hot Water}}$-temperature of the water exiting the storage tank; $T\_{\text{Cold Hot Water}}$-temperature at the cold water inlet of storage tank. The data shown is for a single day (12 April 2016), this date was picked randomly. There are sudden spikes visible in $T\_{\text{Hot\_ Hot Water}}$, at 05:13:00 AM from 22˚C to 60.22 ˚C, and in and $T\_{\text{Cold\_Hot Water}}$ from 15 to 28 ˚C, as well as and $T\_{\text{Hot\_Hot Water}}$ at 17:42:00 PM from 34.10˚C to 74.8 ˚C, suggesting the turning on of the electrical backup element in the storage tank. $T\_{\text{Hot Solar}}$ and $T\_{\text{Cold\_Solar}}$ have reached a maximum temperature of 76 °C at around 16:36 h, while $T\_{\text{Ambient}}$, $T\_{\text{Data\_Box}}$ and $T\_{\text{Cold Hot Water}}$ have remained lower (only fluctuating between 15 °C and 30 °C) throughout the day. All the temperatures are lower between sunset and sunrise and increase as soon as the global radiation rises at around 06:17 h.

### 4.1.1. Global Radiation

The graph of global radiation for the selected days during the month of April 2016, shows that Global solar radiation is almost nonexistent for hours between sun set and sunrise. It it only begins to rise as from 06:17 h, and ceases at around 17:03 h as shown in Fig. 7.

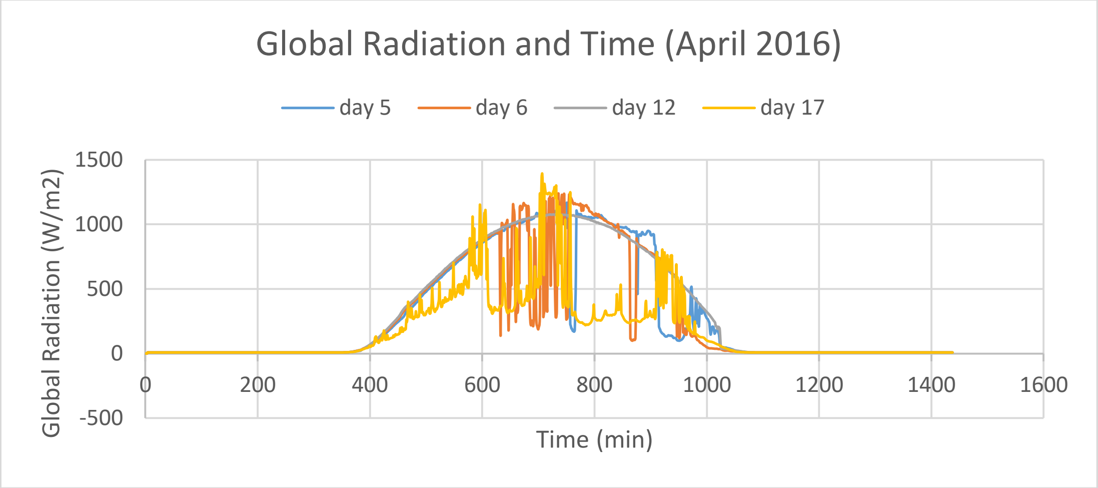


Figure 6 Global radiation and time for April 2016, Windhoek-Namibia

For Some days such as day 2,12-15, 23 and 30, the global radiation curve is smooth (see figure 8, while days like day 3, 4, 17-19, 25 and 29 (see figure 9) are spiky all day long due to random clouds.

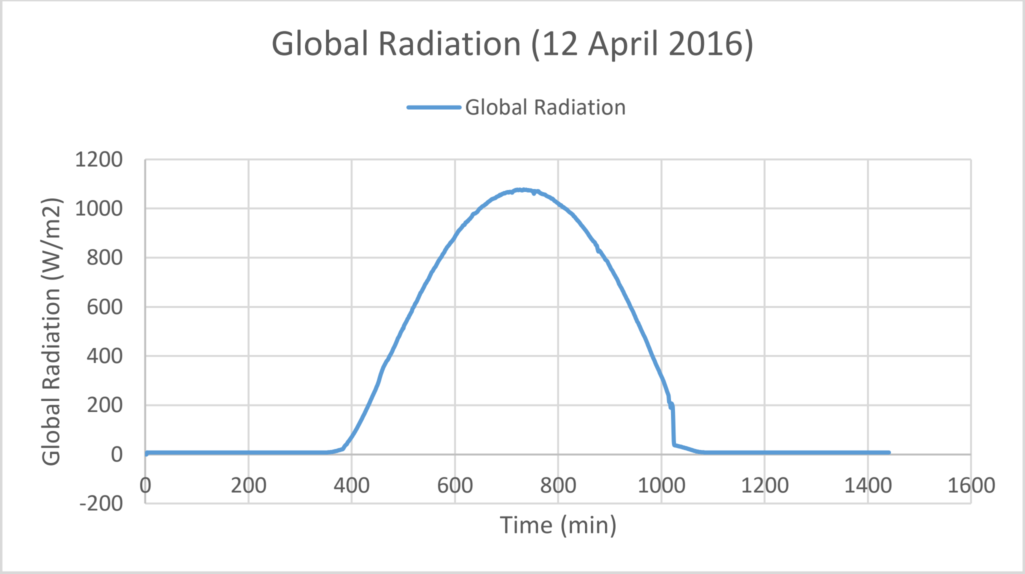


Figure 7 Global radiation and time for 12 April 2016, Windhoek –Namibia

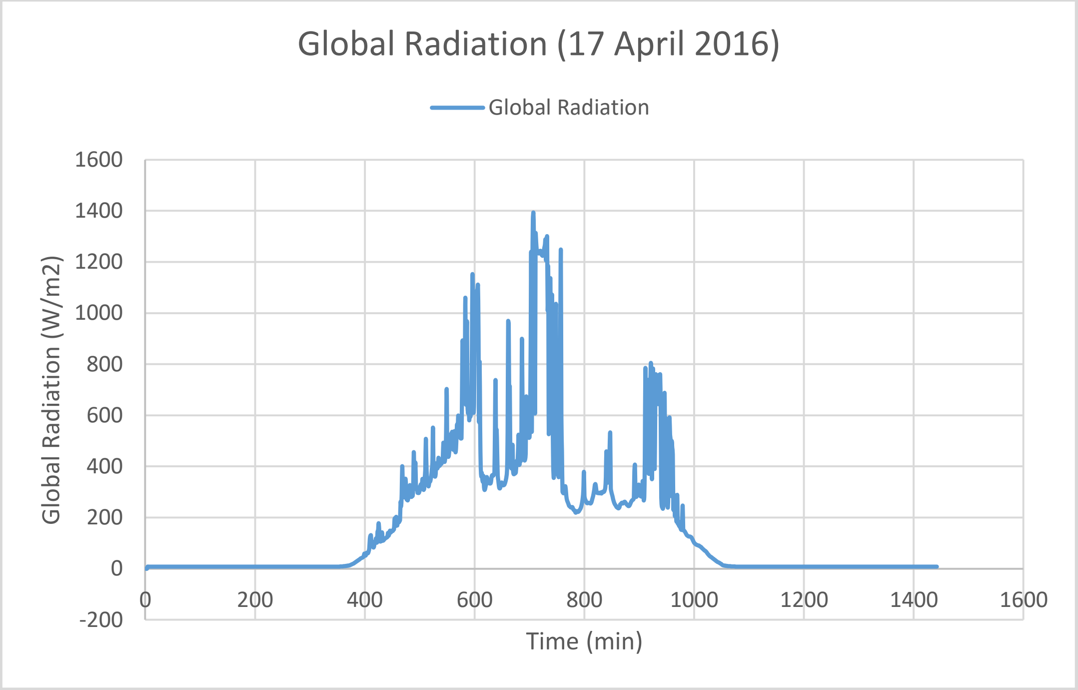


Figure 8 Global radiation and time for 17 April 2016 Windhoek Namibia

For days like day 5 and 6, 8-and 9, 11, 16, 20, and 26 to 28 (see figure 10) the curves are smooth in the morning and spiky in the afternoon or vice versa. The spikiness is caused by the disturbances of the global radiation by atmospheric conditions, such clouds, rain, pressure, dust or wind among others (27).

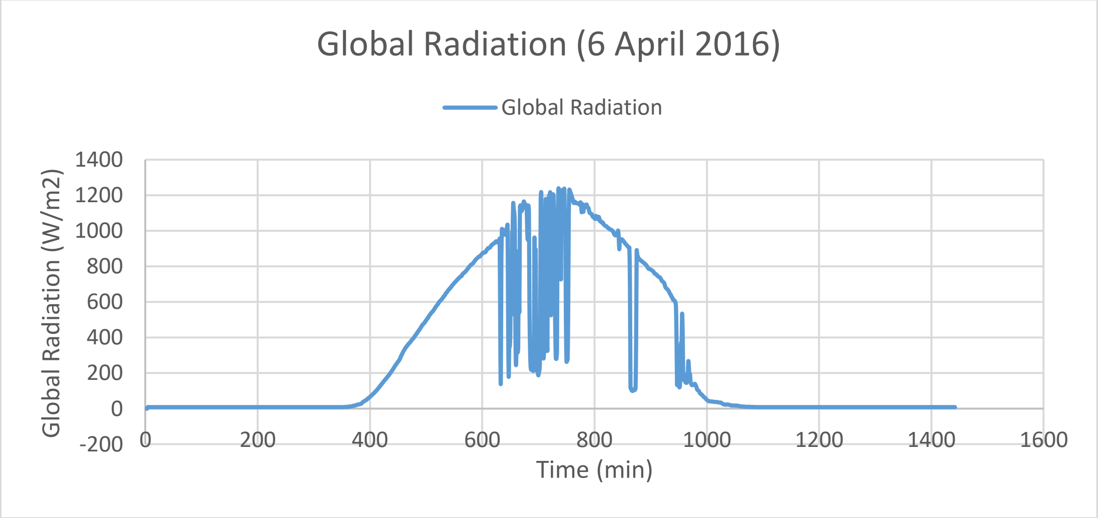


Figure 9 Global radiation and time for 6 April 2016, Windhoek -Namibia

### 4.1.2. Ambient Temperature

The graph below (figure 11) shows the ambient temperature for 4 days of April 2016. The ambient temperature, just like the global radiation increases around sunrise and tends to decrease around sun set.

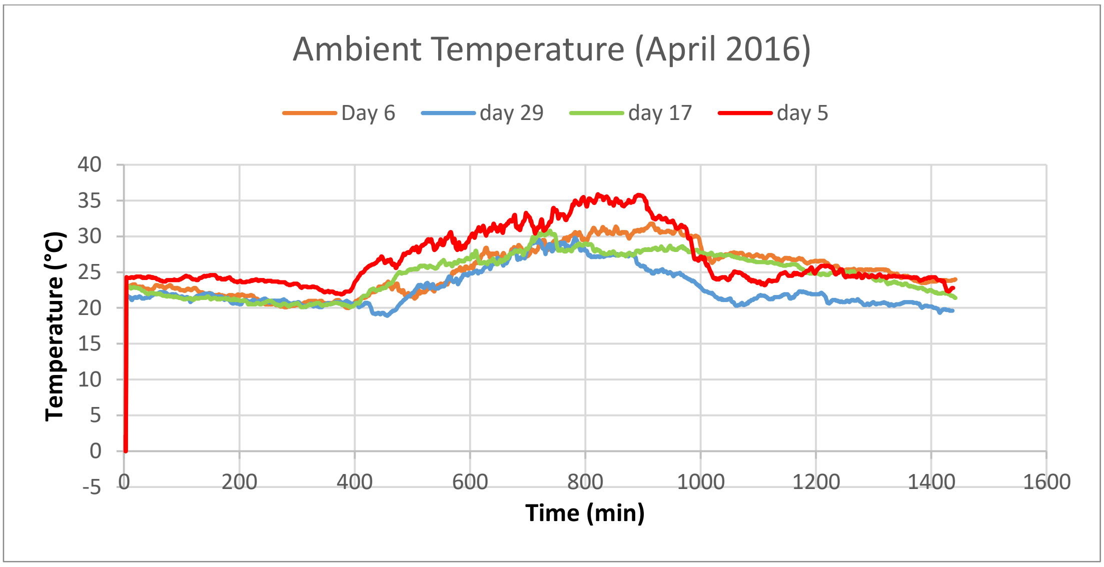


Figure 10 Ambient temperature and time for April 2016, Windhoek Namibia

The rest of the parameters are compared based on the three types of radiation curves previously identified, smooth global radiation curve (day 2,12 to 15, 23 and 30); spiky curve (day 3, 4, 17 to 19, 25 and 29) and smooth curve on some parts of the days and spiky on others (days 5- 6, 8 to 9, 11, 16, 20, and 26 to 28) for a fair and easier comparison, since the global radiation is the key element here.

### 4.1.3. Global Radiation and Flow of water

Day 15 was selected randomly for *smooth global radiation curve* days (see figure 12 below). As discussed in section 3.3.1 $F_{\_Solar}$ is the flow of the working fluid through the collector while $F_{\_Hot\ Water}$, the flow of hot water out of the storage tank. The working fluid only starts to flow through the collector from around 8:53 AM although the radiation increases as from sun rise (6: 30 AM). A spike is seen at around 05:46 AM to 05:51 AM (this is a period of 5 minutes) for $F\_{Hot\ water}$. It is noted that as the radiation falls below 630 $W/m^2$ the flow of water in the collect drops as well until there is no flow at all around sun set.

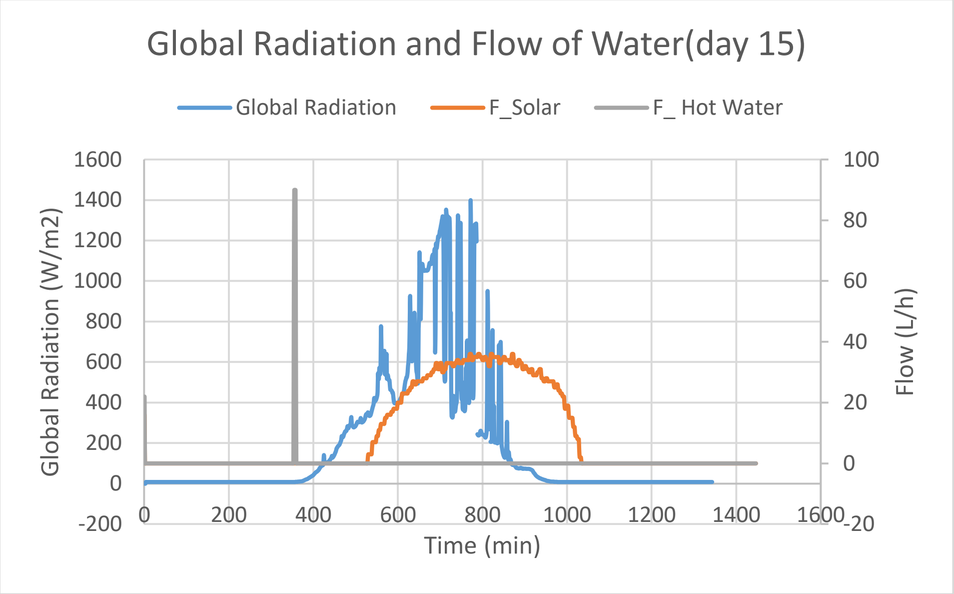


Figure 11 Global radiation, flow of water through the TS-WH installed at NHE house A in Otjomuise and time for 15 April 2016, Windhoek-Namibia

For *spiky global radiation curve days*, day 18 was selected randomly and the results are shown in figure 13 below.

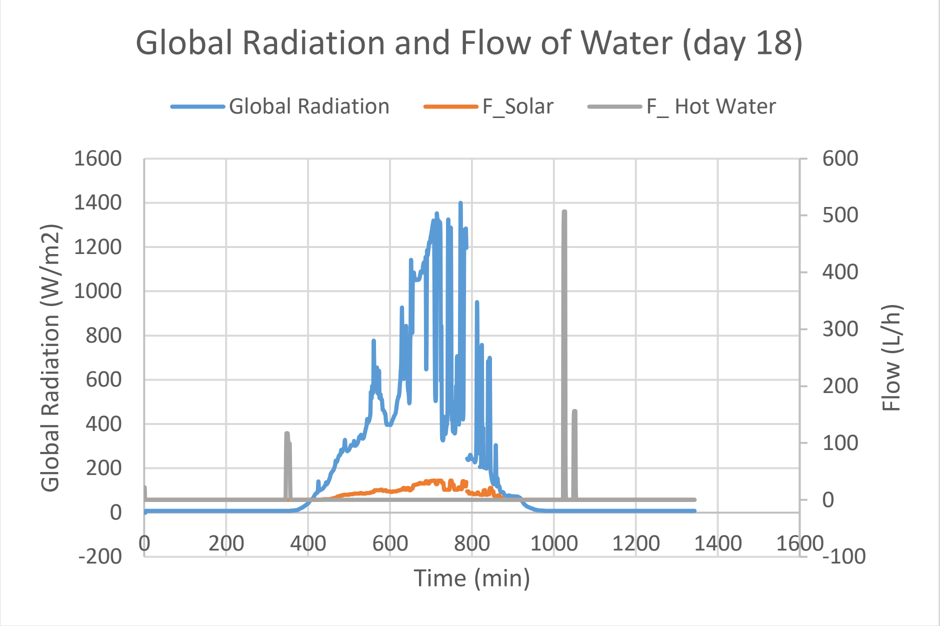


Figure 12 Global radiation, flow of water through the TS-SWH installed at NHE house A in Otjomuise and time for 18 April 2016, Windhoek Namibia,

For *smooth and spiky global radiation curve days*, day 27 was also selected randomly, and the results are shown in figure 14 below.

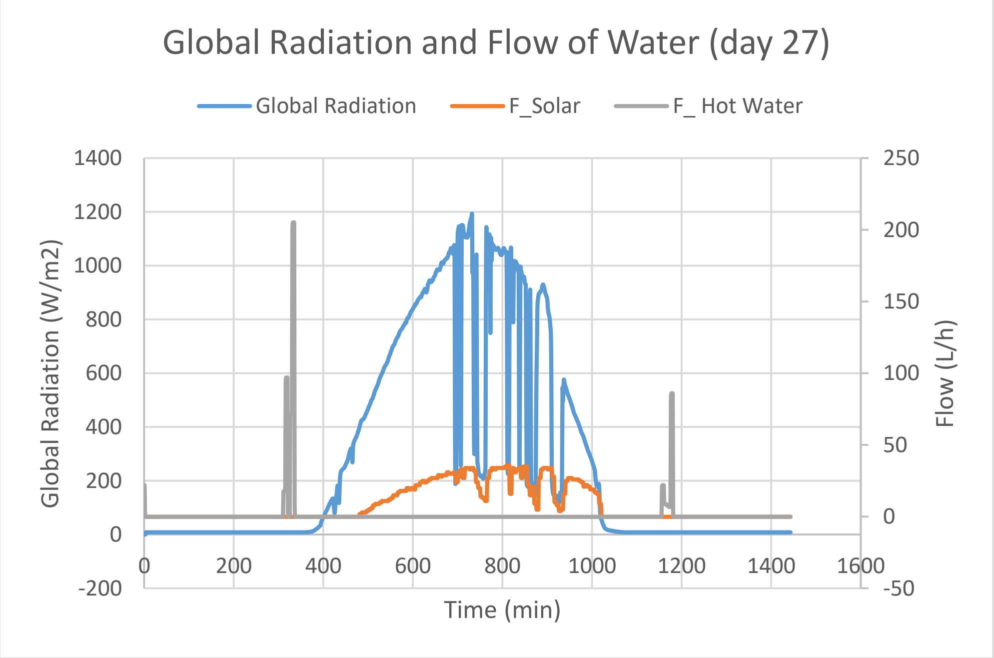


Figure 13. Global radiation, flow of water through the TS-SWH installed at NHE House A in Otjomuise and time for 27 April 2016, Windhoek-Namibia

### 4.1.4. Global Radiation and Volumetric Flow

*For smooth global radiation curve days,* day 12 was picked and the results are shown in figure 15 below.

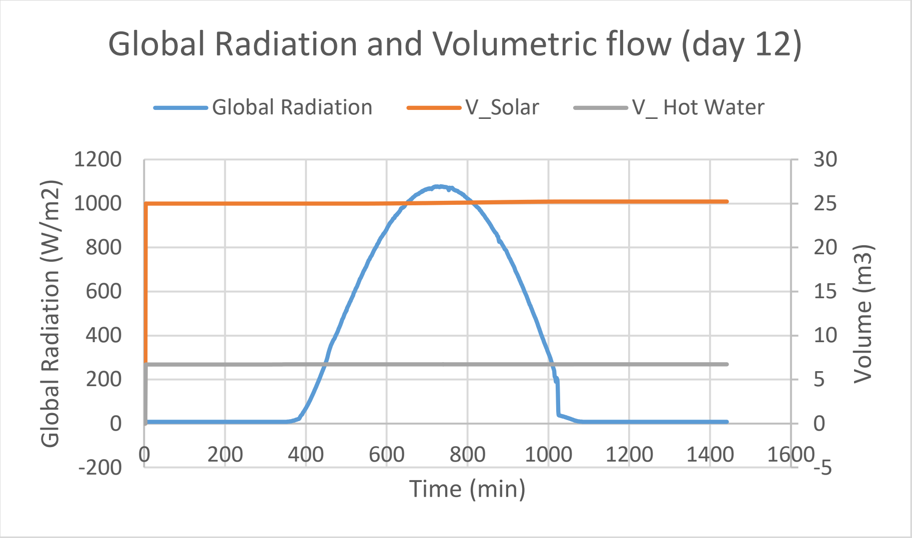


Figure 14 Global radiation, volume of water through the TS-SWH installed at NHE House A in Otjomuise and time for 12 April 2016, Windhoek Namibia

*For spiky global radiation curve days*, day 18 was picked and the results are shown in figure 16 below.

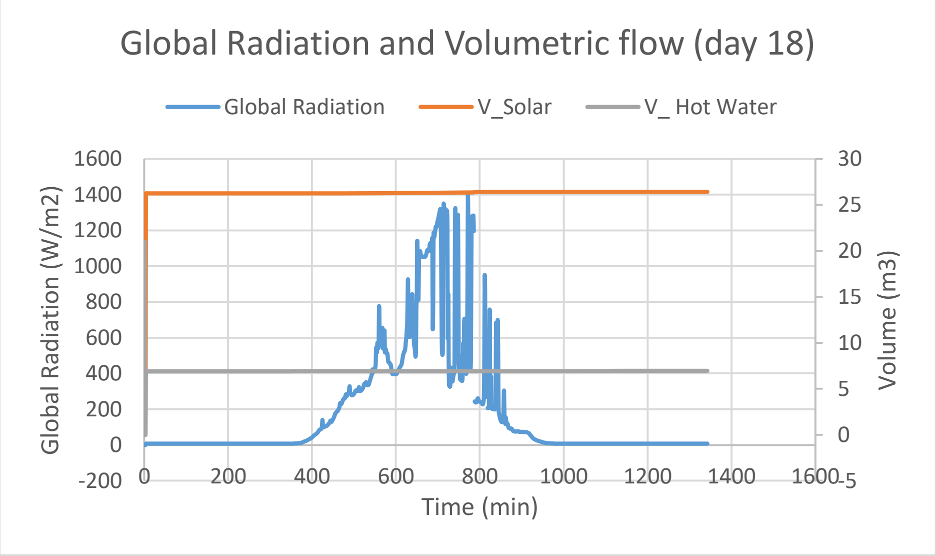


Figure 15 Global Radiation, Volume of water through the TS-SWH installed at NHE house A in Otjomuise and Time for 18 April 2016, Windhoek Namibia

*For smooth and spiky global radiation curve days*, day 6 was selected and the results are shown in figure 17 below

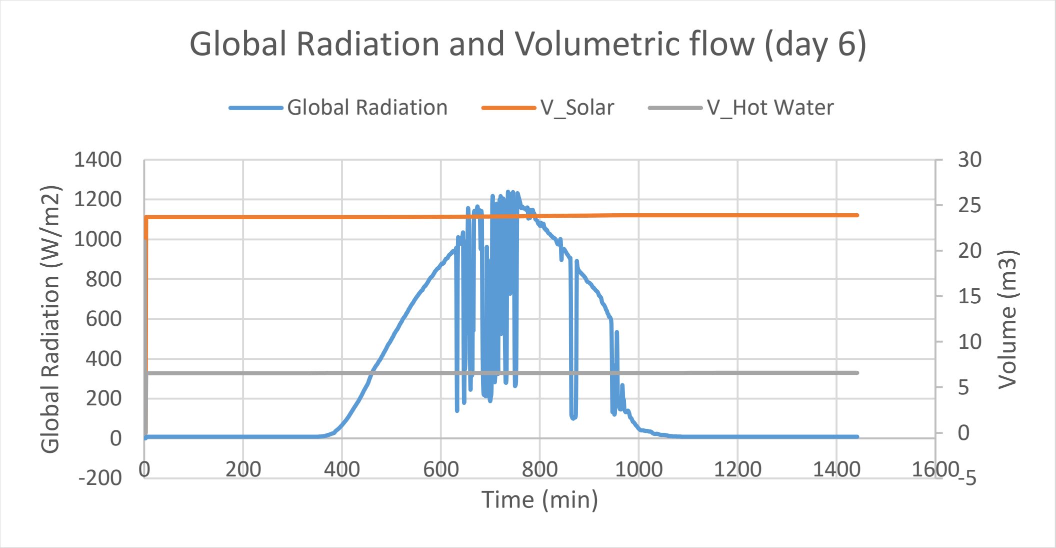


Figure 16 Global radiation, volume of water through the TS-SWH installed at NHE house A in Otjomuise and time for 6 April 2016, Windhoek-Namibia

The volume of water is cumulative, both $V_{Solar}$ and $V_{hot\ water}$. The volume of working fluid passing through the collector ($V_{Solar}$) is dependent of the $F_{\_Solar}$ which was discussed previously (under Global radiation and Flow of water). The $V_{Solar}$ and $V_{Hot\ Water}$ are increasing slightly every day, hence the steps/ ramp (seen on the graphs).

It is easier to stick to the days already analyzed per group when plotting the graphs since the comparisons are related.

### 4.1.5. Global Radiation and Power

*For smooth global radiation curve days,* day 12 was picked and the results are shown in figure 18 below.

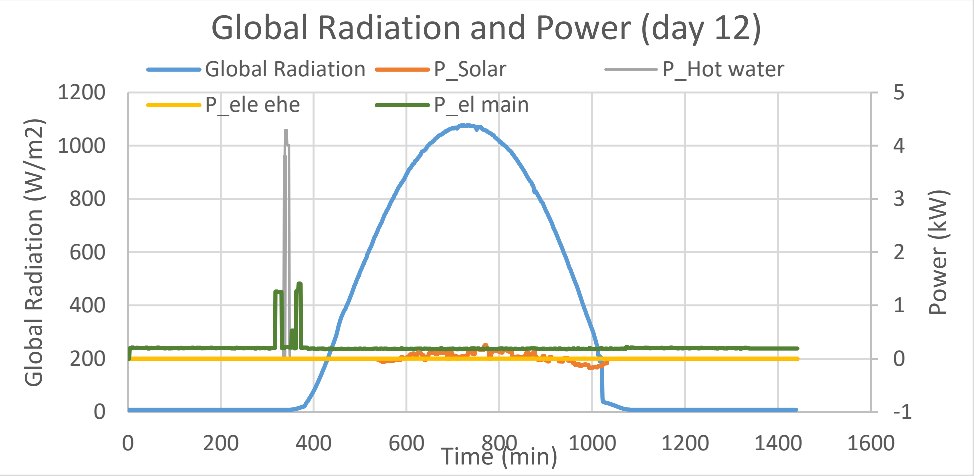


Figure 17 Global radiation, Power associated with the TS-SWH installed at house A in Otjomuise and time for 12 April 2016, Windhoek Namibia

*For spiky global radiation curve days*, day 18 was picked and the results are shown in figure 19 below.

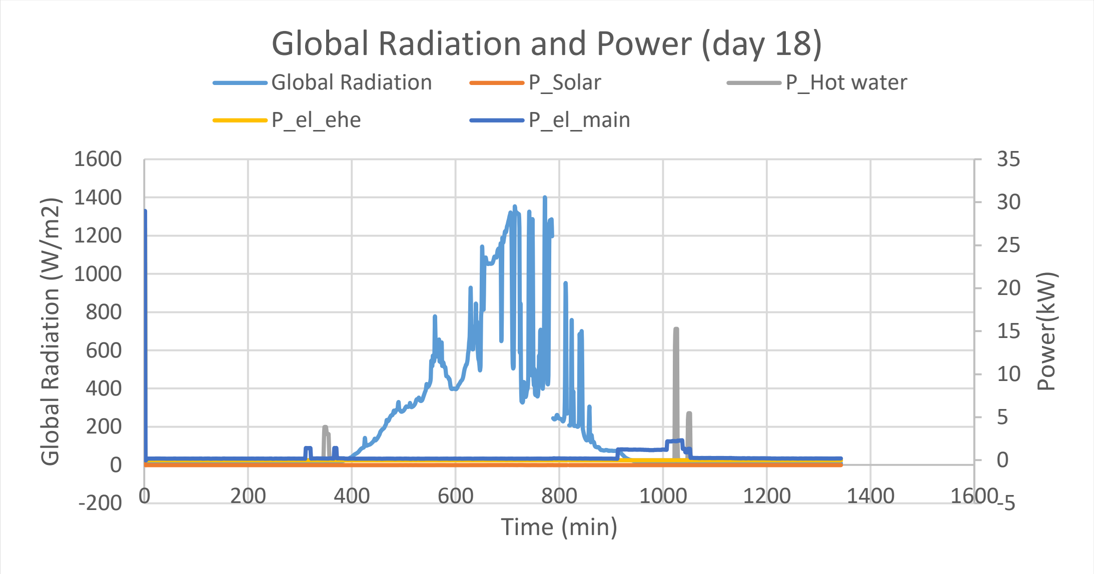


Figure 18 Global radiation, thermal and electrical power associated with the TS-SWH installed at house A in Otjomuise and time for 18 April 2016, Windhoek-Namibia

*For smooth and spiky global radiation curve days*, day 6 was picked and the results are shown in figure 20 below.

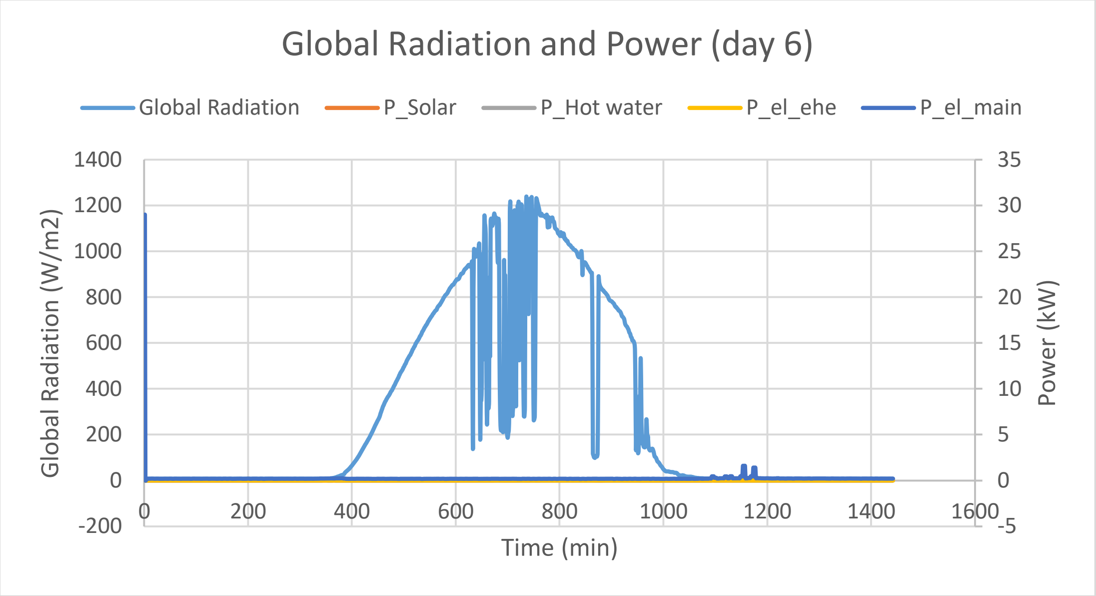


Figure 19 Global radiation, thermal and electrical power associated with the TS-SWH installed at house A in Otjomuise and time for 6 April 2016, Windhoek-Namibia

P_$_{\text{Solar}}$ exist between 10:00 am and 16:00 pm. P_$_{\text{Hot Water}}$ spikes at least twice a day (in the morning hours and later in the evening) indicating the power saved. P$_{\text{\_el\_ ehe}}$ and P$_{\text{\_el\_main}}$ tend to remain constant around zero.

### 4.1.6. Global Radiation and Energy

*For smooth global radiation curve days*, day 12 was picked and the results are shown in figure 21.

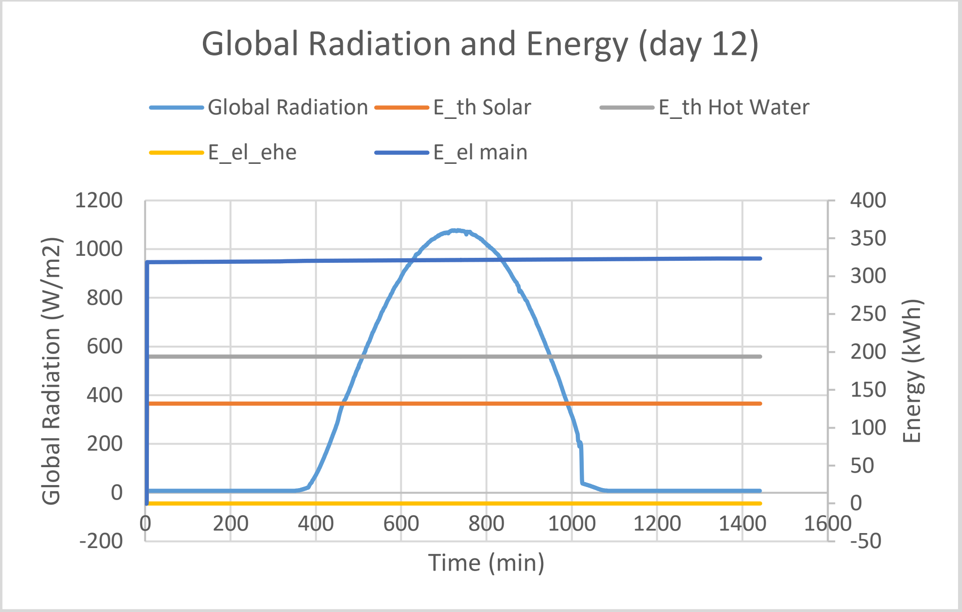


Figure 20 Global radiation, Energy associated with the TS-SWH installed at NHE house A in Otjomuise and time for 12 April 2016, Windhoek-Namibia

*For spiky global radiation curve days*, day 18 was picked and the results are shown in figure 22 below.

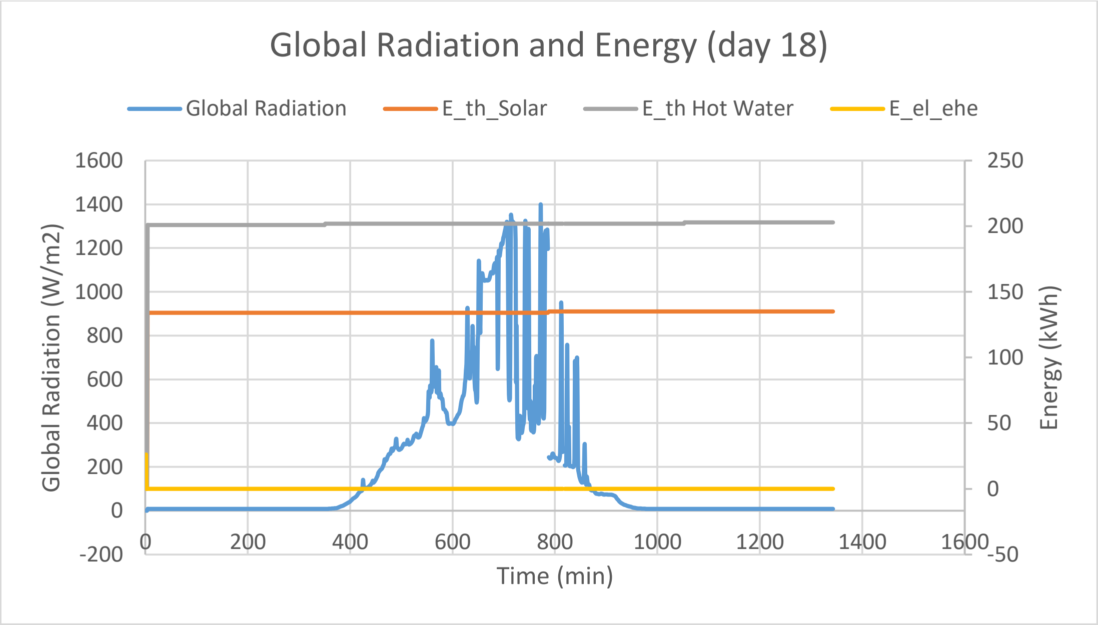


Figure 21 Global radiation, Energy associated with TS-SWH installed at NHE house A in Otjomuise and time for 18 April 2016, Windhoek-Namibia

*For smooth and spiky global radiation curve days*, day 6 was picked and the results are shown in figure 23 below.

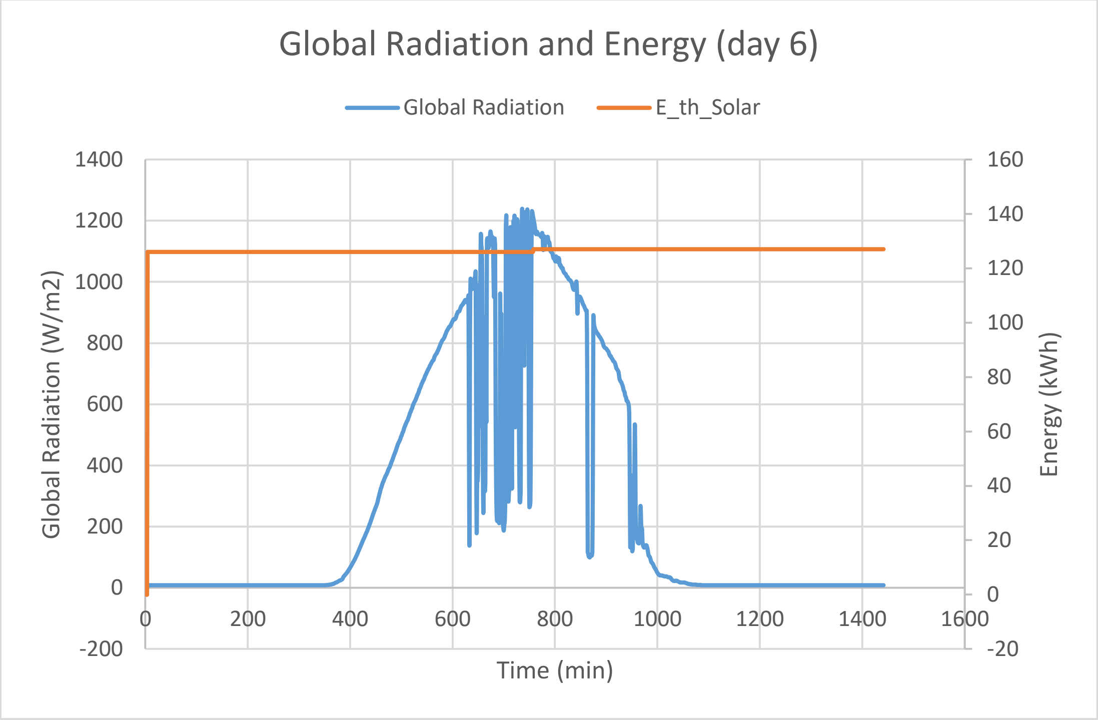


Figure 22 Global radiation, Energy associated with the TS-SWH installed at NHE house A in Otjomuise and time for 6 April 2016, Windhoek-Namibia

The energy associated with this TS-SWH was captured/ recorded in a cumulative manner, however $E_{\_ele\ ehe}$ is always the lowest and close to zero in all the cases. Moreover, $E_{\_th\ Solar}$ have decreased between day 12 and 18 instead of increasing like it has in the days preceding day 12.

### 4.1.7. Energetic Performance of TS-SWH

The performance of the TS-SWH is going to be evaluated using the indices discussed in section 2.5 as follows,

**Solar fraction (SF)**

Using equation [1] discussed under section 2.5, the solar fraction is

$$SF = \frac{564\ kWh/a}{0 + 564\ kWh/a} = 100\%$$

$Q_{solar}$ is equal to 564kWh/a (this is the difference between the energy recorded on the last day and the first day of the month of April 2016 since the energy is captured on a cumulative base, multiplied by 12 months per year, while $Q_{boiler}$ is zero since the the auxiliary heating was never required for the month of April, the assumption is taken for the whole year.

While using equation (2),

**Specific solar energy yield (SE)**

The collector area is of 1.2 $m^2$ as mentioned under section 3.1.1

$$SE = \frac{564\ kWh/a}{1.2m^2} = 470kWh/m^2$$

470kWh/$m^2$ per annum of specific solar energy yield was obtained.

**Energy Yield Ratio (EYR)**

For this TS-SWH the Energy Yield Ratio is calculated as per equation (28) [9], as discussed in section 2.5.

As per table 3 of Arif (9)] the life cycle embodied energy of the 100 lpd solar water system with a flat plate Al-Cu collector of 2$m^2$ is (2450 kWh), hence for a 1.2$m^2$ Al-Cu collector area gives 7317 MJ (2031kWh)

The output energy of this system is 44 kWh of hot water produced per month (average). This is the difference between $E_{th\_Hot\ Water}$ of the first (178 kWh) and the last (222 kWh) day of the month since the Energy is cumulative.

The life cycle output energy of this system is then 10 560 kWh. Thus:

$$EYR = \frac{10560\ \mathrm{kWh}}{2031\ \mathrm{kWh}} = 5.2$$

Energy Yield Ratio is 5.2

**Energy Payback Period (EPBT)**

The energy payback period is calculated as per equation (29).

As per Arif (9) table 1 and 2 the primary embodied energy of the 100lpd solar water system with a flat plate Al-Cu collector of 2m$^2$ is 2450 kWh, hence (interpolating) for a 1.2 m$^2$ is 1470 kWh.

The average monthly primary energy savings of this TS-SWH is 44 kWh, hence 528 kWh annually

$$EPBT = \frac{1470\ kWh}{528\ kWh/year} = 2.8\ years$$

The EPBT of this TS-SWH is 2.8 years (2 years 9 months)

For day 12 April 2016, as per equation [3] the efficiency of the TS-SWH is:

$$\eta_{TS-SWH} = \frac{160\ kg\ x\ 4200\frac{J}{kg\ °C} \times\ (54.2°C)}{1.2\ m^2\ \times\ 465171W/m^2}\% = 65.2\%$$

$T_{\_Hot\ Hot\ Water}$ is 69 °C

T_ Cold Hot Water is 14.8 °C

Global radiation is 465 171 W/m$^2$

While for day 17;

$$\eta_{TS-SWH} = \frac{160\ kg\ x\ 4200 \frac{J}{kg\ °C} \times\ (20°C)}{1.2\ m^2\ \times\ 260138\ W/m^2}\% = 43.1\%$$

T_Hot Hot Water is 37.4 °C

T_ Cold Hot Water is 17.4 °C

Global radiation of 260 138 W/m$^2$

And day 6

$$\eta_{TS-SWH} = \frac{160\ kg\ \times\ 4200 \frac{J}{kg\ °C}\ x\ (50.6°C)}{1.2\ m^2\ \times\ 406537\ W/m^2}\% = 69.7\%$$

T_Hot Hot Water is 68.3 °C

T_ Cold Hot Water is 17.7 °C

Global radiation of 406 537 W/m$^2$

The efficiency is calculated as per the three cases discussed (days with smooth global radiation curve, spiky and a combination of both) in order to have an idea of the lowest and highest efficiency that can be achieved by this TS-SWH.

In order to determine the efficiency of the system, the average efficiency of the three cases should be calculated;

$$Average\ efficiency = \frac{65.2 + 69.7 + 43.1}{3} = 59.3\%$$

Hence the efficiency of the system is therefore 59.3%.

## 4.2. Performance of PVT systems

The results were obtained by Kalogirou et al (2) for different PVT systems installed in three different cities in Europe; The systems are different in terms of solar cells used, pc-Si or a-Si. The PVT systems achieved an increase of the total energy output; however, the electrical energy output of a hybrid system is lower than that of standard PV modules. Pc-Si cells produce more electrical energy than the corresponding a-Si cells. The a-Si cells produced more thermal useful energy in all three locations considered, both types of cells cover all thermal energy required for hot water production in the summer months. These results are necessary in determining which solar cells are suitable for Namibian conditions and needs.

Herrando et al (1) in their experiment, compared the solar irradiance and ambient temperature for different months in London. Summer has almost three times higher irradiance than winter. Although this information is true for London the similar results are expected for Namibia despite the geographical locations of the two cities: hence crucial for comparison.

The hot water outlet temperature from the PVT collector depends on several parameters such as the end user hot water consumption pattern, storage tank size, and cold water supply temperature (3) these temperatures are necessary for a comparison to that of the TS-SWH recorded.

In analysis of the electrical and thermal outputs of the PVT system throughout the year, both electrical and hot water demands are completely covered, however it not the case in other months (2). Would this be the case for the TS-SWH and PVT under the Namibian conditions? Both systems are expected to perform better under Namibian conditions because of the high solar radiation that Namibia receives daily.

Similar to Herrando et al (1), Tiwari et al (50) in their experiment taken in New Delhi (India), both the outlet temperature and tank temperatures of the PVT system begin to increase from around 10:00 and reach their highest points at around 14:00. These results are compared to those of the TS-SWH. Moreover, in the analysis of the overall thermal energy gain for New Delhi for the year of 2007, May (summer) had the highest thermal energy gain recorded while February (spring) had the least. Similar results are expected for the TS-SWH under the Namibian conditions. The PVT system efficiencies or cogeneration efficiency recorded was of about 66% recorded in September and the lowest in January of about 61% (3).

### 4.3. Economic analysis of the TS-SWH

The financial savings are calculated as follows (51):

About 44 kWh of energy monthly is required to heat up the water as discussed in section 4.2. It is also known that the cost of one unit of electricity in 2016 was N$ 1.93 as per the City of Windhoek 2016 tariffs.

This means 44kWh of units is saved monthly since the backup element was not required. Therefore, the financial savings as per equation [9]:

$Total\ Financial\ Savings = 44kWh \times 1.93 \frac{N\$}{kWh} = N\$\ 84.92$ monthly.

N$ 84.92 is saved monthly, hence this translates to N$ 1 019.04 annually.

Since the total cost of installing the TS-SWH system is N$ 49.32 per Liter (14) and given that the installed capacity is 160 Liters, the total cost of the system becomes N$ 7 840.

The return on investment is therefore calculated using equation (13),

$$Return\ on\ Investment = \frac{N\$\ 7\ 840}{N\$\ 1\ 019.04/year} = 7.7\ years$$

The return on investment is 7 years and 8 months.

### 4.4. Economic analysis of PVT Systems

The life cycle analysis is executed in order to obtain the total cost (life cycle cost) and the life cycle savings of the systems. For the sake of economic analysis purposes, the lifespan of the solar thermal system was taken as 20 years (10).. No subsidies were considered in the analysis, as the subsidization schemes for PVT systems vary from country to country and as the economic analysis is performed mainly in order to compare the standard and hybrid systems (10).

The operating cost, maintenance and parasitic costs were considered as 1% of the initial investment and are assumed to increase at a rate of 1% per year of the system operation. The cost of electricity was considered as 0.1€/kW h (N$ 19.8 /kWh), and

Diesel 0.62€/l (N$ 12. 28 /l) while the market discount rate and the general inflation rate to be 6.5% and 5.2% respectively. What is of interest here is mainly the comparison between the savings in electricity and thermal energy and the LCS of the various PVT systems. Kalogirou et al (2) compared the hybrid systems to the independent PV systems in their analysis. However, the analysis, in this thesis, will not pay attention to the PV system as the systems of interest are PVT and thermosiphon systems, however the results (both thermal and electrical energy produced by independent PV and thermal systems and savings associated) are still valuable. The electrical energy difference of about 62% in favor of PVT systems was obtained and solar fraction (percentage of hot water load covered by PVT system) of up to 87%. The life cycle savings obtained are however in negatives. The meaning of these negative values obtained are explained further under section 5.4.

All the data for the PVT systems given above is crucial for comparison to the TS-SWH installed in Namibia. Although the cost of the PVT systems may differ from the TS-SWH, the operation and maintenance costs are not expected to differ a lot, as well as the cost of fuel. The cost of electricity also differs per country, but this is good for a performance comparison in the two countries (Namibia and UK).

### 4.5. Environmental impacts of TS-SWH

The installation and operation of these TS-SWH has a certain amount of avoided $CO_2$ will be determined as per calculation done by (41).

Total energy produced per annum by the TS-SWH is 528 kWh as determined under section 4.1.

About 60% of electricity is imported from ESKOM as per NAMPOWER annual report of 2020 and ESKOM generates its electricity using coal; and only 40% is generated locally from a combination of fuels (hydro power, heavy fuel and coal).

The average $CO_2$ equivalent intensity for electricity generation is (41):

0.982kg/$CO_2$ per kWh of coal and 0.0185kg/$CO_2$ per kWh of hydropower. Only coal and hydropower will be considered since they are the major ones (heavy fuel only accounts for about 4% of locally generated electricity).

Avoided $CO_2$ due to coal:

$$CO_2\ Avoided = 0.6 \times 528\ kWh/year \times 0.982\frac{kgCO_2}{kWh} = 311.1\ kgCO_2/year$$

Hence in the 20 years' lifetime of the TS-SWH, 6222 kg of $CO_2$ due to coal produced electricity is avoided.

Avoided $CO_2$ due to hydropower:

$$CO_2\ Avoided = 0.4 \times 528\ kWh/year \times 0.0185\frac{kgCO_2}{kWh} = 3.9\ kgCO_2/year$$

Hence in its 20 years' lifespan 78kg of $CO_2$ due to hydropower produced electricity is avoided.

The total avoided $CO_2$ by this TS-SWH is then the total of both cases, which is 6300 kg.

Pollution created during manufacturing of collectors (41):

As per table 1 and 2 of Arif (41), a 2m$^2$ flat plate Al-Cu collector has primary embodied energy of 6381 MJ while the other components (storage tank, stand and piping) for this 100lpd systems have 2924 MJ of embodied energy. This is a total of

9305 MJ (2577.5kWh) embodied energy. Hence interpolating for a 1.2 $m^2$ collector area 100lpd system the embodied energy become 1546.5 kWh

Assuming that this energy was generated from coal, the pollution created during the manufacturing of this system becomes:

$Pollution\ during\ Manufacturing = 1546.5kWh \times 0.982\frac{kgCO_2}{kWh} = 1\ 518.2\ kg$ of $CO_2$ emission

## 4.6. Environmental impacts of PVT Systems

Herrando et al (1) in their analysis found that 16t of $CO_2$ can be saved over a lifetime period of 20 years for a PVT system of 1.5 $m^2$aperture area, receiving 850 kWh/$m^2$ of solar radiation annually, hence interpolation of these results shows that the Solar collector of the PVT system matches the collector of the TS-SWH (1.2$m^2$) whose avoided $CO_2$ is 12.8 t. Such system would generate 3 285 kWh of electricity, and heat water with energy equivalent to 2 540 kWh of electricity over its 20-year lifetime. In this assessment, the values of $CO_2$ equivalent emissions associated with grid electricity and natural gas were taken as 0.5246kg $CO_2(e)/kW_eh$ for electricity and 0.1836kg $CO_2(e)/kW_{th}h$ for natural gas.

## 4.7. Comparison of the Results

The table below summarizes the results in terms of energetic performances, economic figures and environmental impacts of the TS-SHW and the hybrid PVT systems for easier comparisons.

Table 4 Summary of the energetic performance, economic figures and environmental impacts of the TS-SWH and hybrid PVT systems

| | | **System Type** | |
|---|---|---|---|
| | | **TS-SWH** | **Hybrid PVT system** |
| **Technical make-up** | **Main Components** | Collector<br>Storage tank | Collector<br>Storage tank<br>*PV cells/modules* |
| **Energetic Performance** | **Solar fraction (%)** | 100 | 68.6 (2) |
| | **Specific Energy Yield (kWh/m$^2$ per annum)** | 470 | ≤515 (2) |
| | **Efficiency (%)** | 59.3 | Thermal: ≤58 (1)(3)<br>Electrical: ≤15 (1)(3)<br>Cogeneration 66% (3) |
| **Economic figures** | **Payback period (years)** | 7.7 | ≥20 years (2) |
| **Environmental impact** | **Avoided $CO_2$ emissions (t)** | 6.3 | 12.8 (1) |

## 4.8. summary

This chapter presented the results obtained for performance parameters of both the TS-SWH and hybrid PVT systems and for the factors that affect them, economic analysis results and environmental impact assessment results for both systems, and finally, summarized these results in a table format for comparison purposes. These results are discussed in chapter 5.

# CHAPTER 5: DISCUSSION OF RESULTS

This chapter discusses and compares the results presented in chapter 4 for both TS-SWH and hybrid PVT systems and subsequently recommends if the PVT system should be used widely in Namibia.

## 5.1. Technical Composition of the TSWH and hybrid PVT system

As stipulated in section 2.2.1 and 2.3.1 both systems, TS-SWH and hybrid PVT have the same basic components which are the collector, storage tank and piping, however the hybrid PVT system comes with the PV module on the surface of its collector and accessories associated with it to enable the generation of electricity. The TS-SWH system in this study has an auxiliary heating / electric back up element.

## 5.2 Performance of TS-SWH and hybrid PVT systems

All the parameters of the solar water heaters are dependent on the solar radiation (33), and the pattern of the solar radiation need to be studied in order to understand the performance of the solar systems (3) hence the charts/graphs  prepared for TS-SWH, parameters are plotted against time, and compared with the global radiation input.

A sudden spike in the $T_{\_hot\_\ hot\ water}$ of the TS-SWH at 05:13:00 AM from 22˚C to 60.22 ˚C was noticed in figure 6 and at 17:42:00 PM from 34.10˚C to 74.8 ˚C and gradually falls back, which means hot water was used at these instances since the temperature of the storage tank outlet was at its ambient temperature (22°C) and when the hot water tap was opened the temperature rose to 60.22°C. The water could have been used for bathing, cleaning dishes or for any other uses that required hot water, in a family house.

In the second case (17:42 PM) the ambient temperature was high that is why the temperature at the outlet of the storage tank is also high, found at 34.10°C, and when the hot water tap was opened the temperature of the hot water outlet of the storage tank increased to 74.8 °C. The difference in the two temperature at the outlet of the tank during these two times is due to the global radiation because its low in the morning hence low water temperature and high in the afternoon, and therefore the higher water temperature (33).

$T_{\_Cold\ Hot\ Water}$ rose from 16 °C to 27 °C at 05:13:00 AM exactly the same time $T_{\_Hot\ Hot\ Water}$ started to rise, and this should mean that the water going into the tank replacing the water leaving was found at a temperature slightly higher than the temperature of the water in the tank. This was still the case at 17:42:00 PM, however, the change in temperature was minor.

$T_{\_Hot\ Solar}$ and $T_{\_Cold\ Solar}$ are increasing with the radiation, and vice versa. These temperatures are related because the inlet and the outlet of the collector are at the same temperature, hence the water picks up this temperature at the inlet very fast; thus $T_{\_Ambient}$, $T_{\_databox}$ and $T_{\_Cold\ Hot\ Water}$ are also related. Although $T_{\_Ambient}$ is influenced by the global radiation (33), $T_{\_databox}$ and $T_{\_Cold\ Hot\ Water}$ are exposed to the environment; that is why they are found closer to $T_{\_Ambient}$.

The hybrid PVT system model generated similar results as expected in the morning, the temperature of the water exiting the collector ($T_{cout}$) is lower than the tank temperature (Tt). Then, from 6 am, the solar irradiance causes the temperature of the water exiting the collector, $T_{cout}$, to increase. At the end of the day the temperature of the flow leaving the collector $T_{cout}$ decreases due to the low irradiance. Although with the thermosiphon system there is no circulation of water between the tank and the collector (no thermosiphon effect), during the early hours of the morning, it’s worth highlighting that the temperature of the water in the collector is found to be less than that of the storage tank (7).

### 5.1.1. Global Radiation

The results of TS-SWH show that global radiation is almost nonexistent for hours between sun set and sunrise. For days whose global radiation curve is smooth (see figure 8), their global radiation was not significantly disturbed by any atmospheric conditions, while days whose radiation curves are spiky all day long (see figure 9) their radiation was disturbed, hence it was fluctuating all day long. While days with smooth curves in the morning and spiky in the afternoon or vice versa (see figure 10), their radiation was being distracted in the afternoon, or in the morning, respectively. The possible atmospheric conditions to alter the radiation include rainfall, clouds, wind and pressure (27). Given that it rains in April, the instabilities of the radiation curve during this month could have been due to the clouds and rainfall. Since the cloudy days results in less light particles available due to the clouds, the solar collectors are expected to underperform because they are not getting sufficient radiation, because of decreased heating capacity of the collector (24). However, the benefit that comes with the rainfall is that when it rains the dirt/ dust particles are washed off the collector, thus increasing absorption of radiation. Bhamare et al.(42) indicated that the collector outlet temperature can be less due to the low radiation intensity, lower ambient temperature variation also results in low collector outlet temperature.

While for the hybrid PVT system, the solar radiation is robust enough to heat the water from 10:00 in comparison to the TS-SWH. It should be noted that this is not due to the configurations, but rather the geographical location of the two systems. There is a gradual increase in water temperature from 10:00h until it starts to reduce after 14:00h, because of the reduction in solar radiation. The decrease in temperature is not that dramatic, indicating that the tank is well insulated, since it’s maintained at about 45˚C.

Summer has higher insolation than winter and spring. This is anticipated to strongly affect the output of the PVT systems during the different seasons (7), hence Summer also has the highest thermal energy gain and spring had the least (29). This is because summer days are sunnier, hence more radiation. Since the ambient temperature is dependent on the solar irradiance, an increment in solar radiation results in an increment in ambient temperature.

### 5.1.2. Ambient Temperature

The graph, in figure 11, shows the ambient temperature for 4 days of April 2016. The ambient temperature, just like the global radiation, increases around sunrise and tend to decrease around sunset, hence the ambient temperature is dependent on the global radiation (14,52). However, unlike the global radiation, ambient temperature is not affected by atmospheric conditions as dramatically and the temperature curves are not spiky like those of global radiation, there is however a gradual decrease, or increase, in the ambient temperature, respectively. It is worth noting that when the absorber plate gets hotter than the ambient temperature the collector emits stored energy instead of absorbing it. This explains why efficiency does not always increase with increased absorber temperature (24).

### 5.1.3. Global Radiation and Flow of water

The working fluid only starts to flow through the collector of the TS-SWH from around 8:53 AM although the radiation increases as from sunrise. This means that the radiation of about 630 $W/m^2$ is needed for the working fluid to start flowing through the collector (thermosiphon effect to begin). A spike is seen at around 05:46 AM to 05:51 AM (this is a period of 5 minutes) for $F_{\_Hot\ Water}$. This could mean someone took a brief shower since it is a rate of about 90 L/h (1,5L/min) of water that was flowing and the time of the day. It is noted that as the radiation falls below 630 $W/m^2$ the flow of the working fluid, in the collector, drops as well until there is no flow at all around sun set.

It is noted that the flow of the working fluid in the collector is strongly affected by the global radiation (33), this is to say that when the global radiation is altered the flow of the working fluid in the collector is also affected. Low global radiation intensity results in a decreased flow of working fluid in the collector, and vice versa. The flow of water out of the storage tank is independent of the flow of the working fluid through the collector (33), which should be the case since the water moves out of the storage tank once the hot water tap is opened and the water flows out due to the gravitational pull.

The collector flowrate of the PVT system affects strongly the overall hot water and electrical delivery performance of the system, however, an increase in the electricity produced at high collector flowrates (160 L/h) may not compensate the decrease in the hot water demand covered. On the other hand, the electrical output of the PVT system increases linearly with the increase in covering factor (P), due to the proportionally larger surface area of the PV module. However, as the PV module area increases, there is less absorber plate area directly exposed to the solar irradiance (which has a higher absorptivity than the PV laminate), so the heat transferred to the water flowing through the PVT collector decreases, diminishing the amount of hot water demand covered.

Overall, high covering factors P are desirable in order to maximize the electrical output, although the hot water production decreases, but to a smaller extent (7).

### 5.1.4. Global Radiation and Volume

The volume of water and working fluid is cumulative, both $V_{\_Solar}$ and $V_{\_hot\ water}$ of the PVT system. They both increase slightly per day, and this is observed in the steps/ ramp (on the graphs in figure 15 and 16). $V_{\_hot\ water}$ depends on $F_{\_Hot\ water}$, which is independent of the global radiation intensity. $V_{\_Solar}$ depends on the $F_{\_Solar}$, which dependent on the global radiation; therefore, the two parameters $V_{\_Solar}$ and $V_{\_hot\ water}$ should not be dependent just like $F_{\_Solar}$ and $F_{\_Hot\ water}$.

### 5.1.5. Global Radiation and Power

The switching on of electrical power from the mains ($P_{\_Main}$) and the global radiation are independent parameters, however $P_{\_Solar}$ depends on the global radiation(52). $P_{\_Solar}$ exists only between sun rise and sunset (as depicted in figures 18-20) around the same time as $F_{\_Solar}$. Additionally, $P_{\_Solar}$ gives rise to $F_{-\ solar}$, which, as discussed earlier, depends on the global radiation. As declared earlier, $P_{\_Solar}$ indicates the solar power incident on the collector while the $P_{\_Hot\ water}$ shows the power saved or the power that would have been drawn by the electric element should there be insufficient radiation to heat up the amount of water flowing out of the storage tank. For all the cases $P_{\_el\_ehe}$ is zero, even for days whose radiation fluctuates, which means it was not necessary for the electric element to kick in as the radiation was sufficient to heat the water. $P_{\_\ hot\ water}$ has shown spikes at some point in all cases, indicating the amount of energy saved by the solar water heater.

### 5.1.6. Global Radiation and Energy

All the energies are cumulative; the most noticeable thing is that the $E_{\_ele\_ehe}$ is always the lowest and close to zero. This should explain that the electric element hardly kicks in. This means that there is, in most cases, enough radiation the heat the water, hence no need for the electric element to take over the heating of water. Since energy is dependent on power consumption, the explanations given for power should be applicable to the energy.

$E_{\_th\ Solar}$ has decreased between day 12 and 18 (see figures 21 and 22), this is unexpected because the $E_{\_th\ Solar}$ is cumulative and the value should have increased instead, this means that this energy is dependent of the radiation (52), hence a decrease in about 20kWh between day 12 and day 18 was experienced. This makes sense because the radiation of day 18 was not stable, so as the radiation of some of the days preceding day 18, hence resulting in a reduction of the overall $E_{\_th\ Solar}$.

### 5.1.7. Energetic performance of the TS-SWH and hybrid PVT system

Solar fraction of 100% was obtained for the TS-SWH from the calculation, however the assumption that the auxiliary heating was not required for the whole year may not be entirely true because not all the months were evaluated. The backup element of this system might be required during rainy days since these months are likely to experience overcast so the radiation may not be enough to heat the water. Additionally, 470kWh/$m^2$ per annum of specific solar energy yield was obtained for this thermosiphon system, however a value of 400-800 kWh/$m^2$ a year have been obtained for other flat plate collectors; therefore, this system is still performing satisfactorily.

Energy Yield Ratio for the TS-SWH was found to be 5.2, this means that in its lifetime this system produces more than five times the energy invested in it. This is very good as it shows that there is a gain. The worst case would be when the EYR is less than one, as it would mean that there is a loss in this investment since the system cannot generate more energy than the amount invested.

The EPBT of the TS-SWH was calculated to be 2 years 9 months, this is a good period given that the lifespan of the TS-SWH is 20 years as the client will be paying off the energy invested in the system within the first three years.

Day 6 recorded the highest efficiency of the TS-SWH of the 3 cases, although day 12 was expected to have a better efficiency because its radiation was not altered by atmospheric conditions. This could be because the rainfall in day 6 could have resulted in lower ambient temperature, hence a significant temperature variation in the ambient temperature in day 6. As discussed by Bhamare et al (42). Moreover, after the fluctuations of the radiation were over the global radiation was increasing high up to 1206W/m$^2$ before it ceased. Day 17 has the lowest efficiency. This is expected because the global radiation was fluctuating all day long, hence it was not high enough to heat the water, hence the low temperature of the hot water in the storage tank.

The average efficiency of 59.3% for the TS-SWH is relatively good for the month of April, hence this efficiency is expected to be higher during winter as the global radiation is hardly disturbed.

The PVT system on the other hand has achieved a solar fraction of 68.6 %, Specific Energy Yield of $\leq$515 kWh/m$^2$ per annum (2), with thermal efficiency of $\leq$58 (1,3) and electrical of $\leq$15 (1,3), which gave better cogeneration efficiency of about $\leq$66% (3).

## 5.2. Economic analysis of the TS-SWH and PVT systems

The return on investment of the TS-SWH is 7 years and 8 months was calculated. This means that within 8 years the amount invested in installation of the solar water heater will be paid off and thereafter this person would be heating water free of charge. This is a good figure given that the life span of the TS-SWH is 20 years and beyond, therefore for more than twelve years this house would not be spending a cent in heating water.

Kalogirou et al (2) in their economic analysis of the PV T systems, made a comparison of the extra equipment required by the solar system against the money saved and the amount of electricity and fuel replaced by solar energy. This is indeed practical since an additional equipment to the solar system is one more difference from the conventional heater. Additionally, subsidy should not be considered since it differs from country to country and subsidy may not be available or in place, in many countries including Namibia although there might be private sponsorships etc.

Smaller negative values of LCS that were obtained, indicate that the payback time of these PVT systems is greater than 20 years although in some cases, positive values were obtained. All cases that give positive LCS refer to the use of a-si cells and generally, for locations with higher available solar radiation the economics give better figures. Although amorphous silicon panels are much less efficient than the polycrystalline ones, they give better figures for the hybrid PVT thermosiphon system with electricity backup. Therefore, it can be concluded that subsidies are a crucial for the introduction of hybrid PVT systems. As mentioned earlier, subsidies are not considered, and the negative amounts of money symbolizes the money that the owner will lose by installing the PVT system instead of buying the electricity from the mains, hence the need for subsidies in order to convince people to install the PVT systems.

Finally, the benefit of the TS-SWH over the hybrid PVT systems is that much shorter times payback periods have been achieved.

## 5.3. Environmental impacts of TS-SWH and PVT systems

The total $CO_2$ emission during the manufacturing of the complete TS-SWH is 1 518.2 kg of $CO_2$. This shows that the TS-SWH may be clean or do not pollute the environment during their operation since the grid electricity was not required but their manufacturing process is not entirely clean as there is $CO_2$ emission. Despite, the total calculated avoided $CO_2$ by this TS-SWH is 6300 kg in its life span of 20 years.

In comparison, a hybrid PVT system avoids about 16t of $CO_2$ over a lifetime period of 20 years for a PVT system of 1.5 $m^2$ collector area (10). This is interpolated to 12.8t of avoided $CO_2$ for a 1.2$m^2$ collector. This is a great number, should more PVT systems be installed, more $CO_2$ emissions will be avoided.

## 5.4. Summary

This chapter discussed the results, where it has looked at the presence of the solar module on the collector of the hybrid PV T system as the difference in the technical composition of the two solar water systems, performance parameters of the hot water systems i.e., Flow of Working fluid in the collector, Temperature at the collector inlet and outlet, Power associated (saved) with hot water, Temperature of hot water exiting the storage tank, among others. The main factors that affect the performance parameters of the hot water systems are the global solar radiation and ambient temperature. The Energetic Performance was evaluated with the Solar fraction, of which the TS-SWH obtained 100% solar fraction, a better figure in comparison to 68.6% (2)of the hybrid PVT system, Specific energy yield of 470 kWh/m$^2$ per annum for the TS-SWH, while PVT with ≤515 kWh/m$^2$ per annum (2) better than the TS-SWH. The TS-SWH has efficiency of 59.3%, while hybrid PVT with thermal efficiency of ≤58 (1,3) and electrical of ≤15 (1,3), which gave better cogeneration efficiency of about ≤66% (3). This PVT system has good performance since the conversion efficiency of solar heat is around 70% and direct conversion of electricity from the sun efficiency of about 17% (53). The TS-SHW has better economic figure, with payback period of 7.7 years as opposed to ≥20 years (2)of the hybrid PVT system. The TS-SWH has Avoided $CO_2$ emissions of 6.3t, while the hybrid PVT has better results of 12.8 t (1)avoided $CO_2$. These results are presented in table 3.

Although there are many parameters to measure energetic performance, economic analysis, the parameters used for comparisons are the ones common in both systems.

In absence of primary data for PVT systems, secondary data that was relied upon and used, may have affected the results and consequently the conclusions. There were also discrepancies detected in data for some days and such data/days were not considered.

# CHAPTER 6: CONCLUSIONS AND RECOMMENDATIONS

This chapter concludes the study by addressing the aim and specific objectives of the study as identified in section 1.3, and makes recommendations of the opportune system and of future studies as follows:

**Technical make-up of the TS-SWH and PVT Systems:** The main components of the solar water heating systems are the collector, storage tank, piping, insulation and glazing, however, the PVT systems deviate, with the solar modules (and accessories associated with it) that are placed on the surface of the collector for the generation of electricity.

**Performance of the TS-SWH and PVT Systems**: Based on the items listed in section 3.3.1, the performance parameters of these systems were learned to be:

$V_{\_Solar}$: Cumulative volume of hot water passing through the collector ($m^3$), $F_{\_Solar}$: Flow of Working fluid in the collector (l/h), $T_{\_hot\_Solar}$: Temperature at the outlet of the collector in (˚C), $T_{\_cold\_Solar}$: Temperature at the collector inlet in (˚C), $E_{\_th\_Hot\_water}$: Cumulative thermal Energy of the hot water in (kWh), $P_{\_Hot\_water\_}$: Power associated (saved) with hot water in (kW), $T_{\_hot\_Hot\_water}$: Temperature of hot water exiting the storage tank in (˚C), $E_{\_ele\_ehe}$: Cumulative Energy used by the electric element in (kWh) and $P_{\_el\_ehe}$: Power consumed by the electric element in (kW), while the factors that are affecting the performance, parameters are: $R_{\_Global}$: Global radiation ($W/m^2$), $T_{\_Ambient}$: Ambient temperature (˚C), $E_{\_th\_Solar}$: Cumulative solar thermal energy incident on the collector in (kWh), $F_{\_Solar}$: Solar Power incident on the collector in (kW), $T_{\_cold\_Hot\_water}$: Temperature of cold-water inlet to the storage tank in (˚C), Covering factor, and mass flow rate.

These performance parameters and factors concur with those discussed in section 2.4.; the most crucial factor is however the global radiation since other factors such as ambient temperature and energy incident on the collector depend on the global radiation. Additionally, without the global radiation the thermosiphon phenomenon as well as solar water heating are not possible.

This study concludes that the PVT system, solar cell choice is based on one’s needs, since pc-si PV modules give higher total energy output compared to a-si PV modules. However, the a-si gives more thermal useful energy and, thus, a higher solar contribution in water heating, hence the a-si cells requires less auxiliary thermal energy and have higher solar fraction than pc-si (12). Therefore, if one prioritizes hot water production over electricity then the a-si cells are the best option. The thermosiphon water heater cannot be judged against this feature since they do not possess solar cells.

Based on the previous claim, some PVT systems have managed to completely cover the household demand and there is surplus of electricity that can be sold to the grid, while the total domestic hot water demand is not completely covered. Sometimes even with a high solar irradiance the electrical demand also experiences significant peaks, which could not be covered by the PVT (12), hence making the PVT systems not 100% reliable throughout the year. However, Namibia receives more solar radiation than the UK, hence better results are anticipated under Namibian conditions.

It was also concluded that the high collector flowrate results in high electrical output (7). The electrical output of the PVT system also increases linearly with the increase in covering factor due to the proportionally larger surface area of the PV module, however there is a reduction of the amount of hot water demand covered.

Another finding is that with the PVT configuration both the outlet temperature and tank temperatures begin to increase from around 10:00h and reach their highest points at around 14:00h, because the solar radiation is robust enough to heat the water from 10:00h. There is a gradual increase in water temperature from that time until it starts to reduce around 15:00h, because of the reduction in solar radiation. However, with the thermosiphon systems, it was noted that the working fluid starts to flow through the collector from around 8:53h although the radiation increases as from sun rise. This means that the radiation of about 630 W/m$^2$ is needed for the working fluid to flow through the collector (thermosiphon effect to begin). The flow of working fluid in the collector is highly affected by the global radiation, this is to say that when the global radiation is altered the flow of the working fluid in the collector is also affected. Low global radiation results in a decreased flow of working fluid in the collector. This difference (in time) could not have been due to the solar water heater configuration but the locations, hence the PVT system is expected to function as early as 8:53 just like the Thermosiphon system, if it was placed in Windhoek, Namibia.

In the thermosiphon systems, the ambient temperature, just like the global radiation increases from sunrise and tends to decrease from around sun set, hence concluding that the ambient temperature is dependent of the global radiation. However, unlike the global radiation, ambient temperature is not affected by atmospheric conditions dramatically, there is however a gradual decrease and increase in the ambient temperature, respectively. Just like ambient temperature, $P_{\_Solar}$ also depends on the radiation; implying that $P_{\_Solar}$ exists between sun rise and sunset. Additionally, $P_{\_Solar}$ gives rise to $F_{-solar}$ and $E_{\_th\ Solar}$. It can be concluded that there is enough radiation to heat the water in Otjomuise in the month of April, since there was no need for the electric element to take over the heating of water; however, a study is needed for all year long in order to arrive at concrete conclusions.

**Economic analysis of TS-SWH and PVT systems:** Better economic figures for PVT systems were obtained for locations with higher available solar radiation. A considerable increase in LCS can be obtained when subsidies are considered, indicating the need of state subsidies in order to promote the installation of these systems (1). This should also be applicable to Namibia who does not seem to have subsidies in place to motivate Namibians to install the solar thermal hot water systems. Henceforth, these systems are expected to perform better under the Namibian conditions since the high recorded solar radiation of about 1100W/m$^2$ in comparison to other countries in which they are installed. About 44 kWh of energy is saved by the TS-SWH monthly in water heating hence, savings of about N$ 1 019.04 annually and a return on investment of 7 years 8 months This is a very good economic result since the lifespan of the system is 20 years, the client would be heating water free of charge for about 12 years. In comparison, PVT systems were found to have longer payback periods of 20 years and more.

**Environmental impacts and benefits of TS-SWH and PVT systems:** The total avoided $CO_2$ by this TS-SWH of 1.2 $m^2$ collector area is of about 6300 kg in its lifespan of 20 years, however 1518.2 kg of $CO_2$ was emitted during the manufacturing process of this TS-SWH. This means that the manufacturing process is not entirely clean. About 12.8t of $CO_2$ is avoided by the PVT systems of the same collector area over their lifespan of 20 years (2). The PVT system achieved more $CO_2$ emissions savings in comparison to the TS-SWH of the same aperture area.

Based on the findings and conclusions from the study, the following recommendations are made:

- Installation of the PVT systems for both domestic and commercial use country wide in order to reduce the electricity demand and environmental impacts arising from the generation of electricity from conventional methods;
- A study of the PVT systems installed in Namibia (under Namibian conditions) as well as an analysis of all year round data collected for the TS-SWH installed in Otjomuise for more reliable comparisons.
- Formulation and implementation of policies and regulations inclusive of subsidies that will encourage consumers to install the solar water heaters, because subsidy associated with the solar water heater has a positive effects on economic viability (9).
- To construct solar water heaters from locally available materials in order to save cost and to create employment.

This chapter concluded that the hybrid PVT system is an opportune system for Namibian condition, since it has demonstrated better cogeneration efficiency and more voided $CO_2$ although a study of this system installed in Namibia is recommended prior.

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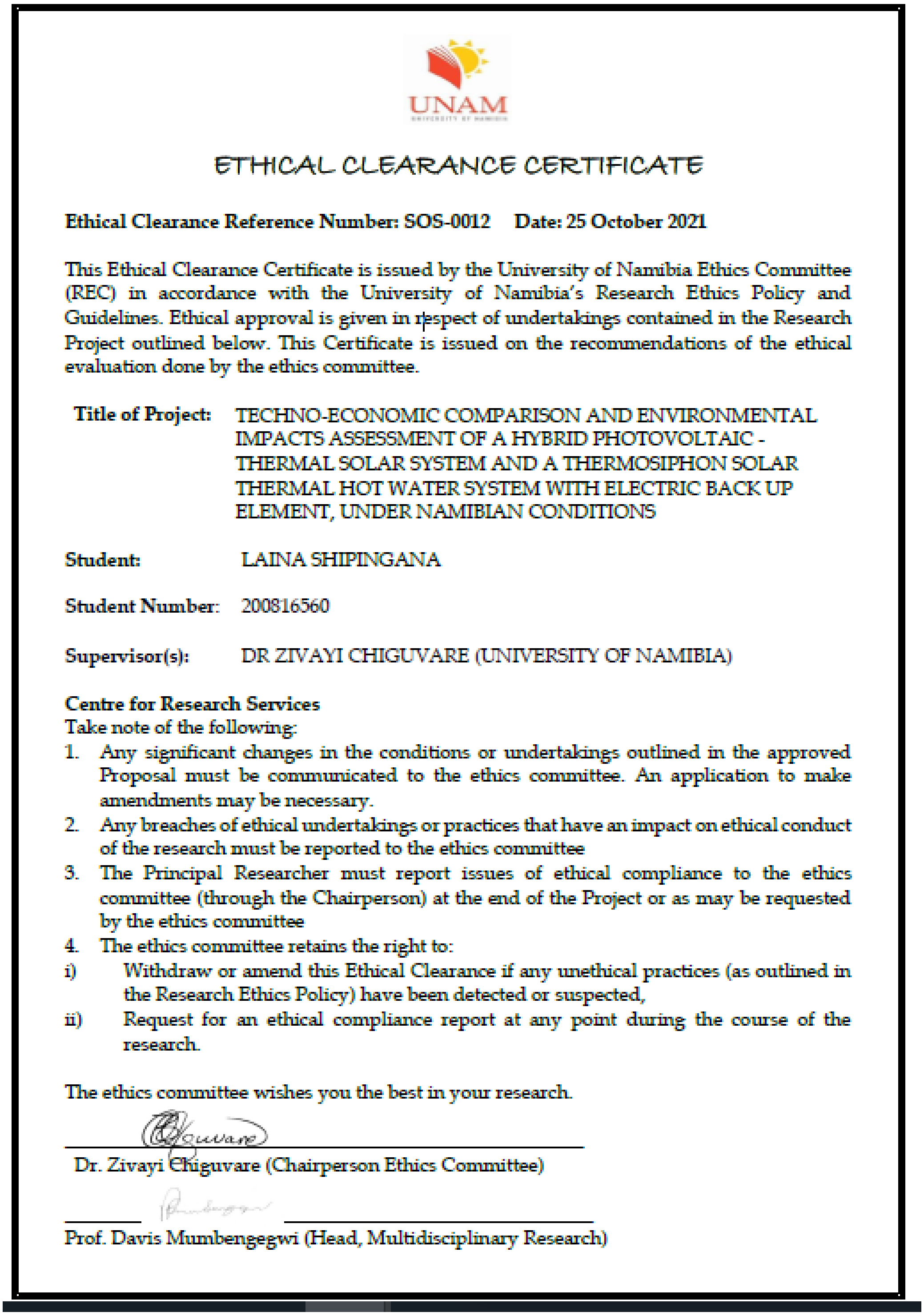
# APPENDIX A: ETHICAL CLEARANCE CERTIFICATE



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## ETHICAL CLEARANCE CERTIFICATE

**Ethical Clearance Reference Number: SOS-0012** **Date: 25 October 2021**

This Ethical Clearance Certificate is issued by the University of Namibia Ethics Committee (REC) in accordance with the University of Namibia's Research Ethics Policy and Guidelines. Ethical approval is given in respect of undertakings contained in the Research Project outlined below. This Certificate is issued on the recommendations of the ethical evaluation done by the ethics committee.

| | |
|---|---|
| **Title of Project:** | TECHNO-ECONOMIC COMPARISON AND ENVIRONMENTAL IMPACTS ASSESSMENT OF A HYBRID PHOTOVOLTAIC - THERMAL SOLAR SYSTEM AND A THERMOSIPHON SOLAR THERMAL HOT WATER SYSTEM WITH ELECTRIC BACK UP ELEMENT, UNDER NAMIBIAN CONDITIONS |
| **Student:** | LAINA SHIPINGANA |
| **Student Number:** | 200816560 |
| **Supervisor(s):** | DR ZIVAYI CHIGUVARE (UNIVERSITY OF NAMIBIA) |

**Centre for Research Services**

Take note of the following:

1. Any significant changes in the conditions or undertakings outlined in the approved Proposal must be communicated to the ethics committee. An application to make amendments may be necessary.
2. Any breaches of ethical undertakings or practices that have an impact on ethical conduct of the research must be reported to the ethics committee
3. The Principal Researcher must report issues of ethical compliance to the ethics committee (through the Chairperson) at the end of the Project or as may be requested by the ethics committee
4. The ethics committee retains the right to:

i) Withdraw or amend this Ethical Clearance if any unethical practices (as outlined in the Research Ethics Policy) have been detected or suspected,

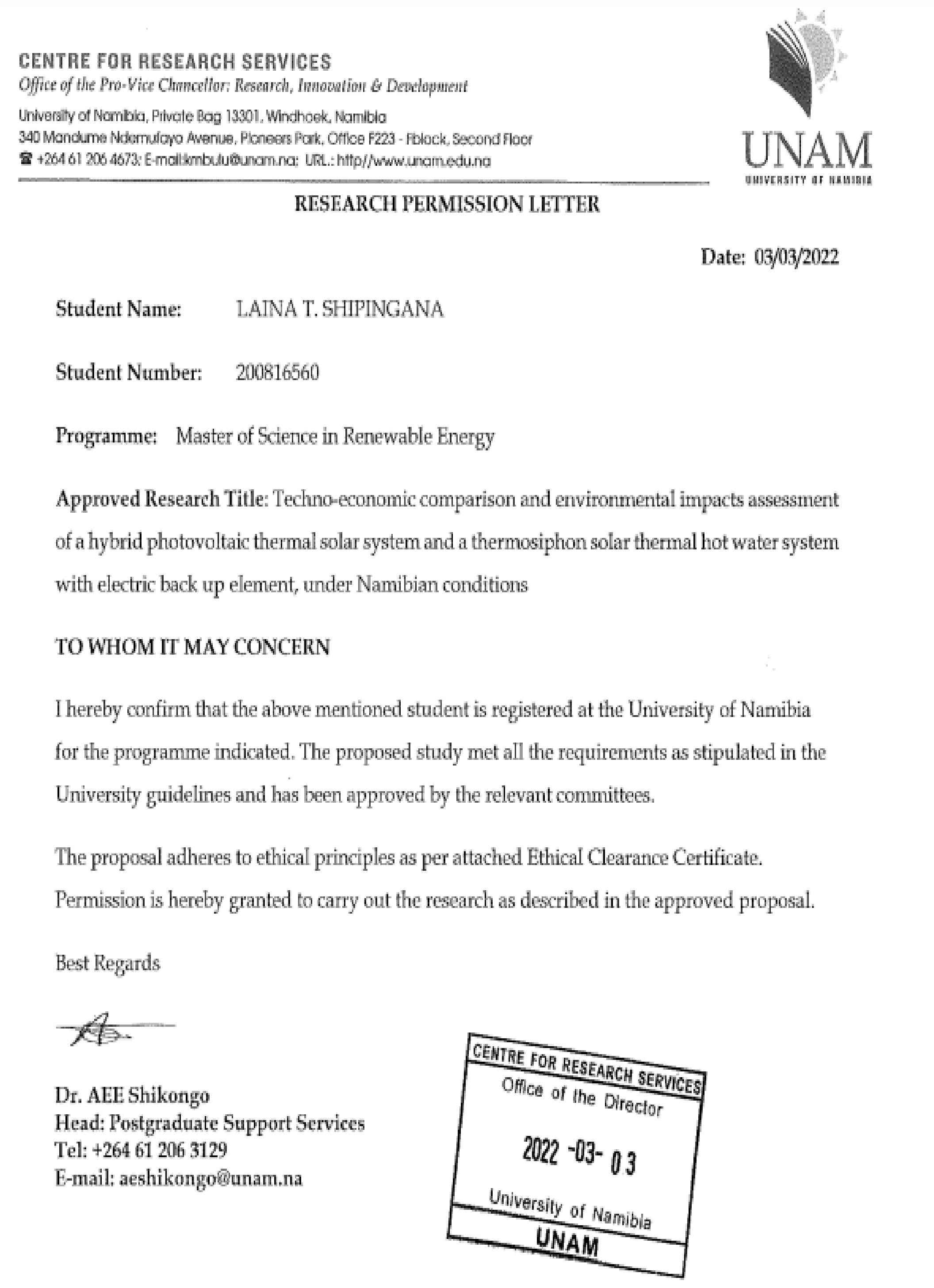
ii) Request for an ethical compliance report at any point during the course of the research.

The ethics committee wishes you the best in your research.

Dr. Zivayi Chiguvare (Chairperson Ethics Committee)

Prof. Davis Mumbengegwi (Head, Multidisciplinary Research)

# APPENDIX B: RESEARCH PERMISSION LETTER



**CENTRE FOR RESEARCH SERVICES**
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UNAM
UNIVERSITY OF NAMIBIA

**RESEARCH PERMISSION LETTER**

**Date:** 03/03/2022

**Student Name:** LAINA T. SHIPINGANA

**Student Number:** 200816560

**Programme:** Master of Science in Renewable Energy

**Approved Research Title:** Techno-economic comparison and environmental impacts assessment of a hybrid photovoltaic thermal solar system and a thermosiphon solar thermal hot water system with electric back up element, under Namibian conditions

**TO WHOM IT MAY CONCERN**

I hereby confirm that the above mentioned student is registered at the University of Namibia for the programme indicated. The proposed study met all the requirements as stipulated in the University guidelines and has been approved by the relevant committees.

The proposal adheres to ethical principles as per attached Ethical Clearance Certificate. Permission is hereby granted to carry out the research as described in the approved proposal.

Best Regards

**Dr. AEE Shikongo**
**Head: Postgraduate Support Services**
**Tel: +264 61 206 3129**
**E-mail: aeshikongo@unam.na**

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