



**DESIGN AND TECHNO-ECONOMIC IMPACT
ASSESSMENT OF A HYBRID SOLAR-ASSISTED HEAT
PUMP FOR WATER HEATING: A CASE OF CENTRAL
UNIVERSITY OF TECHNOLOGY, FREE STATE STUDENT
RESIDENCE**

By

MAMOKONE MARTHA MODISE

Dissertation submitted in fulfilment of the requirements for the degree:

Master of Engineering in Electrical Engineering

in the Department of Electrical, Electronics and Computer Systems

Faculty of Engineering, Built Environment, and Information Technology

Central University of Technology, Free State

Supervisor: Prof. K. Kusakana

Co-Supervisor: Dr S.L. Tangwe

May 2025

DECLARATION

I, MAMOKONE MARTHA MODISE, #####, do hereby declare that this research project, which has been submitted to Central University of Technology Free State for the degree: Master of Engineering in Electrical Engineering, is my own independent work and complies with the Code of Academic Integrity, as well as other relevant policies, procedures, rules and regulations of Central University of Technology, Free State. This project has not been submitted before by any person in fulfilment (or partial fulfilment) of the requirements for the attainment of any qualification.

M.M Modise

Date: **May 2025**

DEDICATION

I dedicate this dissertation to my mother, Bophaletse Piolinolla Modise; this is for us. You have ensured, with guidance, that a dream I once shared with you is possible. Thank you for doing it with love. Thank you for the cups of coffee in the middle of the night when I was studying, a blanket on my shoulder when it was cold and constantly asking if I was OK. Your faith in me made things possible even when I had given up. Thank you, Ma, for building and reminding me of the strength I have, especially at my lowest. Thank you for your presence through it all.

To my son Shaun Kananelo Modise, I am humbled and blessed that God chose you for me. Thank you for being kind to me and filling me with so much love, hope and happiness. Your presence has certified that God is indeed gracious.

To all those who knowingly and unknowingly helped me, your help has added to making the completion of my dissertation possible. Thank you.

Above all, thank you, God, for being the source of my strength and wisdom. I took a step, and you took three more. I trust in You with all my heart, leaning not on my own understanding. Proverbs 3:5.

ACKNOWLEDGMENTS

I would like to say thank you to my supervisors, Prof K. Kusakana and Dr S. L. Tangwe; I only told you what I would love to do academically. You gave it life, nourished it, made it possible, and most importantly, made it a reality. Thank you for your guidance, time, patience and support throughout.

LIST OF ABBREVIATIONS

AAR	Annual average cost
ASHP	Air source heat pump unit
AS – SAHP	Air Source Solar Assisted Heat Pump
ANOVA	Analyses of variance
COP	Coefficient of performance
CPC	Compound parabolic collector reflector
CUT	Central University of Technology
DAS	Data acquisition system
DC	Direct current
DHW	Domestic hot water
DX-SAHP	Direct-expansion solar-assisted heat pump
EF	Energy factor
FV	Future value
GSHP	Geothermal heat pump
HES	Hybrid solar/electric water heating system
HHWS	Hybrid hot water systems
HPWH	Heat pump water heater
HSAASHP	Hybrid solar assisted air source heat pump water heater
IDA ICE	IDA indoor climate and energy software
IX-SAHP	Indirect -expansion solar assisted heat pump
J	Joule

kW	Kilowatt
kWh	Kilowatt-hour
L	Liter
MATLAB	Matric laboratory
MNLR	Multi nonlinear regression model
NPV	Net present value
ODE	Ordinary differential equation
PBP	payback period
PV	Photovoltaic solar collector
PV – ASHP	Photovoltaic assisted air source heat pump
PV – SAHP	Photovoltaic Solar Assisted Heat Pump
PV/T – ASHP	Photovoltaic/ solar thermal assisted air source heat pump
RH	Relative humidity
RMSE	Root mean square error
ROI	Return on investment
SA-ASHP	Solar assisted air source heat pump water heater
SAHP	Solar assisted heat pump water heater
SCs	Solar collectors
SD	Sample days
SF	Solar fraction
SPP	simple payback period
ST – ASHP	Solar thermal assisted air source heat pump
SWH	Solar water heater
USB	universal serial bus cable

W

Watt

ABSTRACT

This research emphasizes the important benefits of retrofitting an outdated and inefficient electric boiler with solar collectors and an Air Source Heat Pump (ASHP) unit making it a Hybrid Solar-Assisted Air Source Heat Pump (HSAASHP) water heating system in a university residence. The study showed that the HSAASHP water heater system offers major reductions in energy consumption and operational expenses, making it both economically feasible and energy efficient. The proposed HSAASHP water heating system greatly reduced electricity expenditures by reducing energy usage from 151 128.9 kWh to 41 036.8 kWh annually. Over the seasons, the Energy Factor (EF) of the HSAASHP water heater ranged from 3 to 5.2, with summer exhibiting the highest efficiency.

The techno-economic analysis further verified the HSAASHP water heater viability with a payback period (PBP) of 2.19 years, a break-even point on the third year, an annualized return on investment (AROI) of 14.39% at the end of its 15-year operation, an investment gain of R2 624 547.17 (139 101 USD) and a profit margin of 87%. Its estimated total net present value (NPV) was R3 027 461.79 (160 455.5 USD), demonstrating its long-term economic advantages.

To predict an Energy Factor (EF) of the HSAASHP water heater, a multi-nonlinear regression (MNLN) model was developed. The MNLN model's r^2 value of 0.9641 illustrated that it was highly accurate, meaning 96% of the difference in the target variable of the model was elaborated by the model. The model further validated its reliability by confirming a good correlation between the expected and measured EF values.

This research tackles the urgent demand for economical and energy-efficient water heating systems in South African university residences. It offers an affordable method to lower energy use, enhance stability in the economy, and support environmental preservation. The favourable results of this research at the CUT Mannheim ladies' residence suggest that other university residences should effectuate similar retrofitting of water heating systems.

The viable approach of this study, by merging economic viability and technological innovation, minimizes the electrical dependency in higher education sectors, which is in line with South Africa's larger objectives of sustainability and energy efficiency.

TABLE OF CONTENTS

DECLARATION	i
DEDICATION	ii
ACKNOWLEDGMENTS	iii
LIST OF ABBREVIATIONS	iv
ABSTRACT	vii
CHAPTER 1: INTRODUCTION	1
1.1 BACKGROUND	1
1.2 PROBLEM STATEMENT	4
1.3 AIM AND OBJECTIVES	4
1.4 RESEARCH QUESTIONS	5
1.5 LIMITATIONS AND DELIMITATIONS	6
1.6 PUBLICATIONS DURING THE STUDY	6
1.7 THESIS OUTLINE	6
CHAPTER 2: LITERATURE REVIEW	8
2.1. INTRODUCTION	8
2.2. RENEWABLE ENERGY WATER HEATING TECHNOLOGIES	8
2.3. DISCUSSION	22
2.4. SUMMARY	22

CHAPTER 3: METHODOLOGY	24
3.1. INTRODUCTION	24
3.2. RESEARCH METHOD	25
3.3. LIST OF MATERIALS AND APPROACH.....	26
3.4. DATA COLLECTION AND PROCESSING.....	31
3.5. THEORETICAL AND MATHEMATICAL INSTRUMENT.....	32
3.6. EXPERIMENTAL SETUP	36
3.7. SUMMARY	40
CHAPTER 4: PERFORMANCE ANALYSIS AND ECONOMIC VIABILITY OF HSAASHP WATER HEATER.....	41
4.1. INTRODUCTION.....	41
4.2. PERFORMANCE OF THE INPUT AND OUTPUT PARAMETERS OF THE HSAASHP WATER HEATER IN A YEAR.....	41
4.3. ANALYTICAL FINDING OF THE PROCESSED DATA.....	44
4.4. TECHNO-ECONOMIC ANALYSIS.....	48
4.5. SUMMARY	55
CHAPTER 5: DEVELOPMENT AND VALIDATION OF MATHEMATICAL MODEL TO PREDICT THE ENERGY FACTOR OF THE HSAASHP WATER HEATER	56
5.1. INTRODUCTION	56

5.2. SAMPLE DAYS AND PROCESSED DATA SET USED TO TRAIN THE NONLINEAR REGRESSION MODEL	56
5.3. DEVELOPMENT OF THE MULTI-NONLINEAR REGRESSION (MNLr) MODEL	58
5.4. RELIEFF USED TO DETERMINE THE WEIGHT AND RANK OF THE INPUT PARAMETERS	61
5.5. VALIDATION OF THE MODEL	62
5.6. COMPARISON OF MEASURED EF AND MODELLED EF USING ONE-WAY ANOVA.....	65
5.7. SUMMARY	67
CHAPTER 6: CONCLUSION	69
6.1. FINAL CONCLUSIONS.....	69
6.2. SUGGESTIONS FOR FURTHER RESEARCH.....	70
REFERENCES.....	72
APPENDICES	87
APPENDIX A: INPUT AND OUTPUT PARAMETERS PERFORMANCE OF THE HSAASHP WATER HEATER	87
APPENDIX B: PERFORMANCE OF THE HSAASHP WATER DURING THE SECOND PHASE OF OPERATION.....	88
APPENDIX C: OPERATING PERFORMANCE OF AN ELECTRIC BOILER AND HSAASHP WATER HEATER	90

LIST OF FIGURES

Figure 1.1: Distribution of electrical energy generated from different sources	1
Figure 2.1: Stand-alone solar water heater	10
Figure 2.2: SWH indirect circulation.....	10
Figure 2.3: SWH direct circulation.....	11
Figure 2.4: Detailed chart of heat pump water heaters	12
Figure 2.5: Integrated-type ASHP unit.....	14
Figure 2.6: Split type ASHP unit	14
Figure 2.7: Geothermal heat pump	16
Figure 2.8: HSAASHP water heater classification	18
Figure 2.9: Indirect SAHP water heater	20
Figure 2.10: Direct SAHP water heater.....	21
Figure 2.11: Parallel SAHP water heater	21
Figure 3.1: Downloading of data from solar collectors' logger.....	32
Figure 3.2: Designed and installed HSAASHP water heater	37
Figure 3.3: HSAASHP water schematic diagram.....	39
Figure 4.1: Monthly relative humidity, temperature, and energy factor.....	43
Figure 4.2: HSAASHP water heater electrical energy consumption and EF	43
Figure 4.3: Daily solar collectors energy usage, energy consumption and SF.....	45
Figure 4.4: Daily ASHP energy usage, energy consumption and COP.....	47
Figure 4.5: Stand-alone ASHP and HSAASHP water heater COP comparison	48

Figure 4.6: Annual electrical consumption of an electric boiler and HSAASHP water heater.....	50
Figure 4.7: Techno-economic analysis graph based on rand saving tariff.....	53
Figure 5.1:Flow diagram of the development of the MNLR model	60
Figure 5.2: Calculated EF vs predicted EF using train set data	61
Figure 5.3: Weights ranking of predictors according to importance with the Energy Factor.	62
Figure 5.4: Calculated EF vs predicted EF using validating set data.....	64
Figure 5.5: ANOVA plots of the predicted and modelled energy factors (test data set) ..	67

LIST OF TABLES

Table 3.1: Devices, sensors and data loggers used in the experimental setup.	26
Table 3.2: Uncertainties of the measured and derived quantities	29
Table 3.3: Cost of the line items for the sensors, transducers and hot water devices used.	30
Table 4.5: Operating performance of an electric boiler and HSAASHP water heater	49
Table 4.6: techno-economic analysis of a HSAASHP water heater	52
Table 5.1: Test data set of a HSAASHP water heater	57
Table 5.2: Validating data set of the input parameters and desired output of the HSAASHP water heater performance	63
Table 5.3: Statistics based on the predicted and modelled outputs with the Multi Non- Linear Regression model	66

CHAPTER 1: INTRODUCTION

1.1 BACKGROUND

South Africa emits more greenhouse gases than any other country in Africa. [1]. The country's dependency on coal in the industrial economy was established in the 1970s [2], which is why coal serves as a primary source of electricity generation [3]. In 2022, coal was the dominant electrical source compared to other electrical sources (nuclear, diesel and gas, hydro, pumped storage, wind, and solar), accounting for 80.1% of electricity generated in South Africa's grid. Figure 1.1 illustrates the distribution of each electrical source [4]. In recent years, the pricing of coal has become more market-oriented, as the price of coal was artificially depressed during the price regulation period. The price has risen quickly due to its resource, production, and environmental costs, as well as the supply and demand dynamics on the market [5]. Nene et al. [5], using the Vector Error Correction Model, proved that an increase in coal prices results in an increase in electricity prices.

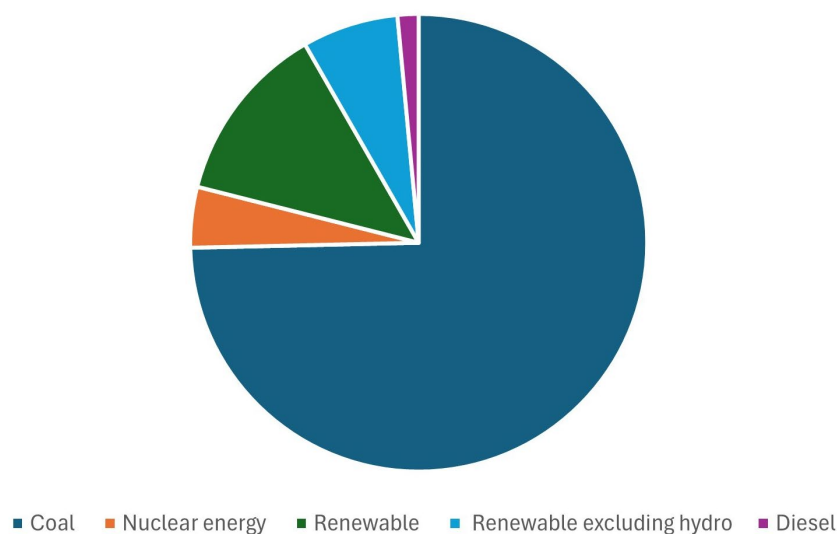


Figure 1:1: Distribution of electrical energy generated from different sources

In standard residential buildings in South Africa, geysers are used for heating water and may consume 40–60% of the building's energy [6]. In commercial buildings such as hotels, hospitals, prisons, and student residences in universities, geysers are used to heat water [7]. The commercial sector comprises 40% of electric boiler usage for heating water, with university residences being the primary consumers. [8]. Universities in South Africa are under increasing pressure to control electricity use and expenditures by becoming more energy-efficient [9]. University buildings serve various purposes, including education (lecture rooms, libraries, and laboratories), administration (offices), and educational support (residential facilities). Education and administrative buildings consume moderate amounts of electricity, while university residences have a higher electricity consumption.

Geysers and boilers are hot water storage tanks with a resistive element used for heating water. The difference between them is storage capacity; boilers have a capacity greater than 500 L but less than 3 000 L, while geysers have common sizes, such as 150 L, 3 kW and 200 L, 4 kW[8],[6]. This convectional technology uses an enormous amount of electricity when heating water and has standby losses due to heat loss in the hot water to the geyser casing and outlet pipe [10], [11]. The operational cost of an electric boiler is high due to increasing electricity tariff rates and significant energy consumption from system inefficiencies. The literature shows that for every 1 unit (1 kWh) of electricity consumed, 0.912 units (Joules) of thermal energy are produced by a boiler [12].

Solar water heating (SWH) systems have proved to be an effective technology for converting solar energy into thermal energy, with an efficiency of approximately 50–70% when compared to an electrical direct conversion system, which has an efficiency of merely 17% [13]. Replacing electrical geysers with SWH would have significant cumulative savings

over 10 years and would result in overall electricity savings of between 55% and 85%, depending on the model, consumption patterns, and available local solar energy [14], [15].

An Air Source Heat Pump (ASHP) is an energy-efficient mechanical device that uses electrical energy to transmit heat from the air to the water inside a tank to supply sanitary hot water. Additionally, it is popular compared to other types of water heating systems due to its lower initial cost and ease of maintenance. [16], [17], [18][19]. There are two ASHP water heater categories, namely integrated (add-on) and split (retrofit); their payback period (PBP) is 3.9 and 5.2 years, respectively [19].

Hybrid hot water systems supply the hot water demand by combining solar thermal collectors with other technologies, such as electric or gas water heaters, as auxiliary systems [20]. Using a hybrid hot water system that combines solar collectors with a heat pump can increase hot water production by 40% compared to a stand-alone solar system. [21]. The PBP for a wind-PV hybrid-powered heat pump water heater system is 3 years and 9 months, while the PBP for a hybrid solar and gas water heater is 7.2 years. [22].

There is a need to address the challenges of using electricity to operate electric boilers, particularly in a university setting. This study proposes a combination of a solar collector, and an air source heat pump called a Hybrid Solar-Assisted Air Source Heat Pump (HSAASHP) water heater. This project will be implemented in the Mannheim Ladies' Residence at Central University of Technology, Free State. The 2 000 L boiler uses a 24 kW electric boiler element for sanitary water. The research involves the design and installation of the energy-efficient HSAASHP water heater and the deployment of a Data Acquisition System (DAS) to monitor its performance in a bid to assess the techno-economic benefits of the HSAASHP water heater. The outcome of this study should be an energy-efficient hot water system which is less costly to maintain.

1.2 PROBLEM STATEMENT

Mannheim Ladies' Residence uses an inefficient electric boiler (2 000 L, 24 kW), and its electricity source comes from the Eskom grid, generated by a coal thermal power plant. [23],[24]. The associated electrical consumption and cost of hot water heating in the Mannheim residence are daunting, and the production of hot water from the electric boiler contributes to a significant increase in global warming potential and climate change [23]. This work proposes the HSAASHP water heater to the stated issues.

However, the process of obtaining useful information through a DAS to monitor the performance of the HSAASHP water heater is costly and time-consuming [25].

Hence the need for life cost analysis of the HSAASHP water heater needs to be conducted using actual system price costs and day-to-day operation of the HSAASHP water heater as references.

Furthermore, the use of a surface response model in an ASHP water heater and limited information is available in the literature on the use of a surface response model for the prediction of the energy factor of an HSAASHP water heater at a student residence[24].

1.3 AIM AND OBJECTIVES

The aim of this research is to design and model the energy factor of an HSAASHP water heater and perform a techno-economic analysis of the system.

The objectives of the research are as follows

- To design and install an efficient HSAASHP water heater.

- To determine the Coefficient Performance (COP) of an ASHP, the Solar Factor of solar collectors, and the Energy Factor (EF) during the operation time in the HSAASHP system.
- To develop a response surface model to predict the Energy Factor of the proposed HSAASHP system.
- To assess the economic benefits of retrofitting the existing boiler with HSAASHP.

1.4 RESEARCH QUESTIONS

- How can a DAS be designed and built to monitor the performance of the HSAASHP water heater?
- How can a Solar Fraction (SF) from the solar collectors be determined during operation time in the HSAASHP?
- How can a COP of the ASHP be determined in the HSAASHP water heater during operation time?
- How can an EF of the HSAASHP water heater be determined during the operating time for a day and the entire monitoring period?
- How can a multi-linear regression model be developed to predict the EF of the HSAASHP water heater with electrical energy consumed, ambient temperature, relative humidity and wind speed as the input parameters?
- How can a HSAASHP water heater demonstrate economic viability compared to conventional water heating systems?

1.5 LIMITATIONS AND DELIMITATIONS

The study is limited to one experiment, and it is solely at the CUT residence.

1.6 PUBLICATIONS DURING THE STUDY

Modise, Mamokone M., Kanzumba Kusakana, and Stephen Tangwe. "Techno-Economic Analysis of Hybrid Solar-Assisted Air Source Heat Pump Systems in University Residences." In *2025 33rd Southern African Universities Power Engineering Conference (SAUPEC)*, pp. 1-6. IEEE, 2025.

1.7 THESIS OUTLINE

This thesis has been divided into six chapters, with the main research results being presented in Chapters 4 and 5.

Chapter 1 comprises the research background, the problem statement, the aim and objectives, and the descriptions of the other chapters that make up the full thesis.

Chapter 2 presents a literature review on different technologies of water heating systems, their techno-economic analyses, and previous studies conducted in relation to the current study. Furthermore, key findings are discussed.

Chapter 3 A research methodology encompasses the research design, the derivation of the response surface model to predict the EF, and the method of implementation of the techno-economic viability of the installed HSAASHP water heater.

Chapter 4 presents the analytic and modelled results as part of the result and discussion chapters. It deals with both the analysis of the factors influencing the performance of the HSAASHP water heater based on the processed and collected data from the installed data loggers and the development of the response surface model to predict the EF of the HSAASHP water heater. It also discusses the techno-economic analysis of the installed HSAASHP water heater, which was conducted and compared to that of the baseline from the retrofitted electric boiler. The PBP of the HSAASHP water heater and baseline systems were calculated and compared, with reference to the possible savings at the end of the project lifetime.

Chapter 5 discusses a mathematical model of the HSAASHP water heater that has been designed, developed and presented in this chapter. The multi-nonlinear regression model was developed to determine the modelled EF and compare it with the calculated EF. Different data sets are used to train and validate the model.

Chapter 6 entails a general discussion, summative conclusion, and general recommendations of the whole thesis.

CHAPTER 2: LITERATURE REVIEW

2.1. INTRODUCTION

This chapter presents the background literature on electric geysers or boilers and energy-efficient water heaters with an emphasis on HSAASHP water heaters and discusses their efficiency, payback time, operation, and drawbacks.

This chapter consists of five sections, namely the introduction, background of different water heating technologies (solar water heater, stand-alone heat pump water heaters, hybrid hot water systems and HSAASHP), different mathematical models developed to determine the operations of heat pump water systems, and a summary of the chapter.

2.2. RENEWABLE ENERGY WATER HEATING TECHNOLOGIES

2.2.1. Solar Water Heater (SWH)

Solar water heating systems have been demonstrated to be an efficient technology for converting solar energy into thermal energy with an efficiency of approximately 50–70% compared to solar electrical direct conversion systems, which have an efficiency of 17% [13]. Typically, it is made up of a solar collector and storage tank [26]. The schematic diagram is illustrated in Figure 2:1 [27]. There are numerous types of solar collectors on the market, and they can be broadly classified as either a flat plate, evacuated tube, or parabolic trough [28]. For low-temperature thermal applications, such as sanitary water heating, flat plates and evacuated tube collectors are used [29]. The drawbacks of

SWHs are that solar collectors (SCs) can only provide hot water at a high rate when solar radiation is sufficient, meaning they are ineffective at night. [30].

Islam et al. [31] classified solar water heaters into two categories: direct and indirect, as illustrated in Figure 2:2 and Figure 2:3 [32]. The collector in the direct system heats water directly, whereas the collector in the indirect system heats a heat transfer fluid, which is then passed through a condenser or a heat-exchanging device to heat water [31]. Similarly, based on the circulation of working fluids, SWH circulation systems can be classified as passive or active [31]. In a passive circulation system, the working fluid circulates naturally without the assistance of a mechanical pump, whereas an active circulation system uses a mechanical pump to force the working fluid to circulate [31]. SWHs play a crucial role in both domestic and industrial sectors due to their convenience and low maintenance requirements. [13]. They have a higher capital cost compared to geysers, even though they are economical viable in the long run [33]. In 2012, the average price per square metre was R4 191[34].

Varghese et al. [35] illustrated that a solar water heating system with a Compound Parabolic Collector (CPC) reflector has a PBP of two years [35], and a study performed by Sustainable Energy Africa found that replacing electrical geysers with SWHs would have a significant cumulative saving over a 10-year period [14]. Solar water heater in India has a PBP of 2.5 years when replacing an electric boiler with it [36]. Research based on published papers confirmed that the PBP of stand-alone solar water heaters can range from 2.98–8.24 years, depending on the system design, capital cost and the hot water consumption [37].

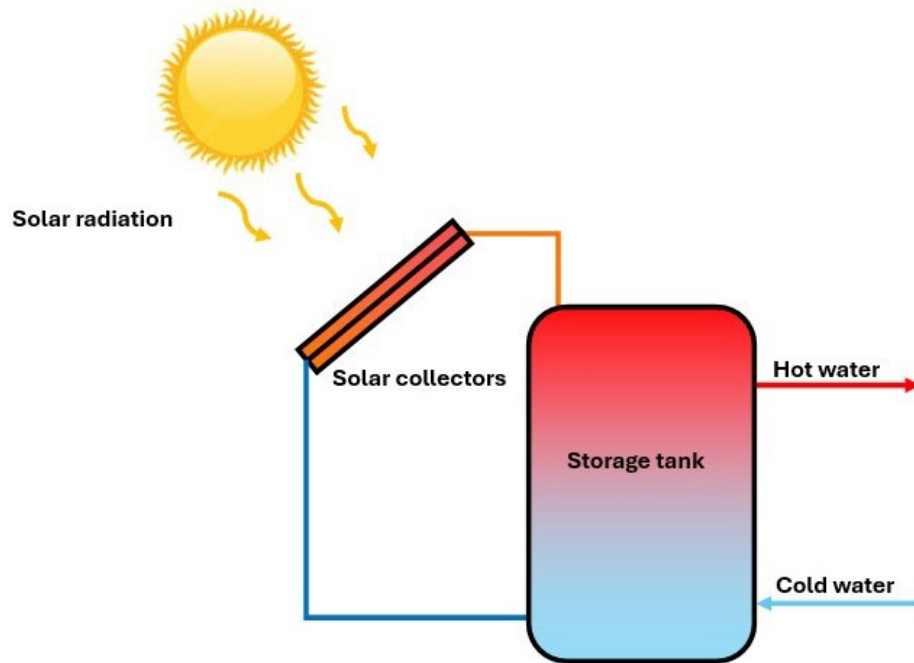


Figure 2:1: Stand-alone solar water heater

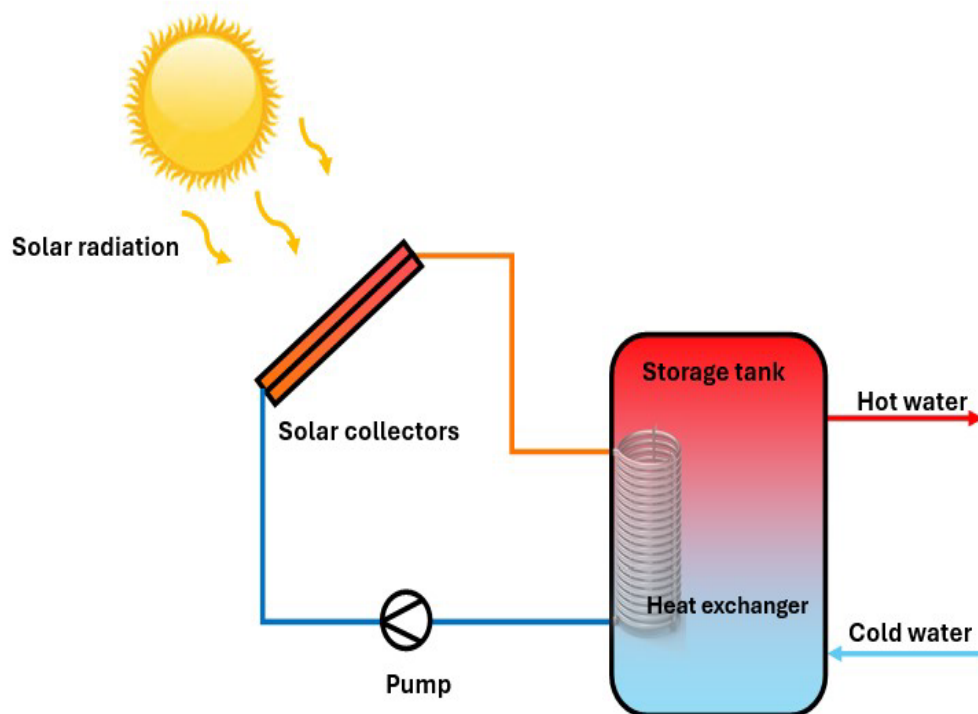


Figure 2:2: SWH indirect circulation.

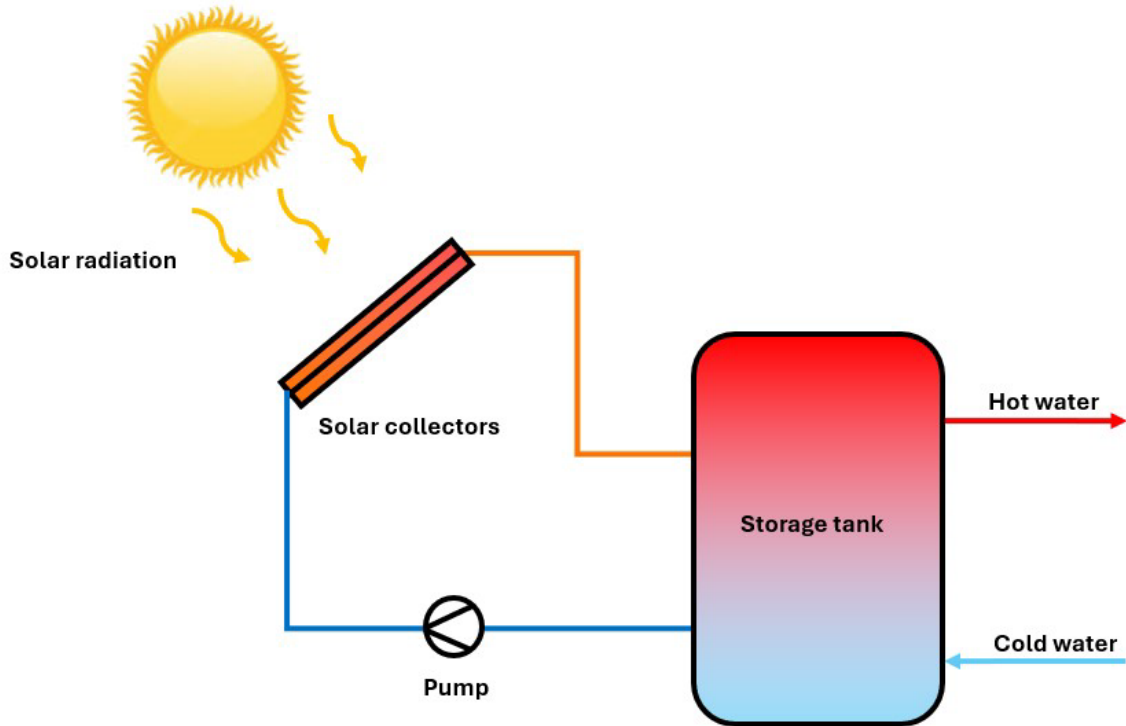


Figure 2:3: SWH direct circulation

2.2.2. Heat Pump Water Heater (HPWH)

HPWHs, illustrated in Figure 2.2, are energy conversion devices that use some electricity to transfer higher temperature heat from the ground, sun, or air to a building's heating and hot water circuits [38], [39]. Types of HPWHs are determined by their energy sources; among the most common types are air-source, geothermal, and solar HPWHs [40]. The COP of heat pump systems is affected by a variety of parameters, including the temperature of the low-energy source, the temperature of the delivered useable heat, the working media used, and the properties of heat pump system components [41]. For every 1 unit (kilowatt) of input electrical energy, HPWH produces three Joule of useful thermal energy due to its COP of three, and for the same amount of thermal output, it uses less electrical energy than a conventional electric water heater [42], [43].

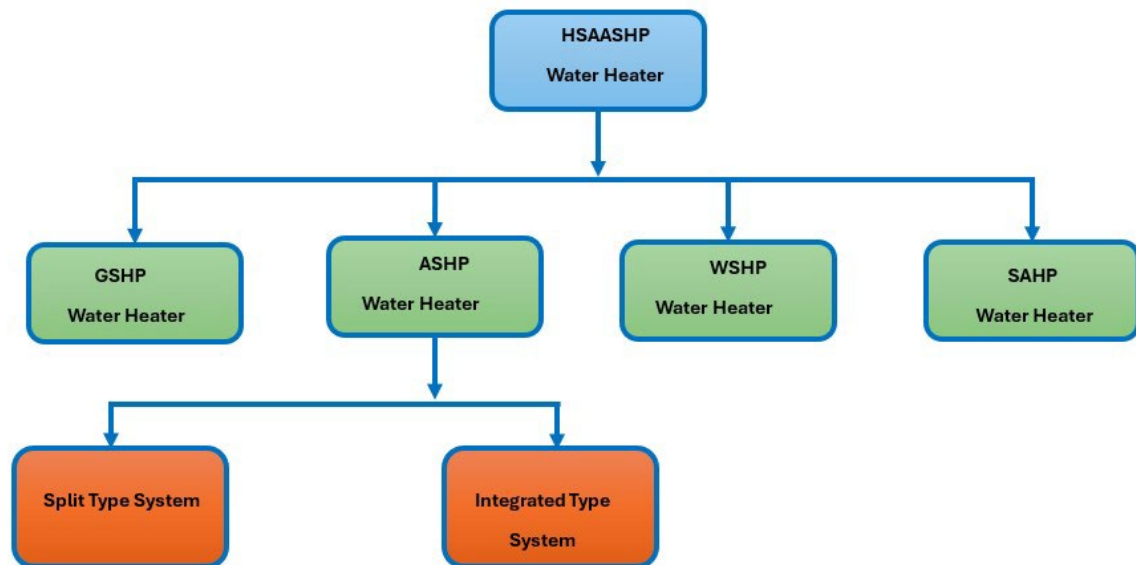


Figure 2:4: Detailed chart of heat pump water heaters

2.2.3. Air Source Heat Pump (ASHP) unit

The ASHP unit is an energy-efficient mechanical device that uses electrical energy to transmit heat from air to the water inside a tank to supply sanitary hot water [44]. In comparison to other types, it is generally considered the most popular option due to its lower capital costs and simpler maintenance [45]. One of its drawbacks is that during winter when the outdoor air temperature drops, the surfaces of the fin-tube heat exchanger outside the heat pump frost easily, which will decrease the efficiency of the heat pump unit [46].

ASHP water heaters are divided into two categories, namely integrated (add-on-) and split (retrofit)-type [47], as seen in Figure 2.3. [48]. The integrated ASHP water heater illustrated by Figure 2:5 has the water tank and ASHP unit arranged in a condensed manner,

with the condenser hidden in the water tank and the ASHP unit situated above the water tank [49].

The split-type ASHP water heater illustrated by Figure 2:6 has copper pipes linking the water tank and the ASHP unit, which is situated under the water tank [50].

Their PBP is 3.9 and 5.2 years, respectively; however, due to Eskom tariff increases over the years, the ASHP water heater PBP could reduce to 3.3 and 4.1 years, respectively [19].

Gang et al. [51] discusses ASHP water heater heating modes, namely cyclic and instantaneous modes, stating that during cyclic heating, water is cycle-heated and circulates between a water tank and a condensing heat exchanger. As the temperature of the circulating water steadily rises, condensation pressure also rises. The ASHP water system functions under dynamic conditions during the whole heating process, gradually bringing the water to the set temperature. In the instantaneous heating mode, water passes through the condensing heat exchanger only once to attain the desired temperature. It is a rather steady operating condition since the condensing heat exchanger's inlet and outlet water temperatures and condensing pressure are both constant during the heating process.

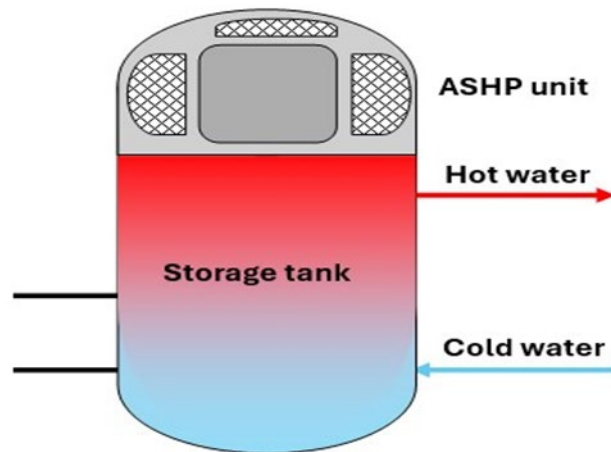


Figure 2:5: Integrated-type ASHP unit

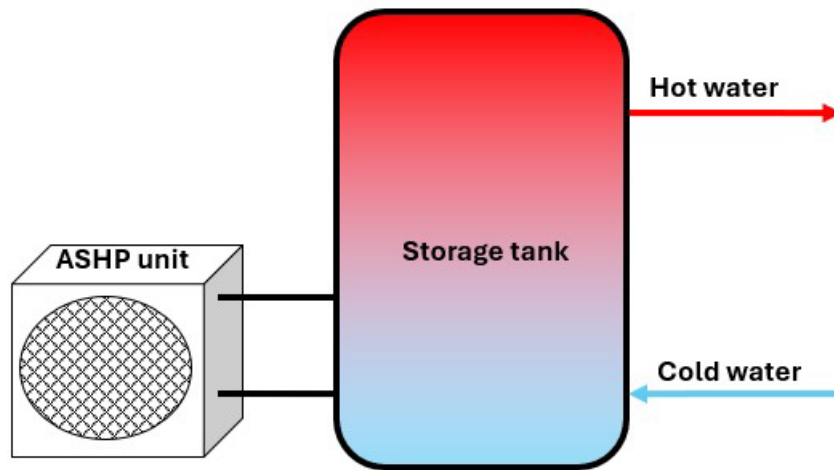


Figure 2:6: Split type ASHP unit

2.2.4. Geothermal Heat Pump (GSHP)

The GSHP illustrated by Figure 2:7 is a central heating and/or cooling system that moves heat into or out of the ground to provide heating, cooling, and frequent hot water [52]. It has four configurations, namely open loop, vertical closed loop, horizontal closed loop and closed loop configuration [53], [54] .

The advantages of this system include high energy efficiency, negligible pollution, sustainability, consistent operation, low maintenance costs, and no requirement for large, intrusive and intelligent equipment outside the structure [55]. Furthermore, a GSHP delivers reliable performance even in varying ambient temperature [56]. The disadvantages of this type of heat pump include the potential to trigger seismic activities, such as dormant volcanoes and earthquakes [57]. Additionally, there is no assurance that the energy generated from the geothermal source will surpass the capital investment due to the high installation costs of geothermal power plants [58]. The PBP is 7.4 years for a geothermal heat pump of a life span of 10 year [59].

Lohani et al. [60], using a building simulation software (IDA-ICE), analyzed and compared the energy and exergy flow for a space-heating system with different heat generation plants and found the GSHP is better than ASHP or conventional heating system. The landmark requirement of an ASHP is significantly lower than that of a GSHP [41], and the COP of a GSHP ranges from 3–5, while that of an ASHP ranges from 2.3–3.5 [60], [61].

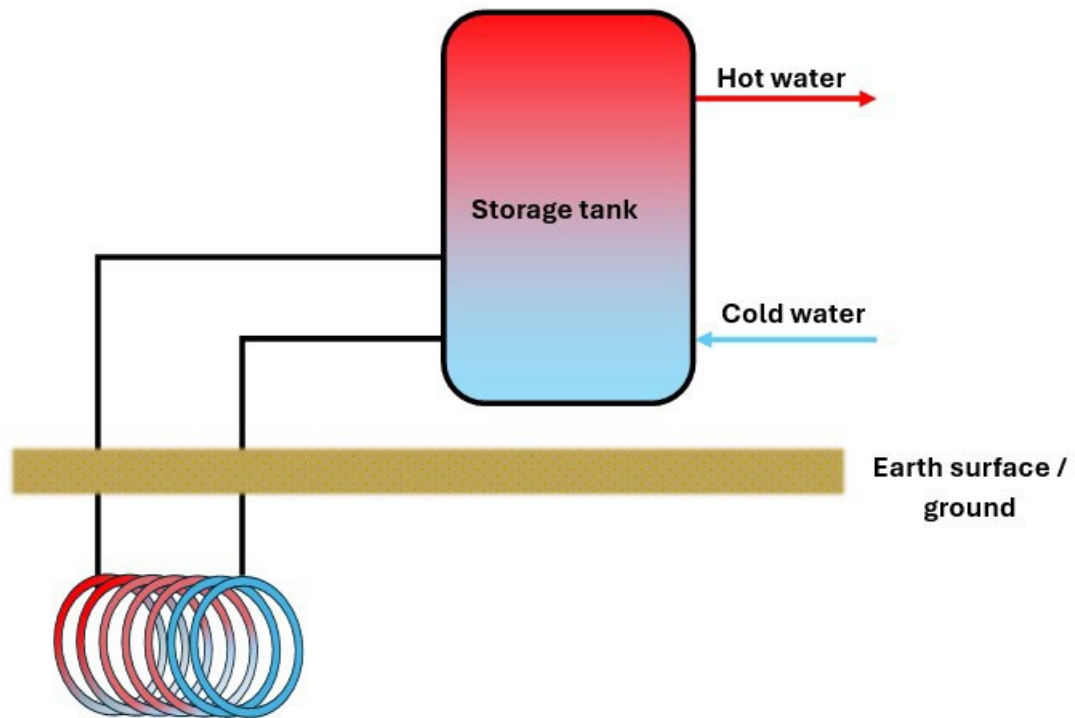


Figure 2:7: Geothermal heat pump

2.2.5. Hybrid Hot Water Heater (HHWH)

An HHWH supplies hot water demand by combining solar thermal collectors with other technologies, such as electric or gas water heaters as auxiliary systems [62]. It consists of SCs operating in the natural convection mode, a hot water tank and an electric heater [63]. A hybrid water heating system combines tank storage with small-capacity distributed water heaters and a high-efficiency distribution system to improve energy efficiency and system performance without the technical complications of interconnection [64]. Using a hybrid hot water system reduces the energy used for heating water, which reduces the energy costs [65]. Compared to conventional system it presents an energy consumption that is 54.9% lesser [66] .

Dudkiewicz et al. [65] assessed a hybrid domestic hot water system using SCs and a gas boiler and discovered that 81.4% of the energy needed to supply DHW (Domestic Hot Water) is supplied by SCs and the remaining 18.6% by a gas boiler.

Cui et al. [67] investigated the techno-economic of a hybrid PVT assisted heat pump with a life span of 25 years, and discovered the PBP is 4.15.

Chen et al. [22] studied a hybrid residential hot water system with solar and gas, both experimentally and theoretically. Their economic comparison showed that in Shanghai, the hybrid supply system has greater economic benefits than a traditional gas water heater, with a PBP of 7.2 years.

Nuntaphan et al. [21] investigated the performance of the combined solar water heater and heat pump using a simulation program and discovered that there is a 40% increase in hot water temperature when using a hybrid system than a stand-alone solar system.

2.2.6. Hybrid Solar Assisted Air Source Heat Pump (HSAASHP) water heater with a mathematical model

The HSAASHP water heater has two configurations, namely parallel and series solar-assisted heat pump (SAHP). The series water heater has two categories, namely the indirect-expansion solar-assisted heat pump (IX-SAHP) and the direct-expansion solar-assisted heat pump (DX-SAHP) [68]. Figure 2.6 illustrates the layout of the HSAASHP water heater. The different configurations are shown in Figure 2:9, Figure 2:10 and Figure 2:11 [69],[70], [71].

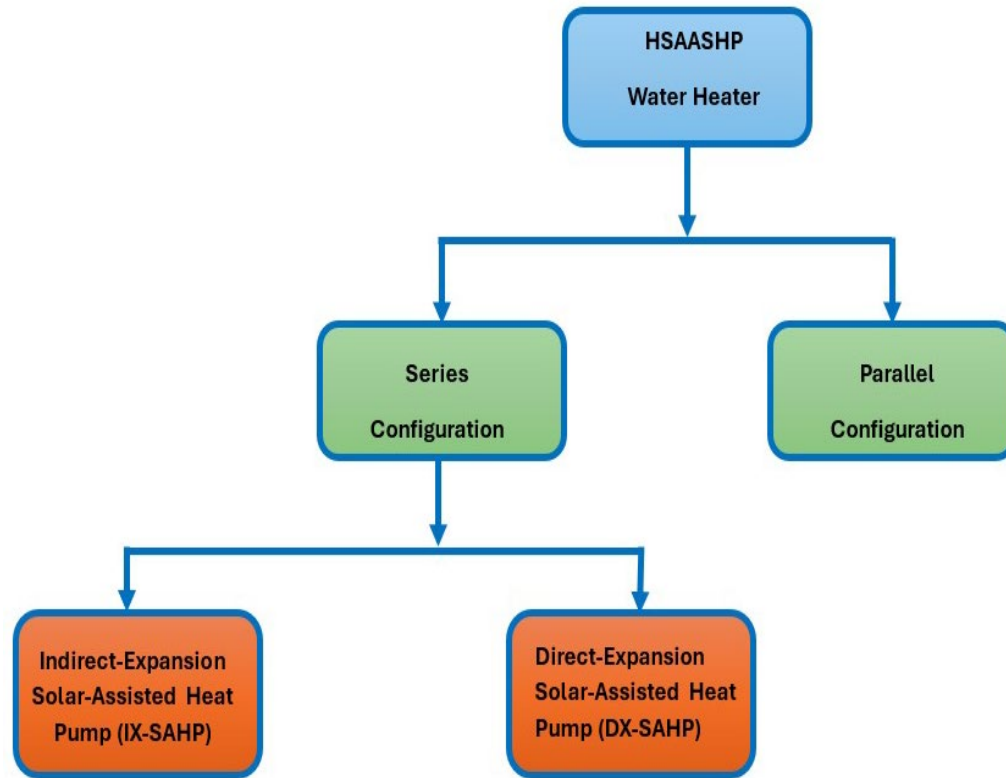


Figure 2:8: HSAASHP water heater classification

According to Li et al. [72], the Solar Assisted Air Source heat pump (SA-AHP) is a parallel configuration of the SAHP in which the heat pump absorbs energy from the ambient air, and the dual-energy source is a hybrid system where the source of energy can either come from the outdoor atmosphere or SCs. This study defines the proposed HSAASHP water heater system.

Energy supplied to the evaporator determines the configuration of the SAHP system, whether it can be connected in series, parallel or dual [73]. From the perspective of the solar process, this system operates similarly to a typical SWH system. However, the heat pump provides supplemental energy to ensure a consistent supply of hot water [74] and they both supply heat to the DHW tank independently to ensure a consistent supply of hot water [75].

Long et al. [76] stated that the combination of solar and air energy can overcome the limitations of the SC as an unstable energy source and the poor performance of the ASHP in low-temperature settings. The use of HSAASHPs improves the efficiency of both systems.

Meng et al. [77] proved that coupling SCs and an ASHP for heating purposes is a good financial solution.

Wang et al. [78] did a systematic review on ASHP systems which are assisted by solar energy namely Solar thermal assisted air source heat pump (ST-ASHP), Photovoltaic assisted air source heat pump (PV-ASHP) and Photovoltaic/ solar thermal assisted air source heat pump (PVT-ASHP), the review determined the COP of each hybrid system to be 2.9, 3.75, and 3.03 and the payback period is 5-10 years, moderate and long payback period respectively.

Mustapha et al. [79] investigated a techno-economic analysis of a Hybrid Photovoltaic Thermal (PVT) solar assisted heat pump system for domestic hot water and power generation and found it to be 14 years.

Cavelletti [80] developed a DAS which enables automatic control and real-time assessment of performance of over 50 measured operating parameters, to enhance efficiency of a HSAASHP water heater.

Hohne et al. [81] developed a mathematical model for a HSAASHP water heater to minimize electrical energy cost and reduce greenhouse gases considering parameters such as number of solar collectors, size of tank and demand profile.

Godswill et al [82] developed a mathematical model for a Hybrid solar/heat pump water heater based on energy based equations which results to saving of 56% on electrical energy consumption, and saves R2.23 per day.

Li et al. [83] constructed a quasi-steady-state mathematical model to study the mode switching criterion and operation performance of a hybrid heat pump system integrating photovoltaic/thermal and air sources. The simulation results indicated that an HSAASHP water heater could sustain greater heating capacity than a single heat source heat pump and demonstrate the notable potential for energy conversion. The system can efficiently use solar and air energy to achieve a double output of heat and electricity because it has heating and generating power of 1 585 W and 162 W, respectively. The COP can reach 4.76, and the electric efficiency can reach 13.5%. Therefore, the HSAASHP water heater system can deliver excellent performance while requiring a relatively low initial investment and minimal floor space.

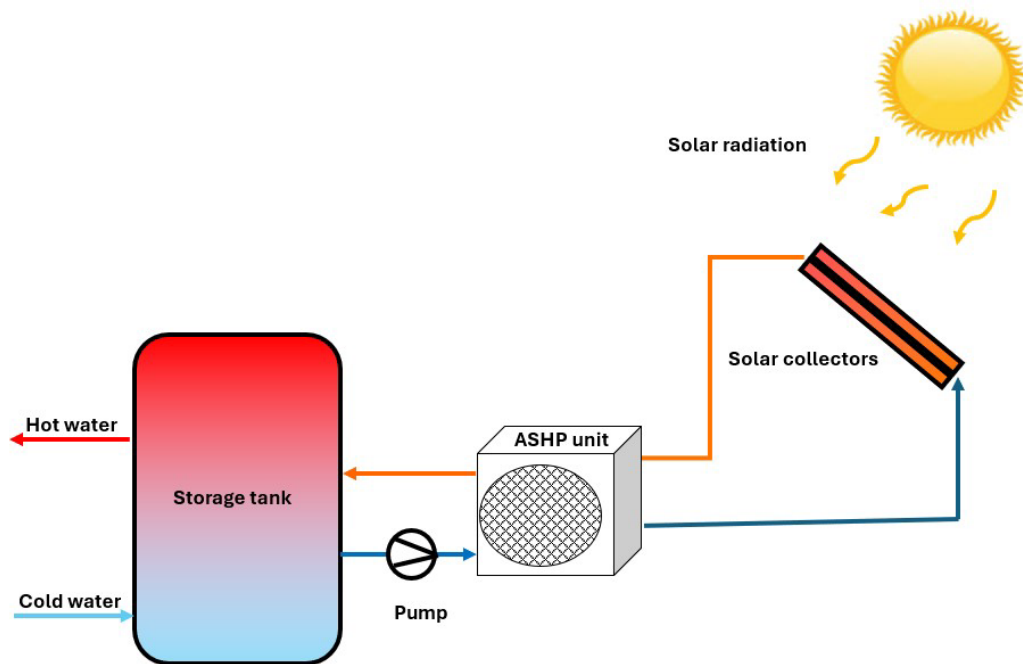


Figure 2:9: Indirect SAHP water heater

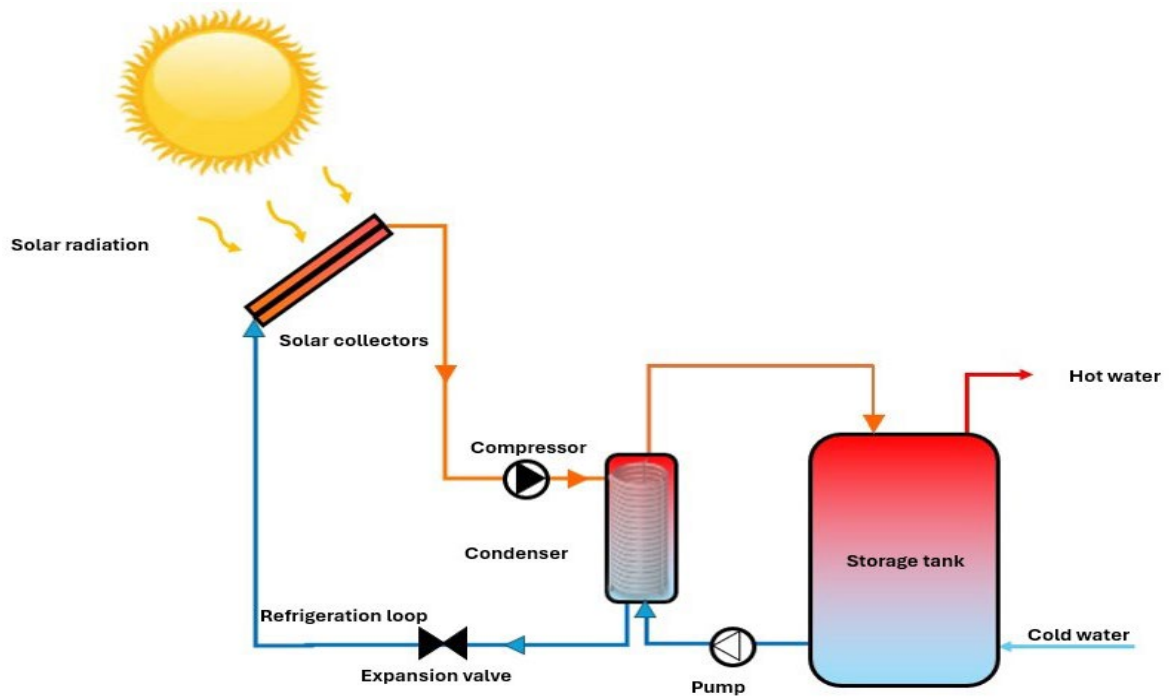


Figure 2:10: Direct SAHP water heater

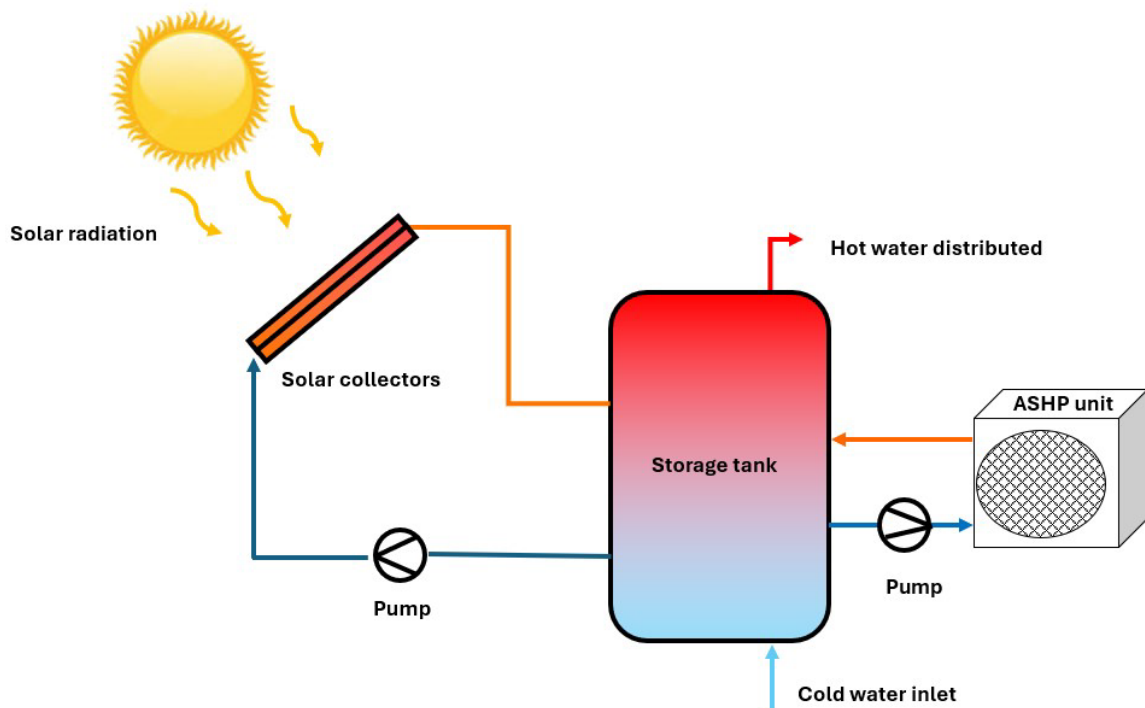


Figure 2:11: Parallel SAHP water heater

2.3. DISCUSSION

2.3.1. Main findings from the review

The review has shown that an ASHP unit is an ineffective during the winter due to frost. Additionally, a solar water heater can only supply hot water at a high rate when there is sufficient solar radiation, which is why its performance declines at night. This means that neither water heating system can supply a constant supply of hot water. In addition, the studies also indicated that many hot water systems have high initial costs. In the configuration of the HSAASHP system discussed, the sensing of different temperature set points has not been addressed. This indicates that the system is always operational, leading to an increase in electrical energy consumption. There is limited literature on the HSAASHP water heater mathematical model used, especially the multi-nonlinear regression model. However, the ASHP and stand-alone SWH mathematical model has been discussed. There is a need for an energy-efficient hot water system that is environmentally friendly and can provide a continuous supply of hot water throughout all seasons. A multi-nonlinear regression model can be developed to monitor the EF of the system using data from the designed and installed DAS.

2.4. SUMMARY

In this chapter, comparisons of the different water heating systems were made using literature from other authors. The water heating systems discussed are the SWH, ASHP water heater, hybrid hot water systems and HSAASHP water heater with a mathematical model. The focus of these water heating systems is the PBP, initial costs, efficiency, and

configurations. The available literature indicates how cost-effective and efficient the HSAASHP water heater is compared to the SWH and ASHP water heaters.

Mathematical models developed with different configurations have been discussed. Most research focuses on linear regression, but there is limited literature on multi-nonlinear regression models. In addition, MATLAB software is discussed, as well as how to analyse the operation of different systems using mathematical models.

The use of HSAASHP water heaters in university residences will be financially beneficial, given the PBP and the electric energy usage. In addition, a mathematical model with a surface response will help with the ASHP water heater not running even when the water tank set point temperature has been reached, which will guarantee a constant water supply and use less electricity.

CHAPTER 3: METHODOLOGY

3.1. INTRODUCTION

This chapter elaborates on the overall research methodology with a special focus on the design of the experimental setup, collection and processing of critical data, uncertainties in the experimental and calculated measurements, as well as the fundamental principles and mathematical equations employed in a bid to achieve the specific research objectives. This chapter consists of seven sections, namely the introduction, research methods, list of materials and software used, experimental setup, theory and equations, collection and processing of relevant data, and finally, the summary.

The HSAASHP water heater is installed in the Mannheim Ladies' Residence on the Bloemfontein campus of the Central University of Technology, Free State. The residence has a basement and two floors, which accommodate 121 female students. It has 55 double rooms and 11 single rooms. The HSAASHP water heater comprises a 2 000 L electric boiler with a 24 kW deactivated element. The electric boiler is retrofitted with evacuated tubes and a 6 kW input ASHP unit to produce sanitary hot water for the occupants. Furthermore, sensors are connected to the HSAASHP water heater to record the measured system readings during the research period. In this chapter, the experimental setup is presented, and the software is also discussed.

3.2. RESEARCH METHOD

The research method that will be used is quantitative, and the accomplished deliverables are as follows:

3.2.1. Design and installation of the HSAASHP water heater

An experimental setup was designed to show the HSAASHP water heater layout, illustrating the connection of all major units or components used in constructing and installing the energy-efficient hot water heating system. The experimental setup helps in the installation of the HSAASHP water heater and in installing the sensors at precise locations on the HSAASHP system.

3.2.2. Developing a response surface model to predict the HSAASHP water heater Energy Factor (EF)

Measuring sensors incorporated into data loggers were installed on the HSAASHP water heater (ASHP and SCs) to predict the EF. The surface response model is a nonlinear multiple regression model. The input parameters include the electrical energy consumed by the HSAASHP water heater, as well as the relative humidity and the ambient weather conditions. The training and validation of the developed surface response model have been completed.

3.2.3. Assessment of the economic benefits of the proposed HSAASHP water heater

Electricity expense records for sanitary hot water in the residence were kept monitoring the difference in electrical energy consumed when the existing electric boiler

produced the hot water and when it was produced by the installed HSAASHP water heater. Initial costs and the number of years the system would operate were used to determine the PBP. Electricity records of the electric boiler were used to determine the energy consumed prior to the retrofit with the ASHP unit and the SCs. The EF was determined by summing the calculated COP of the ASHP and the SF of the SCs. The difference between the electric boiler energy during the baseline and HSAASHP during the assessment periods provided the actual electrical energy-saving.

3.3. LIST OF MATERIALS AND APPROACH

The list of materials and quantities used in the experimental setup is presented in Table 3.1.

Table 3.1: Devices, sensors and data loggers used in the experimental setup

Items	Material	Quantity
1	Power meter with inbuilt data logger	1
2	Water flow meters	3
3	Temperature sensors	12
4	Ambient temperature and relative humidity sensor	1
5	24 kW, 2 000 L electric boiler	1
6	6.0 kW input ASHP unit	1
7	Evacuated tube collectors (each unit consisting of 10 evacuated tubes)	8
8	Controller systems (heat pump controller unit and solar collector controller unit)	2
9	Pyranometer	1
10	Anemometer	1

11	Waterproof and weatherproof enclosures	2
12	Wind vane	1
13	Temperature data loggers (four external channels)	3
14	Water flow meter data logger	1
15	Mini-weather station data logger (U30-NRC data logger)	1
16	5 W solar panel	1
17	4.5 V DC battery	1
18	Solar radiation shield	1
19	USB cable	1
20	Hoboware pro software	1
21	Power track software	1
22	MATLAB software (version 2021a)	1

3.3.1. Measurement accuracies and uncertainties

The percentage inaccuracy of the measured parameters was calculated using uncertainty analysis, depending on the cause of the inaccuracy. The experiment's uncertainty is classified into two categories [84]:

- (1) Random uncertainty, which results from the accuracy of the instrument
- (2) Systematic uncertainty brought on by the calibration of the measurement

The precision of performance calculations was impacted by errors in experimental observations. Equation 3.1 is used to calculate the errors in results that were predicted [84], [85].

$$w_r = \sqrt{\left[w_1 \frac{\partial R}{\partial x_1}\right]^2 + \left[w_2 \frac{\partial R}{\partial x_2}\right]^2 + \left[w_3 \frac{\partial R}{\partial x_3}\right]^2 + \dots \dots \dots + \left[w_n \frac{\partial R}{\partial x_n}\right]^2} \quad (3.1)$$

Whereby

$w_1, w_2, w_3, \dots \dots w_n$ = Uncertainty in the independent variables

R = given function

$X_1, X_2, X_3, \dots, X_n$ = independent variables

w_r = total uncertainty.

The combined uncertainties equation for both type A and Type B is given by Equation 3.2 below [86].

$$U = \sqrt{U_A^2 + U_B^2} \quad 3.2$$

Whereby

$U_A = \frac{\sigma}{\sqrt{n}}$: U_A = Type A uncertainty for a specified parameter or metering

n = number of experimental trials or data

σ = standard deviation.

$U_B = \frac{u}{\sqrt{3}}$: U_B = Type B uncertainty is a function of the accuracy of the metering

sensors or transducers

u = accuracy of the transducers

The statistical averages and standard deviations from the collected measurements served as the basis for the Type A uncertainty [87] and they are shown in Table 3.2. In addition, Equation 3.1 can be used to obtain the derived uncertainty of the desired values (SF, COP, and EF). Alternatively, type B uncertainties can be estimated based on the sensor accuracy [88]. Table 3.2 provides the total uncertainty of the given quantities.

Table 3.2: Uncertainties of the measured and derived quantities

Quantity	Type A uncertainty	Type B uncertainty	Combined uncertainty
Ambient temperature (°C)	± 0.200	± 0.120	± 0.233
Relative humidity (%)	± 0.250	± 0.140	± 0.287
Water flow rates measurements (L/min)	± 0.010	± 0.006	± 0.012
Power consumed by split-type ASHP system (kW)	± 0.130	± 0.003	± 0.130
Water and refrigerant temperature measurements (°C)	± 0.250	± 0.120	± 0.277
Electrical energy consumed (kWh)	± 0.130	± 0.025	± 0.132
Thermal energy gained (kWh)	± 0.190	± 0.042	± 0.195
Coefficient of performance (COP)	± 0.260	± 0.203	± 0.330
Solar fraction (SF)	± 0.060	± 0.020	± 0.063
Energy factor (EF)	± 0.320	± 0.223	± 0.390

3.3.2. Cost breakdown on the list of materials used

Table 3.3 shows the cost of the line items for the sensors, transducers and hot water devices used in the study.

Table 3.3: Cost of the line items for the sensors, transducers and hot water devices used

Item	Material	Quantity	Amount
1.	Quali-track portable 3-phase	1	R 31 320.50
2.	100 Amp Clip-on CTs	3	R14 698. 62
3.	USB interface cable	1	R 217.35
4.	Water/Soil temp sensor 6FT	4	R5 405.00
5.	Water/Soil temp sensor 20FT	4	R5 888.00
6.	Water/Soil temp sensor 50FT	4	R6 619.40
7.	HOB0 4 CH pulse I/P logger	1	R7 433.89
8.	U30 NRC Logger weather STN	1	R16 761.25
9.	Solar panel Assy 5W	1	R3 034.85
10.	Temp R/H sensor 12 Bit 2M	1	R5 675.25
11.	Wind speed sensor C/W 3M CAB	1	R9 589.85
12.	Wind Dir sensor C/W 3M cable	1	R13 476.85
13.	Crossarm Full	1	R2 875.00
14.	RS3-B Radiation shield	1	R2 701.35
15.	SIL Pyranometer cable 3M	1	R6 576.85
16.	U30 Battery 10AH cable	1	R1 868.75
17.	6 kW unit heat pump unit	1	R104 937.50
18.	1x10 vac Tube solar heater	8	R80 270.00
19.	Water circulation pump	1	R4 157.25
20.	Smart switch	1	R13 177.85
21.	HOBOWARE PRO software	1	R13 656.25
22.	Installation and consumables	1	R39 042.50
23.	Sundries	1	R10 062.50
24.	Testing and commissioning	1	R2 156.25
25.	System's enclosure (weatherproof)	1	R7 187.50

26.	Delivery cost	1	R5 920
	Total		R402 910

3.4. DATA COLLECTION AND PROCESSING

The HSAASHP water heater has loggers connected to it, which are used to record weather conditions, the ambient temperature of the water, and the electrical energy consumption of the ASHP water heater. For the collection of the raw data from the loggers, a software program called Hoboware Pro was used to download the collected or recorded data from the loggers. The data was downloaded using a laptop with the Hoboware Pro software. Figure 3.1 illustrates the downloading of the data, which was then exported and processed after using MATLAB software. The raw data were processed into 30-minute intervals over 24 hours to monitor the performance of the HSAASHP water heater. The monitoring of the HSAASHP water heater was done in a second-phase operation from 08:30 to 18:30 when both solar collectors and ASHP were active. During this second-phase operation, three input parameters were considered, namely electrical energy consumption (E_t) of the ASHP, ambient temperature (T_a) and the relative humidity (RH), and the desired output (EF) was calculated with equation ($COP + SF = EF$). The calculated EF was used as the baseline for the multi-nonlinear regression model, which will then help the model assess the performance of the HSAASHP water heater.



Figure 3:1: Downloading of data from solar collectors' logger

3.5. THEORETICAL AND MATHEMATICAL INSTRUMENT

Equation 3.3 below determines the electrical energy used by the ASHP during operation time [24].

$$E_{ASHP} = Pt \quad (3.3)$$

Equation 3.4 below determines the electrical energy used by the ASHP during operation time [89].

$$SF = \frac{m_1 c (T_o - T_i)}{E_{sol}} \quad (3.4)$$

Whereby

SF = solar fraction of the HSAASHP water heater collectors

m_1 = mass of the water heated by the collectors (kg)

c = specific heat capacity of water (kJ/kg °C)

T_a = ambient temperature

T_o = initial water temperature from the water tank

T_i = final water temperature preheated by solar collectors.

Equation 3.5 below determines the COP of the HSAASHP water heater ASHP [90].

$$COP = \frac{m_2 c (T_o - T_i)}{E_{ASHP}} \quad (3.5)$$

Whereby

COP = coefficient performance of the ASHP

m_2 = mass of the water preheated by the ASHP (kg)

c = specific heat capacity of water (kJ/kg °C)

T_o = initial water temperature on the inlet of the ASHP unit (°C)

T_i = final water temperature by ASHP on the outlet of the ASHP unit (°C)

Equation 3.6 below determines the equation of the energy factor of the HSAASHP water heater [91].

$$EF = COP + SF \quad (3.6)$$

Whereby

EF = Energy Factor of the HSAASHP water heater

COP = Coefficient of performance of the ASHP

SF = Solar fraction of the solar collectors.

The multi-nonlinear regression model to predict the EF using the input parameters (electrical energy, ambient temperature and relative humidity (weather parameter) is given by Equation 3.7 [92].

$$y = \frac{\beta_1 X_2 - X_3 / \beta_5}{(1 + \beta_2 X_1 + \beta_3 X_2 + \beta_4 X_3)} \quad (3.7)$$

Whereby

Y = Energy factor

x₁ = electrical energy consumed

x₂ = ambient temperature, and x₃ = relative humidity.

The relief F test from MATLAB was used to determine the rank of each input parameter by weights of importance to the desired output.

Equations 3.8 and 3.9 below calculate the cost saving of each season, and the sum is the annual cost savings, which is represented by Equation 3.9 below [93]. Tariffs are considered in all the cost-saving calculations.

$$\text{Winter cost saving} = \text{number of days} \times \text{average day cost saving} \quad (3.8)$$

Where winter duration = 92 days

Where summer duration = 273 days

$$\text{Annual cost saving} = \text{summer cost saving} + \text{winter cost saving} \quad (3.9)$$

The economic cost analysis is performed with respect to the initial financial value and the PBP of the HSAASHP water heater, which is 20 years [94]. A simple payback period (SPP) is defined as the period (in years) that an investment must yield a return on its

investment or take for positive cash flow to surpass the initial investment, and it does not consider the value of money at the time of return. On the other hand, the Net Present Value (NPV) considers the present value by measuring the difference between the present values of cash inflows and outflows at a target rate of return or cost of capital [95].

For the HSAASHP water heater, the PBP will be determined using the NPV, and the viability of the HSAASHP water heater will be determined by the NPV value being positive; if not, the HSAASHP water heater is not viable [96].

The HSAASHP water heater was monitored for a period of a year (January–December 2023) to analyse its operation in all seasons.

Equation 3.10 below calculates the simple payback period (SPP) of the HSAASHP water heater [97].

$$SPP(yrs) = \frac{\text{Initial investment}}{\text{Annual cost saving}} \quad (3.10)$$

Whereby

SPP = simple payback period.

Equation 3.11 below is the net present value (NPV) payback period (PBP) [97].

$$NPV(yrs) = AAR \left[\frac{(1+i)^n - 1}{i(1+i)^n} \right] - IC \quad (3.11)$$

Whereby

AAR = Annual Average Cost

N = lifespan of the HSAASHP water heater

I = discount rate

IC = initial cost.

Equation 3.12 below is the return on investment (ROI) formula [98].

$$ROI = \frac{\text{Revenue after investment} - \text{Amount invested}}{\text{Amount invested}} \quad (3.12)$$

Whereby

ROI = Return on Investment

Equation 3.13 below is the annualized ROI [99]

$$\text{annualized ROI} = \sqrt[n]{IBC - 1}$$

Whereby

n = number of years

IBC = initial base cost

3.6. EXPERIMENTAL SETUP

Figure 3.1 shows the designed and installed HSAASHP water heater, which consists of a 2 000 L storage tank obtained from an electric boiler with a 24 kW element which was deactivated. The 2 000 L electric boiler with a deactivated element was used as a water storage tank and retrofitted with eight evacuated tubes that were placed on the rooftop of the residence (SCs use solar radiation as a source of energy during the heating cycle) and a 6 kW, 3-phase ASHP (ASHP unit uses electricity from the grid as a source of energy during the vapour compression refrigeration cycle).



Figure 3:2: Designed and installed HSAASHP water heater

During periods of hot water consumption by the students in accommodation, cold water from the mains is used to fill the storage tank. This hot water system has eight temperature sensors, T_1 , T_2 , and T_3 , installed at the bottom, middle and top of the tank to measure the water temperature at their respective positions. T_4 and T_5 measure the water temperature at the inlet and outlet of the ASHP, T_6 and T_7 measure the water temperature at the inlet and outlet of the SCs, and lastly, T_8 measures the water temperature at the outlet of the storage tank to the building. The three-phase, 370 W water circulation pump (PU2) helps to circulate the water between the storage tank and the SCs during the heating cycles, while the single-phase 100 W water circulation pump (PU1) assists in the circulation of water between the storage tank and the ASHP unit.

Data from the HSAASHP water heater are stored using the DAS. The amount of water heated by the ASHP unit is measured by the flow meter (F1). The water heated by the SCs during heating cycles and stored in the storage tank is measured by the flow meter (F2), and the amount of hot water used by residents is measured by the flow meter (F3). A quality track analyzer is attached to the power line supplying electricity to the HSAASHP water heater. This device is a three-phase power meter with built-in data logging capability. Data loggers are connected to all the measuring sensors to store the recorded data. Using Hoboware Pro software and the power track software, all data loggers are configured to log every minute during the monitoring period. A laptop is used to download the data set stored in the data loggers, and MATLAB is used to process the data for further analysis. The HSAASHP water heater is automatically controlled by a combination of a SCs' controller and an ASHP controller. A pyranometer, anemometer, wind vane, relative humidity and temperature sensors are mounted next to the solar collectors. The pyranometer is a sensor used to measure solar irradiance; it quantifies the total solar energy (both direct and diffuse) received per unit area. The wind vane shows the direction from which the wind is blowing, while an anemometer measures wind speed, and it is important for understanding wind patterns. The ambient temperature and relative humidity sensor measure the temperature of the surrounding environment and the amount of moisture in the air relative to the maximum amount of moisture the air can hold at a given temperature. These instruments and sensors are essential for gathering data on environmental conditions, which can be used for analysis, prediction, and control in a wide range of applications.

When solar energy is available, the HSAASHP water heater simultaneously absorbs heat from the ambient air via the evaporator unit and from the sun through the SCs. In

this case, the SCs and ASHP unit heats water simultaneously, and the process is continuous. The water will not be heated to 55 °C (set point temperature) through a one-pass circulation. The hot water in the storage tank will achieve the set point temperature through the re-circulation method whereby the water will circulate between the condenser of the heat pump unit and tank, as well as the heat exchanger of the SCs and the tank, before reaching the desired water temperature of 55 °C. The schematic diagram in Figure 3.2 is used as a reference to illustrate the process of heating water using the HSAASHP water heater.

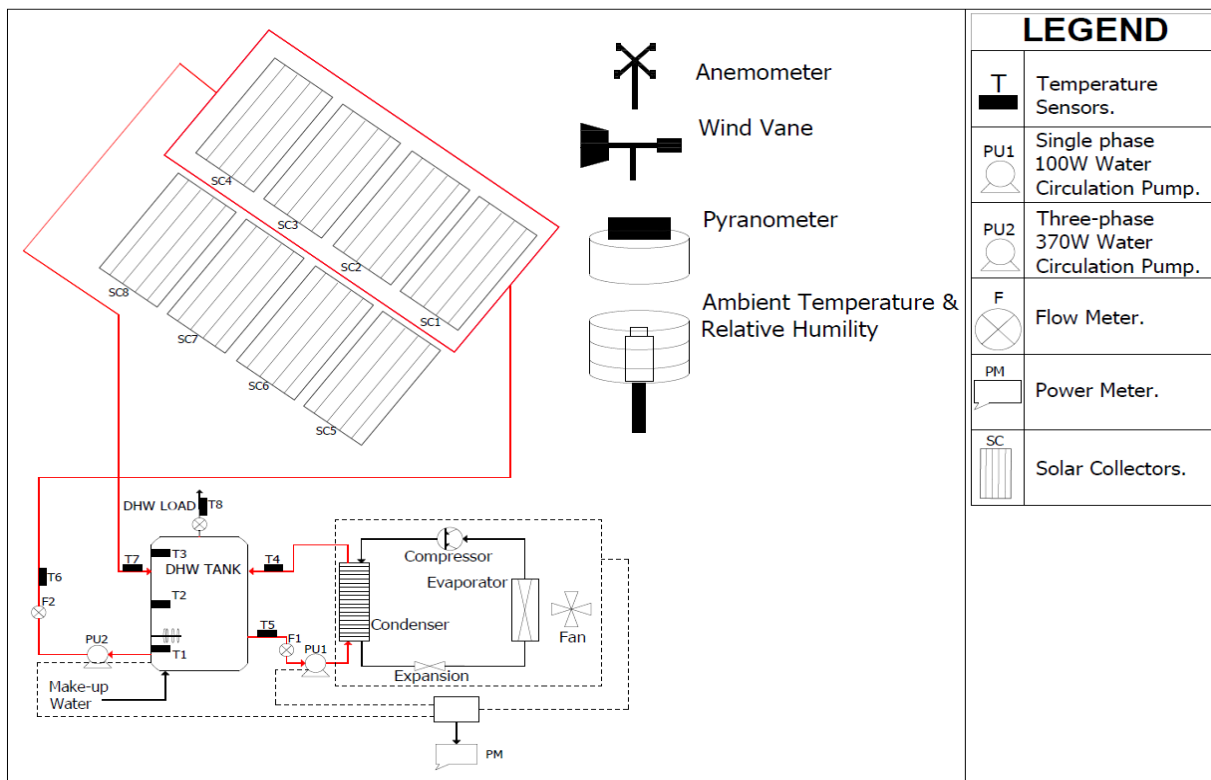


Figure 3:3: HSAASHP water schematic diagram

3.7. SUMMARY

In this chapter, the research methods were described, which are both qualitative and quantitative. The materials and software used were listed, including their cost breakdown, which will help determine the break-even point of the HSAASHP water heater and PBP. The discussion also included measurement accuracy and uncertainties, highlighting the errors in the predicted results for SF, COP, and EF. The developed nonlinear model equation using the selected input parameters and the techno-economic analysis equations were presented. The study also indicated that the NPV is used to determine the PBP.

CHAPTER 4: PERFORMANCE ANALYSIS AND ECONOMIC VIABILITY OF HSAASHP WATER HEATER

4.1. INTRODUCTION

This chapter is divided into four sections, excluding the introduction. Section 1 discusses the performance of the monitored input and output parameters of the HSAASHP water heater in a year. Section 2 discusses the analytical findings of the processed data (where the performance of the SCs and ASHP unit during the activity period are discussed separately as subsections). Section 3 discusses the techno-economic analysis of the HSAASHP water heater (where the operating performance of an electric boiler and HSAASHP water heater, as well as the net cost saving of an HSAASHP water heater, are discussed as subsections). Lastly, Section 4 provides the summary, where the conclusion of the whole chapter is presented.

4.2. PERFORMANCE OF THE INPUT AND OUTPUT PARAMETERS OF THE HSAASHP WATER HEATER IN A YEAR

The study was conducted at the Mannheim Ladies' Residence, which is student accommodation at Central University of Technology, Free State in Bloemfontein. For the desired output (EF), the input parameters considered from the DAS for this study are electrical energy consumption (ASHP unit and the circulating water pump of SCs), ambient temperature, and relative humidity. Figure 4:1 and Figure 4:2 indicates the monthly input parameters during the active phase during the whole year, and the data collected is shown

in Appendix A. During the period January to December 2023, Figure 4:1 shows that the ambient temperature ranges from 10.44 °C to 27.17 °C, with a mean of 18.82 °C. The relative humidity ranges from 45.92% to 70.30 %, with a mean of 55.83%. The electrical energy consumed by the ASHP unit (E_{COP}) ranges between 242.79 and 1 792.02 kWh, with an average of 1 025.92 kWh. The electrical energy consumed by the SCs (E_{SOL}) ranges from 566 to 3 136.04 kWh with an average of 2 393.81 kWh, and the desired output (EF) ranges from 3.00 to 5.20 with a mean of 4.05.

The annual analysis of the weather parameters and EF in Figure 4:1 shows that during winter, the relative humidity is higher compared to the summer. Meanwhile, ambient temperature is lower in winter and higher in summer. The analysis shows that for a higher EF of 5.2, as in January, the ambient temperature must be high and relative humidity low. That defines the relationship of relative humidity as being inversely proportional to EF and ambient temperature directly proportional to EF.

The annual analysis of the electrical energy consumption and the EF in Figure 4:2 shows that when E_{COP} and E_{SOL} sum up to 809.3 kWh in February the EF is high, which at this point is 5. When the sum of both electrical energy consumptions is high, as in the May at 5 120 kWh, the EF decreases to 3.5. The relationship between electrical energy consumption and EF can be determined as inversely proportional to each other.

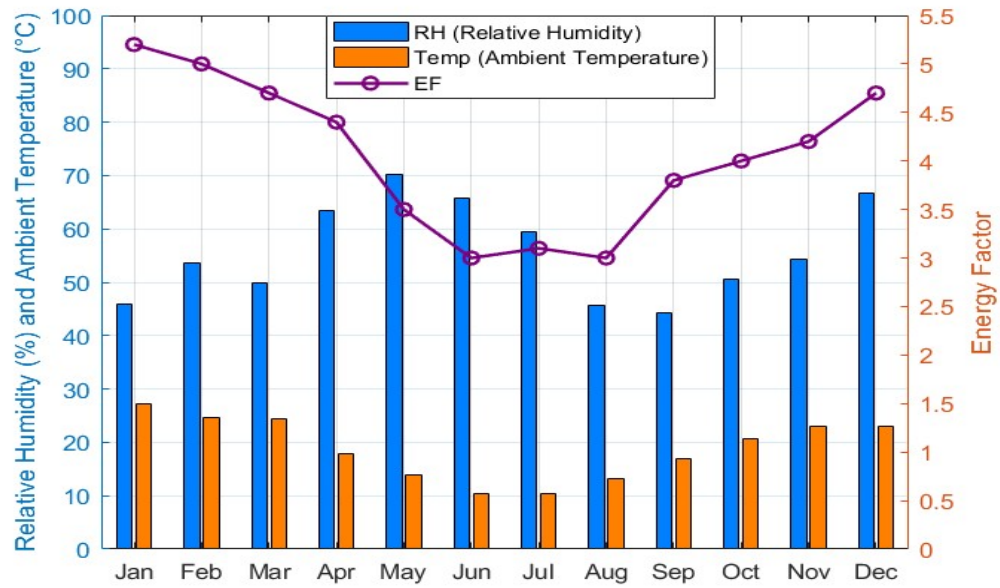


Figure 4:1: Monthly relative humidity, temperature, and energy factor

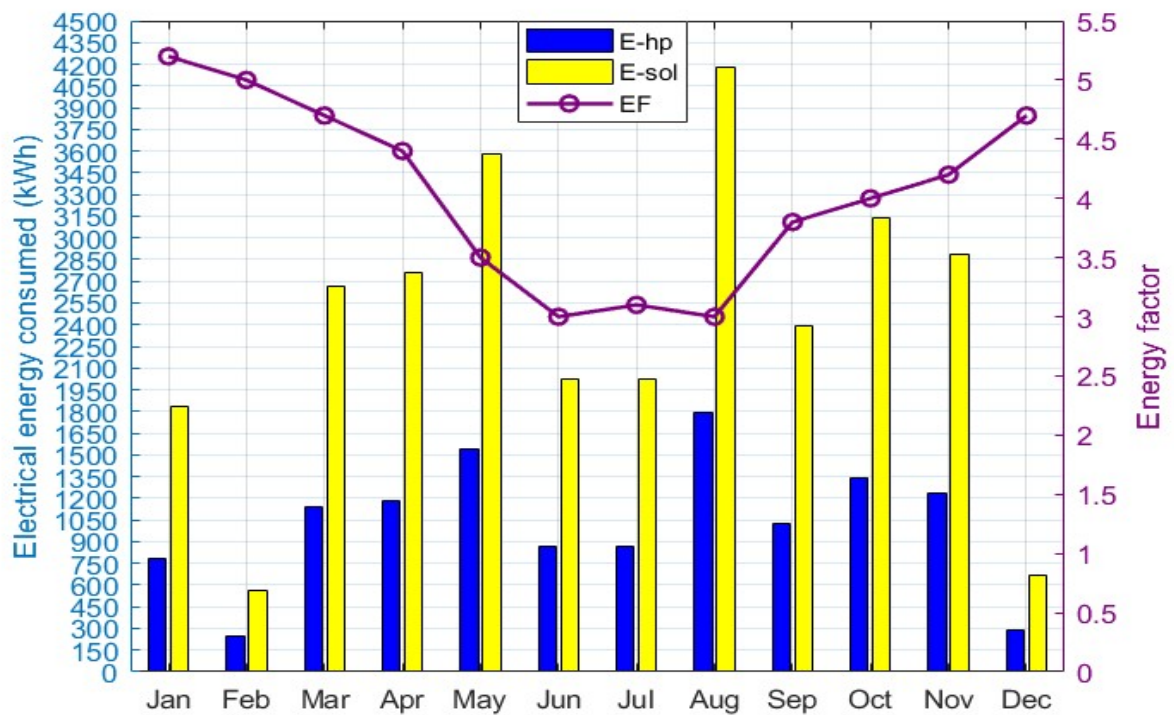


Figure 4:2: HSAASHP water heater electrical energy consumption and EF

4.3. ANALYTICAL FINDING OF THE PROCESSED DATA

4.3.1. Performance of the SCs in the HSAASHP water heater during the second phase.

The detailed data collected on the performance of the SCs during the active or second phase is shown in Appendix B1. The sample days and input parameters were monitored in January and February 2023 during the active phase of the HSAASHP water heater (which is the phase where the ASHP unit and the SCs are active or functioning simultaneously from 08:30 to 18:30). The sample days (SD) specify the days used in January and February to monitor the efficiency of the SCs. The flow (FR-SC) counts the water flowing into the SC inlet each day during the active phase. T_{in} -SC is the ambient temperature of the water flowing into the inlet of the SCs, and T_{out} -SC is the outlet water temperature from the water flowing from the outlet of the SCs. The thermal energy gained (Q_{sc}) is the thermal energy gained from the SC heating cycle during the active phase. Solar energy (E_{sol}) is the energy collected from the sun and used by the SCs for the heating of sanitary water during the active phase every day during the monitoring stage.

According to the analytic finding of the processed data in Appendix B1, the FR-SC counts range from 1 212 to 2 616 counts with a mean of 2 283. The minimum T_{in} is 53.33 °C with a maximum of 57.37 °C and a mean of 54.4 °C. The minimum T_{out} is 53.75 °C with a maximum of 57.85 °C. The thermal energy gained (Q_{sc}) ranges from 193.6 to 369.0 kWh, with a mean of 289.1 kWh. The solar energy (E_{sol}) ranges from 22.33 kWh to 48.39 kWh with a mean of 42.23 kWh. The solar fraction of the HSAASHP in January and February 2023 during the active time ranges from 0.562 to 0.867, with a mean of 0.696. It must be stated that with reference to the ambient temperature of the water within the

vicinity of the SCs and out, the HSAASHP water heater functioned well, given the fact that during the active state, it is near the set point temperature of 55 °C. Moreover, the SCs with the SF attained prove that the HSAASHP system functions better than a stand-alone solar water heater [100].

The analysis of the thermal energy gained, electrical energy consumption and SF in Figure 4.3 below shows that during the active phase, because of the motor circulating water from the tank to the SCs on top of the roof, the electrical energy consumption is higher than the thermal energy gained. When the electrical energy consumption decreases, SF increases, as seen on Day 6. With constant electrical energy consumption on Days 9 to 11, when the thermal energy gained increased, SF increased, and when it decreased, the SF also decreased.

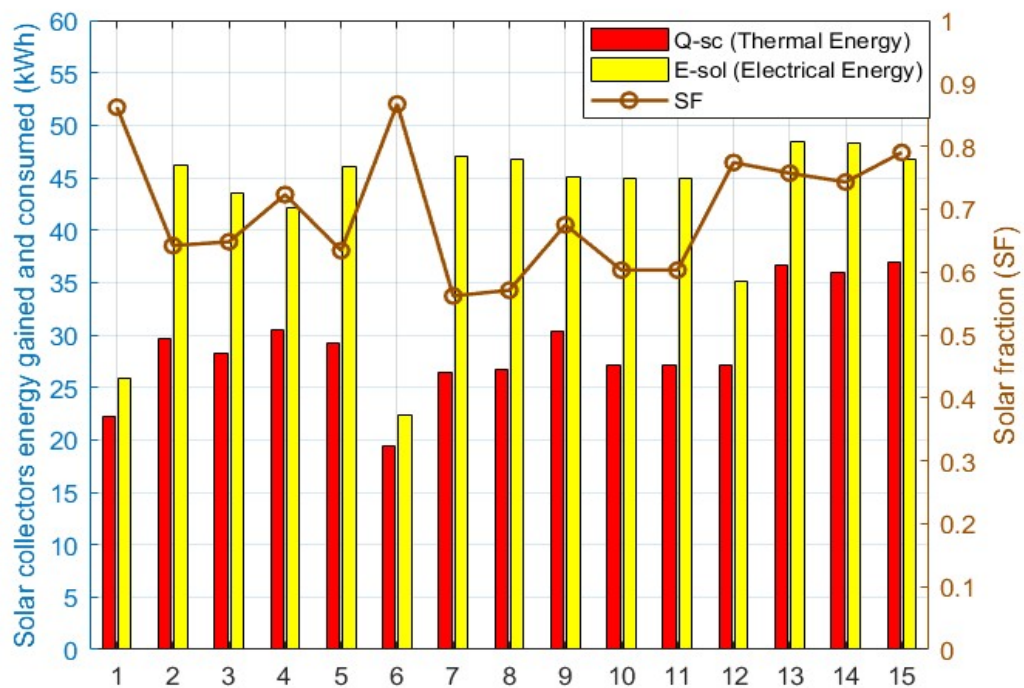


Figure 4.3: Daily solar collectors energy usage, energy consumption and SF

4.3.2. Performance of the ASHP unit in the HSAASHP water heater during the second phase

The detailed data collected on the performance of the ASHP unit during the active or second phase is shown in Appendix B2. The sample days and monitored input parameters in January and February 2023 during the active phase of the HSAASHP water heater (the phase where the ASHP and the solar collectors are active or functioning simultaneously, from 08:30 to 18:30). The sample days (SD) specify the days used in January and February to monitor the efficiency of the SCs. The flow counts (FR-HP), track the water flowing into the ASHP unit inlet each day during the active phase. T_{in} -HP is the temperature of the water flowing into the inlet of the ASHP unit, and T_{out} -HP is the temperature of the water flowing from the outlet of the ASHP unit. The thermal energy gained (Q_{HP}) is the thermal energy gained from the ASHP unit heating cycle during the active phase. Electrical energy (E_{HP}) is the electrical energy consumed by the ASHP unit to heat sanitary water during the active phase of the monitoring period.

According to the analytic findings of the processed data in Table 4.3, the FR-HP counts ranged from 38 to 138 counts with a mean of 82.33. The minimum T_{in} is 47.46 °C with a maximum of 55.35 °C and a mean of 52.33 °C. The minimum T_{out} is 51.95 °C with a maximum of 59.93 °C. The thermal energy gained Q_{HP} ranges from 41.7 to 255.8 kWh with a mean of 118.6 kWh. The electrical energy (E_{HP}) ranges from 15.20 kWh to 54.50 kWh, and the mean is 30.0 kWh. The COP of the HSAASHP in January and February 2023 during the active time ranges from 2.39 to 5.29, with a mean of 3.68. The COP of an HSAASHP water heater is higher than that of a stand-alone ASHP unit, as demonstrated by the COP and energy consumption achieved by the ASHP unit compared to a stand-

alone unit, which is reduced. Figure 4.1 illustrates that using the standard COP of a stand-alone ASHP is 3 [101],[102].

The analysis of the thermal energy gained, electrical energy consumption and COP in Figure 4.4 below shows that during the active phase, the thermal energy gain dominates the electrical energy consumption. When the thermal energy gained increases, the COP also increases, and when it decreases, the COP also decreases. The graph also indicates that an increase in electrical energy consumption results in an increase in thermal energy gained. Figure 4.4 certifies the rule of an ASHP water heater that the electrical energy consumed by the ASHP to heat water will always be less than the thermal energy gained [103]. It can also be stated that higher electrical energy consumed results in higher thermal energy gained, as seen on Day 8. It is safe to say that electrical energy consumed and thermal energy gained are proportional to each other.

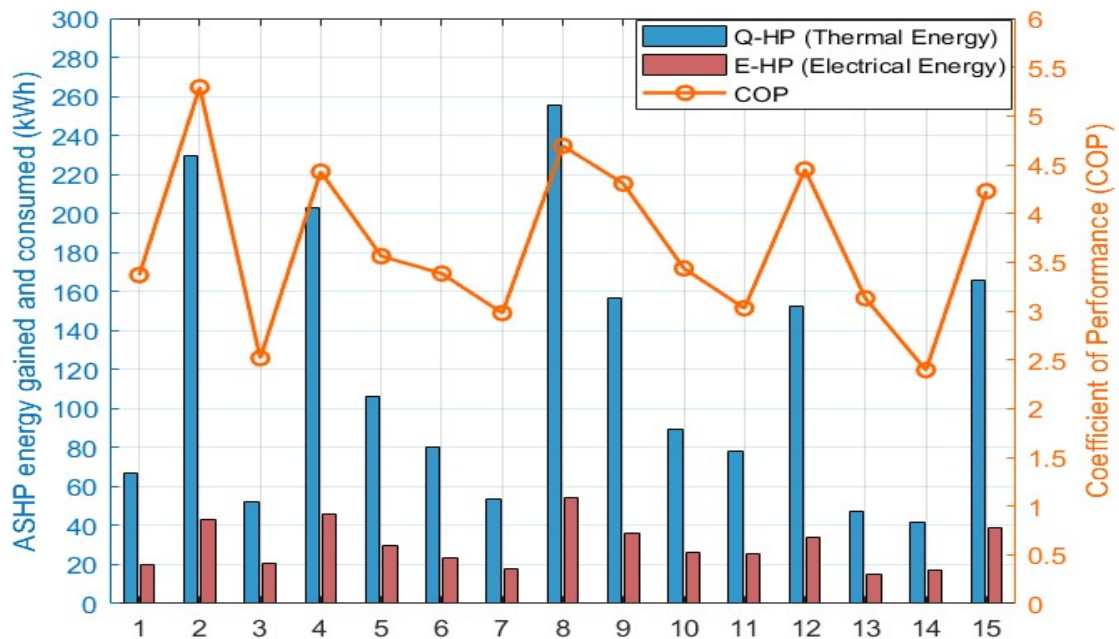


Figure 4.4: Daily ASHP energy usage, energy consumption and COP

The COP of an ASHP ranges from 2–4 [38] and it is used as a reference to measure or compare the COP of the HSAASHP water heater. Figure 4.5 shows that the HSAASHP water heater COP minimum is greater than two and the maximum greater than four. It can be concluded that the efficiency of the HSAASHP water heater in terms of COP is higher than the stand-alone ASHP unit.

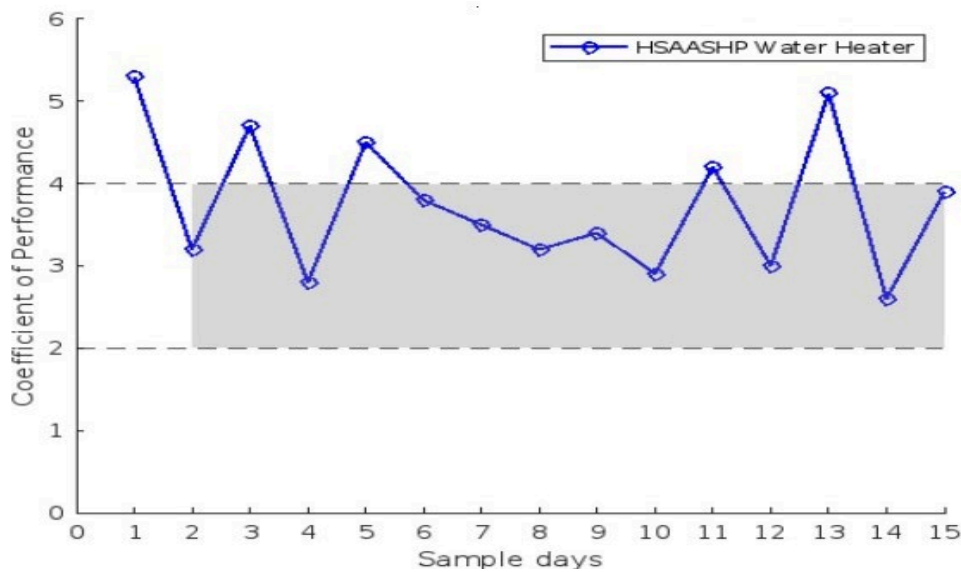


Figure 4.5: Stand-alone ASHP and HSAASHP water heater COP comparison

4.4. TECHNO-ECONOMIC ANALYSIS

4.4.1. Operating performance of an electric boiler and HSAASHP water heater

Table 4.4 illustrates the monthly electrical energy consumed by an electric boiler (assumed consumption) and the HSAASHP water heater separately in 2023. Students' activities, such as their periods of occupation in the residence, were taken into consideration. The assumed electric boiler electrical consumption ranges from 3 852.26 to 16 844.96 kWh, with a total annual consumption of 151 128.9 kWh. The HSAASHP water

heater's monthly electrical energy consumption ranges from 809.3 to 5 973.4 kWh, with a total electrical energy consumption of 41 036.8 kWh. The monthly EF in both seasons ranges from 3.0 to 5.2, with a higher EF in summer than in winter.

Table 4.4: Operating performance of the electric boiler and HSAASHP water heater

Months	Boiler Et (2023) (kWh) baseline	Activities	HSAASHP Et (2023) (kWh)	EF	Seasons
Jan	12926.08	30%	2613.971	5.2	Summer
Feb	3852.26	25%	809.3	5	Summer
Mar	17065.98	100%	3812.814	4.7	Summer
Apr	16514.46	100%	3941.4	4.44	Summer
May	16844.96	100%	5120.057	3.5	Winter
Jun	8324.41	50%	2890.357	3	Winter
Jul	8439.84	50%	2890.357	3.1	Winter
Aug	16844.98	100%	5973.4	3	Winter
Sep	12390.53	75%	3422.8	3.8	Summer
Oct	17046.59	100%	4480.057	4.0	Summer
Nov	16598.92	100%	4129.086	4.2	Summer
Dec	4279.87	25%	953.2	4.7	Summer
Total	151128.9		41036.8		

Figure 4.1 shows that in 2023, with the same activities, the energy consumption of the electric boiler was higher than that of the electrical energy consumed by the HSAASHP water heater. With reference to Table 4.3, the electric boiler consumed significantly more energy overall (151 128.9 kWh) compared to the HSAASHP water heater (4 136.8 kWh). The graph illustrates the efficiency of the HSAASHP water heater, highlighting its

advantages derived from the SCs and ASHP unit. The hybrid hot water unit uses less electricity, which is consumed by the ASHP unit when heating the sanitary hot water. Due to higher SF and the COP, the EF improves throughout the summer season. The Hybrid solar/electric water heating system (HES) which in this case is a HSAASHP water heater it uses less electricity during this season because there is high solar availability, which favours the temperature of the ASHP water heater and results in less electricity being used. During the winter season, there is a slight increase in electricity used by the HSAASHP water heater due to the decrease of SF and COP, which increases reliance on electricity. Throughout the seasons, the boiler consumed more electricity than the HSAASHP water heater, proving that the HSAASHP water heater is more efficient in providing sanitary hot water compared to the electric boiler [104], [105].

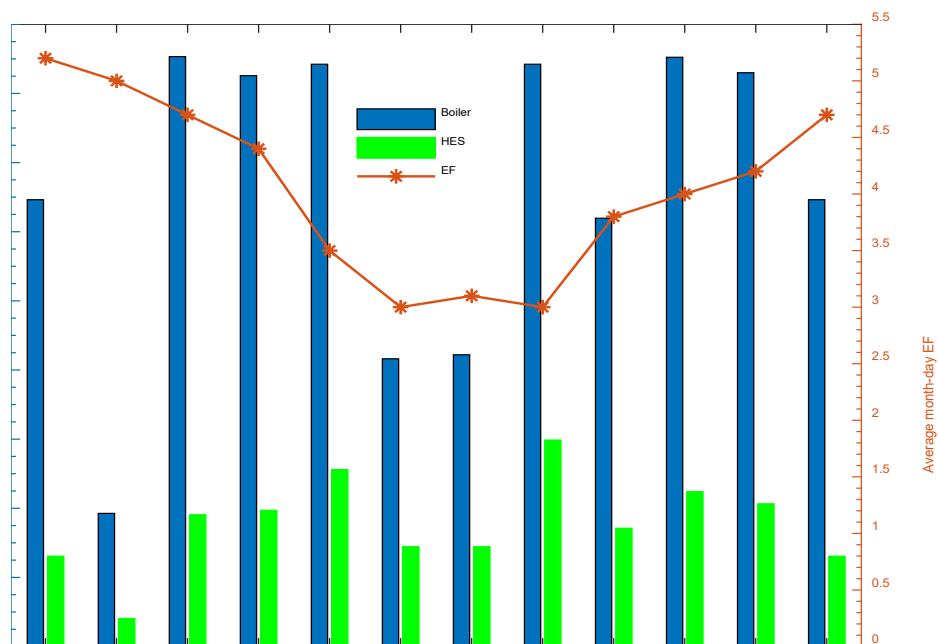


Figure 4:6: Annual electrical consumption of an electric boiler and HSAASHP water heater

4.4.2. Net cost saving of an HSAASHP water heater

Techno-economic analyses assess the technical and financial viability of various technologies, it includes cost estimation for commercial-scale facilities, process design, simulation, and data for life-cycle assessments [106],[107]. The break-even point was determined using the NPV method. The electrical energy savings from the traditional electric boiler and the HSAASHP water heater is 110 092.1 kWh, while the annual tariff is R1,758/kWh, the hike in tariff is 7,5%, and the lifespan of the HSAASHP water heater is estimated at 15 years. At the time of writing the conversion of South African rands (ZAR) to United States Dollars (USD) was 1 ZAR = 0.053 USD [108]. The total initial cost of the HSAASHP water heater was R402 910 (21354,23 USD) (including delivery costs, loggers, flow meters, water pipes, evacuated SCs and other materials mentioned in Table 3.3 in Chapter 3). The costs incurred include R1 000 every three years for maintenance during the lifespan of the HSAASHP water heater, R3 000, and R2 000 for decommissioning, which will be incurred at the end of the water heater's lifespan. This brings the total cost to R5 000. The total cost incurred is the sum of the initial costs, maintenance and decommissioning, which is R407 910. The annual cost savings, as in the future value (FV) of the money, is calculated by multiplying the annual electrical energy consumption savings by Eskom's tariff, including the tariff increase rates. A combination of the annual cost savings of the FV and the annual rate of return (r) is the annual cost savings expressed as the net present value of money (NPV). The techno-economic cost analysis on table 4.6 considered a 6.5% annual rate of return (r). According to Table 4.6, the PBF of the HSAASHP water heater is 2.19 years, and the break-even point on the 3rd year. The total NPV at the end of the 15-year lifespan is R3 027 461,79 (160 455,5 USD), with an investment gain of R2 624 547.17 (139 101USD), an annualized ROI of 14.39% and profit

of 87%. Table 4.1: Techno-economic analysis of a HSAASHP water heater shows the detailed techno-economic breakdown of the HSAASHP water heater based on a levelized annual energy saving, steady tariff hikes and NPV annual saving.

Table 4.1: Techno-economic analysis of a HSAASHP water heater

Saving/kW h	No of years	Year	tariff	FV sav/R	NPV sav/R	CUMSUM NPV	
	0						402910
110092,1	1	1,758	193541,91	0,06	182586,71	182586,71	
110092,1	2	1,890	208057,56	0,06	185170,48	367757,19	
110092,1	3	2,032	223661,88	0,06	187790,82	555548,01	
110092,1	4	2,184	240436,51	0,06	190448,24	745996,25	1000
110092,1	5	2,348	258469,26	0,06	193143,26	939139,51	
110092,1	6	2,524	277854,44	0,06	195876,42	1135015,93	
110092,1	7	2,713	298693,53	0,06	198648,26	1333664,19	
110092,1	8	2,917	321095,54	0,06	201459,32	1535123,51	1000
110092,1	9	3,135	345177,71	0,06	204310,16	1739433,66	
110092,1	10	3,371	371066,04	0,06	207201,34	1946634,99	
110092,1	11	3,623	398895,99	0,06	210133,43	2156768,42	
110092,1	12	3,895	428813,19	0,06	213107,02	2369875,44	1000
110092,1	13	4,187	460974,12	0,06	216122,68	2585998,12	
110092,1	14	4,501	495547,24	0,06	219181,02	2805179,15	
110092,1	15	4,838	532713,28	0,06	222282,64	3027461,79	2000

Figure 4.2 shows the cumulative NPV starting at zero in 2023 and increasing gradually to 2038, where the total saving is R3027461,79 (160455,5 USD). The capital and

maintenance costs remain constant throughout the 4 years maintenance at R1 000 (53 USD) and decommissioning at the end of the HSAASHP water heater at R2000 (106 USD). The tariff hikes show a steady increase from R1.758/kWh in 2023 to R4.838/kWh in 2038, which demonstrates a steady increase in electrical energy costs over the years. In the year 2.19, the cumulative NPV matches the initial cost spent on the HSAASHP water heater, even with the ongoing increasing hiking tariff. That suggests that the HSAASHP water heater is viable and has financial benefits.

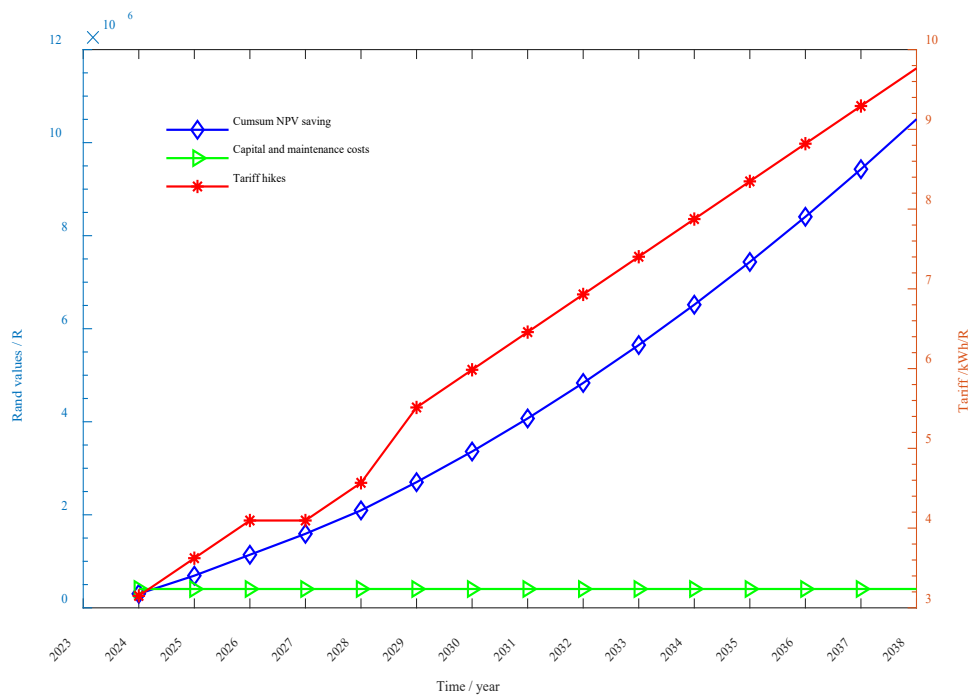


Figure 4:7: Techno-economic analysis graph based on rand saving tariff

Figure 4.8 illustrates BEP analysis of the HSAASHP water heater, which shows the capital and maintenance costs remains constant throughout the maintaining years at R1000 (53USD) and the decommissioning cost of R2000 (106USD) on the 15th year. The total costs (initial and maintenance costs) sums up to R407 910 for the whole life span of the

system, it breaks even on the third year of the HSAASHP water heater life span, when the NPV exceeds the total costs of R407 910 (21354.23USD). The red section on figure 4.8 indicates that the HSAASHP water heater is running on a loss the invested capital has not been retrieved yet. The green section after the BEP indicates that the HSAASHP water heater is doing a profit, because the break-even point has been reached. With reference to the proposed HSAASHP water heater life span (15 years), investment cost, and total costs, this certifies that the HSAASHP water heater is viable and has financial benefits, given the year it breaks even.

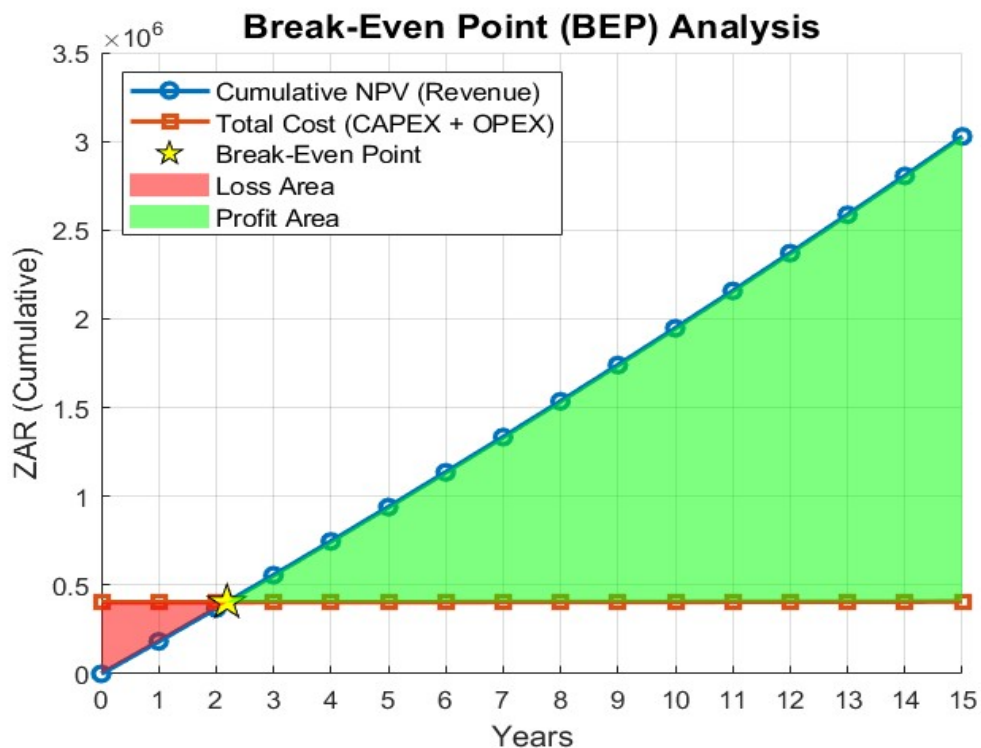


Figure 4:8: HSAASHP water heater BEP analysis

4.5. SUMMARY

Before the retrofitting of the 2 000 L (24 kW) electric boiler with the SCs and ASHP, the electric boiler's electrical energy consumption for heating water ranged from 3 852.26 to 16 844.96 kWh, with a total annual consumption of 151 128.9 kWh. The retrofitted electric boiler with ASHP unit and evacuated SCs, called the HSAASHP water heater, had a monthly electrical energy consumption ranging from 809.3 to 5 973.4 kWh and a total electrical energy of 41 036.8 kWh. The monthly average daily EF in both seasons ranged from 3.0 to 5.2, and summer had a higher EF than winter. The designed and installed HSAASHP water heater has proven to be economically viable, with a PBP of 2.19 years and a break-even point which is on the 3rd year of the HSAASHP water heater. The total NPV at the end of the 15-year lifespan is R1 0503 958 the investment gain is R10 098 957.10 with an AROI of 2493.5%, an annualized ROI of 24.24% and a profit of 87%.

CHAPTER 5: DEVELOPMENT AND VALIDATION OF MATHEMATICAL MODEL TO PREDICT THE ENERGY FACTOR OF THE HSAASHP WATER HEATER

5.1. INTRODUCTION

This chapter consists of seven sections. Section 1 introduces the chapter and the subsequent sections in the chapter. Section 2 discusses the sample days and processed data set used to train the nonlinear regression model, while Section 3 discusses how the nonlinear regression model was developed. Section 3 also weights the input parameters used in the developed model using the reliefF algorithm on MATLAB. Section 4 validates the multi-nonlinear regression model. Section 5 compares the calculated and predicted EFs and lastly, Section 6 summarizes the whole chapter.

5.2. SAMPLE DAYS AND PROCESSED DATA SET USED TO TRAIN THE NONLINEAR REGRESSION MODEL

The data set used to train or test the model is the data set downloaded from the designed and installed DAS during the second phase of operation (08:30–18:30) when both ASHP and SCs were operating. The HSAASHP water heater was monitored for eight hours from 08:30–18:30, and the monitoring was done in 30-minute intervals. The processed data used is from January and February 2023. The input parameters considered for the desired EF (output) are electrical energy consumption (of the ASHP and SCs water

circulating pump), ambient temperature and relative humidity. Table 1 illustrates the processed data set used for training the model. The data set ranged from 38.78 to 77.45 kWh for the total electrical energy consumed, with an average of 57.65 kWh. The ambient temperature ranged from 16.70 to 31.33 °C, with a mean of 26.98 °C. The relative humidity ranged from 18.63 to 69.56%, with a mean of 29.78%. With these input parameter values, the calculated EF ranged from 3.666 to 6.037, with a mean of 4.426. The average calculated EF was 4.426 and is greater than 4.00, which implies that the HSAASHP water heater was utilizing both free solar energy and aerothermal energy to produce sanitary hot water and was more efficient [91].

Table 5.1: Test data set of the HSAASHP water heater

SD	Period (hh:mm)	Et (kWh)	Tamb (°C)	RH (%)	EFcal	EFmod
1	08:30-18:30	38.78	16.7	57.7	4.329	4.421
2	08:30-18:30	74.50	23.08	29.36	6.037	6.126
3	08:30-18:30	52.55	31.12	20.24	3.666	3.891
4	08:30-18:30	76.07	27.9	18.63	5.194	5.078
5	08:30-18:30	54.03	29.34	20.51	4.197	4.138
6	08:30-18:30	42.46	20.68	69.56	4.361	4.121
7	08:30-18:30	41.87	26.69	30.28	3.742	3.761
8	08:30-18:30	77.45	30.02	21.64	5.055	4.955
9	08:30-18:30	68.28	29.45	25.32	4.601	4.977
10	08:30-18:30	57.14	30.33	23.89	4.041	4.077
11	08:30-18:30	57.14	30.23	23.5	4.084	4.081
12	08:30-18:30	64.18	31.33	23.06	4.331	4.258

13	08:30-18:30	46.97	25.48	27.12	3.988	4.022
14	08:30-18:30	48.74	26.97	26.05	3.812	3.991
15	08:30-18:30	64.65	25.39	29.94	4.961	5.071

5.3. DEVELOPMENT OF THE MULTI-NONLINEAR REGRESSION (MNL) MODEL

A multi-nonlinear regression model was developed to determine the EF of the HSAASHP water heater, using the electrical energy consumption (x_1), ambient temperature (x_2), and relative humidity (x_3) as the input parameters and figure 5.1 illustrates that. The importance or rank of these input parameters was determined using the relief algorithm [109]. The accuracy of the HSAASHP water heater was determined using the root-mean-square-error, p-value and determination coefficient by referencing the modelled output (EF) to the calculated output (EF) [24]. A polyfit graph was used to determine the relationship between the calculated and developed EF values. The equation for the developed mathematical model is given in Equation 5.1 below [92]

$$y = \frac{\beta_1 x_2 - x_3 / \beta_5}{(1 + \beta_2 x_1 + \beta_3 x_2 + \beta_4 x_3)} \quad (5.1)$$

Whereby

y = energy factor

x_1 = energy consumption of the HSAASHP (kWh)

x_2 = ambient temperature ($^{\circ}\text{C}$)

x_3 = relative humidity (%)

β_1 = the scaling factor of x_2 ($^{\circ}\text{C}$)

β_2 = scaling factor of x_1 (kWh)

β_3 = another scaling factor of x_2 ($^{\circ}\text{C}$)

β_4 = scaling factor of x_3 in (%)

β_5 = another scaling factor of x_3 (%)

MATLAB coding was utilized to build the MNLR model, with the modelled equation serving as the optimization function. The desired output (EF) of the model was represented by y , and x_1 , x_2 , and x_3 are the input parameters, and β_1 , β_2 , β_3 , β_4 and β_5 are the scaling constants assigned to specific input parameters. The input parameter, x_1 , has β_2 assigned to it, x_2 has β_1 and β_3 assigned to it, and x_3 has β_4 and β_5 assigned to it. The initial values of the input and output parameters from the test data set obtained from the HSAASHP water heater loggers were used to determine the scaling factor values (β_1 , β_2 , β_3 , β_4 and β_5), with values of 2.637×10^9 , -1.634×10^8 , 9.510×10^8 , 5.413×10^6 and 1.390×10^{10} , respectively. It should be noted that the test data set was also used to train the MNLR model. Using the train data on the developed model gave a correlation coefficient (r), root mean square error (RMSE), determination coefficient (r^2), and the p-value between the measured EF and the modelled EF to be 0.9819, 0.118, 0.9643 and 0.9982, respectively. Based on the train data set, the model proved to be accurate, because the p-value was greater than the threshold value of 0.05, the determination coefficient was close to 1, and the root mean square error was close to zero and less than the smallest measured value of the EF, which is 3.542. Figure 5.1 shows the graph of the predicted and measured EF for the HSAASHP water heater.

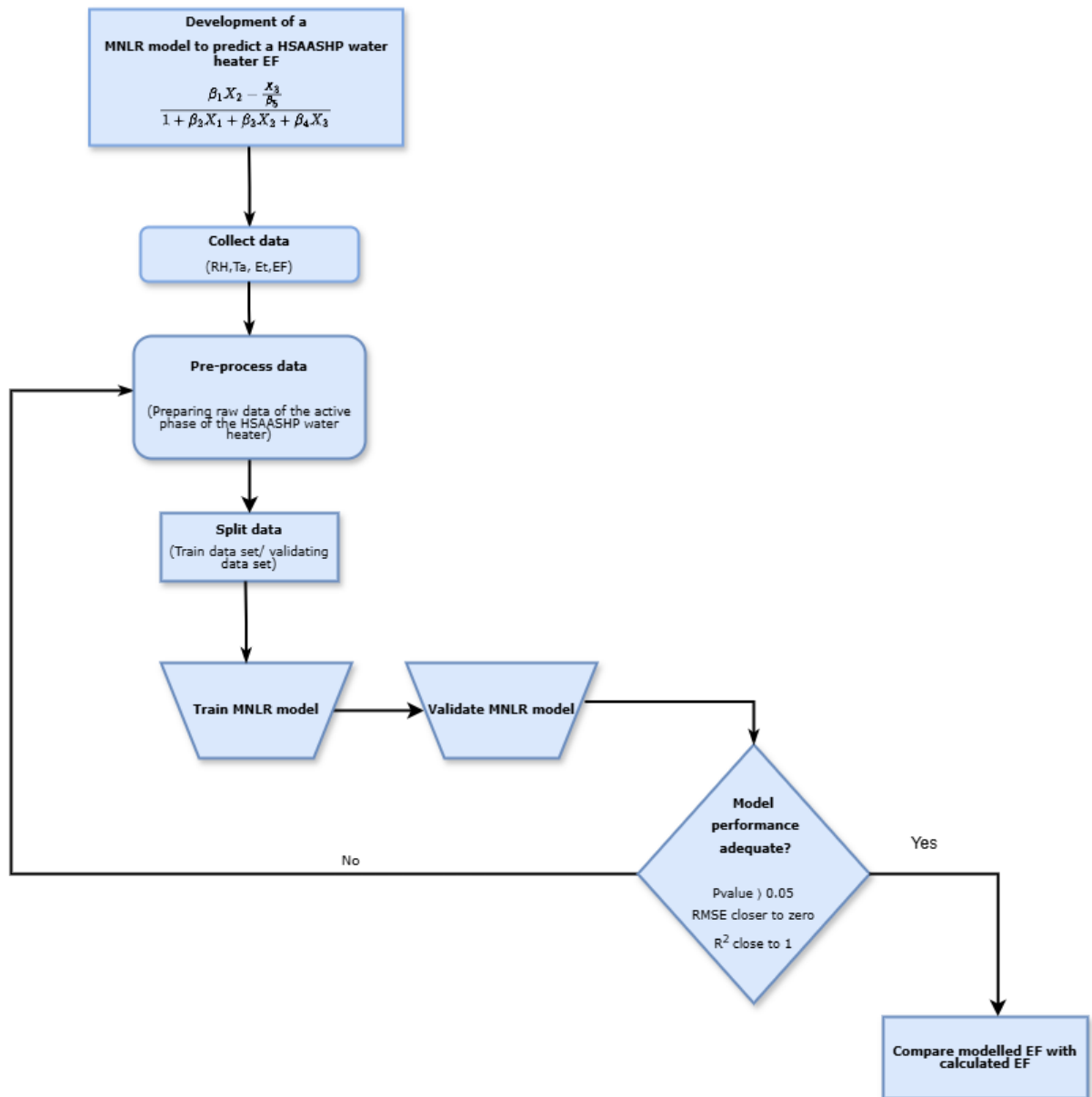


Figure 5:1:Flow diagram of the development of the MNLR model

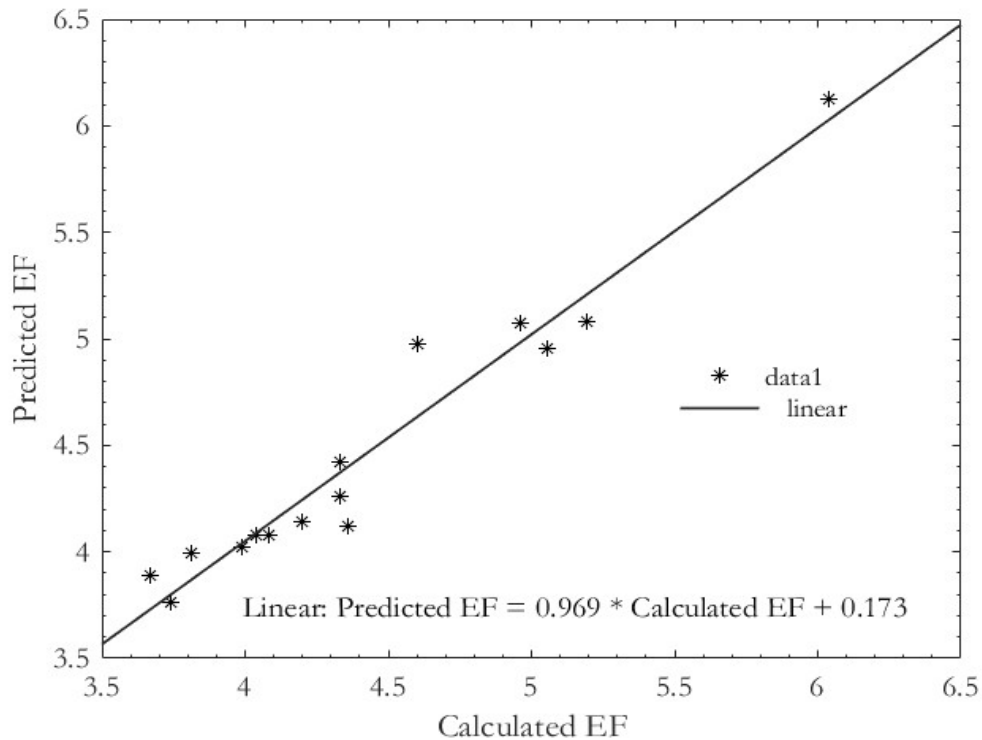


Figure 5:2: Calculated EF vs predicted EF using train set data

5.4. RELIEFF USED TO DETERMINE THE WEIGHT AND RANK OF THE INPUT PARAMETERS

The weight and rank of the input parameters were determined using a reliefF algorithm on MATLAB [110]. Determining the weight and rank of the input parameters were achieved by writing a command $(\text{rank}, \text{weight}) = \text{reliefF}(\text{x y k})$, whereby x = input parameters, y = output and k = number of potential predictors, in this instance, a default setting of 10 was used. The weight ranges from -1 to 1. A positive number implies the input parameter is a primary factor, and a negative number implies that the input parameter is a secondary factor. A higher positive value means that the input parameter contributes significantly to the desired output. The input parameters that had to be ranked according

to their importance were x_1 = electrical consumption, x_2 = ambient temperature and x_3 = relative humidity. The results indicated that electrical consumption is a primary factor of weight (0.1564), while the ambient temperature and relative humidity are secondary factors with weights (-0.002) and (-0.0176), respectively.

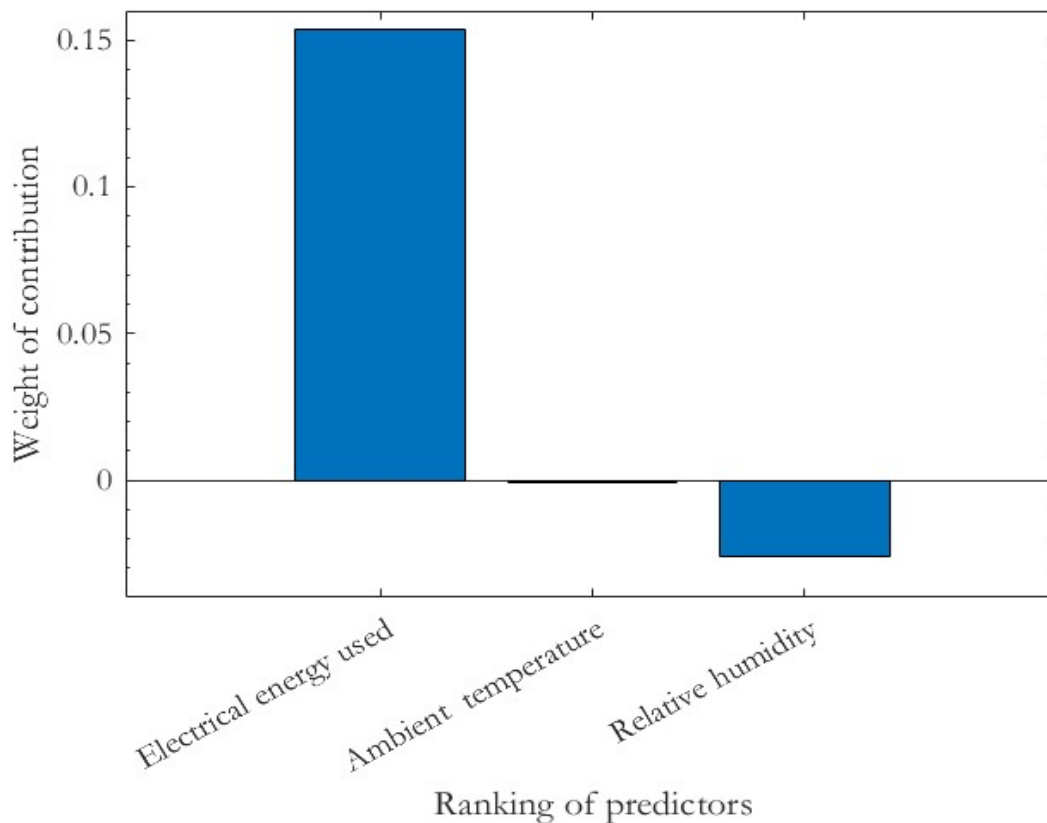


Figure 5:3: Weights ranking of predictors according to importance with the Energy Factor

5.5. VALIDATION OF THE MODEL

For validation of the MNLR model, another set of data from the data loggers, installed to collect data from the HSAASHP water heater, was used. The processed data

were taken from March 2023. The data used for validation of the second phase was taken when the evacuated SCs and ASHP were both active. The HSAASHP water heater validating set data was monitored for eight hours from 08:30 to 18:30, the monitoring was done in 30-minute intervals. Table 5.2 illustrates the validating data set of the HSAASHP water heater.

The validation data set shows a range from 32.13 to 74.01 kWh of the total electrical energy consumed, with an average of 55.74 kWh. The ambient temperature ranged from 20.87 to 36.45 °C with a mean of 28.95 °C, while the relative humidity ranged from 41.78 to 54.39% with a mean of 47.34%. The EF ranged from 3.451 to 5.295, with a mean of 4.147.

Table 5.2: Validating data set of the input parameters and desired output of the HSAASHP water heater performance

SD	Period	Et	Tamb	RH	EFcal	EFval
	(h)	(kWh)	(°C)	(%)		
1	08:30–18:30	64.25	36.45	49.82	4.044	3.933
2	08:30–18:30	61.87	34.17	42.43	4.103	3.984
3	08:30–18:30	74.01	27.3	41.78	5.295	5.106
4	08:30–18:30	69.69	27.12	47.47	4.906	4.877
5	08:30–18:30	62.60	33.67	54.39	4.011	4.020
6	08:30–18:30	69.94	33.93	45.10	4.397	4.243
7	08:30–18:30	46.9	32.51	48.77	3.451	3.645
8	08:30–18:30	36.92	20.87	43.35	3.740	3.917
9	08:30–18:30	39.16	21.67	51.26	4.000	3.944
10	08:30–18:30	32.13	21.82	49.00	3.524	3.649

On the validating data set the average daily energy and cost usage are used to validate the MNLR model monitoring the electrical consumption of the ASHP (kWh), ambient temperature (°C), and relative humidity (%). The results revealed that the root mean square error (RMSE), determination coefficient (r^2), and the p-value between the calculated EF and the modelled EF were 0.1320, 0.9640 and 0.9514, respectively. The r^2 of 0.9514 suggests that 95% of the difference in the target variable is explained by the model. The modelled output values of the validating data set correlate with the output values of the calculated values. Figure 5.3 shows the predicted and calculated values of the energy factor using the validation data set.

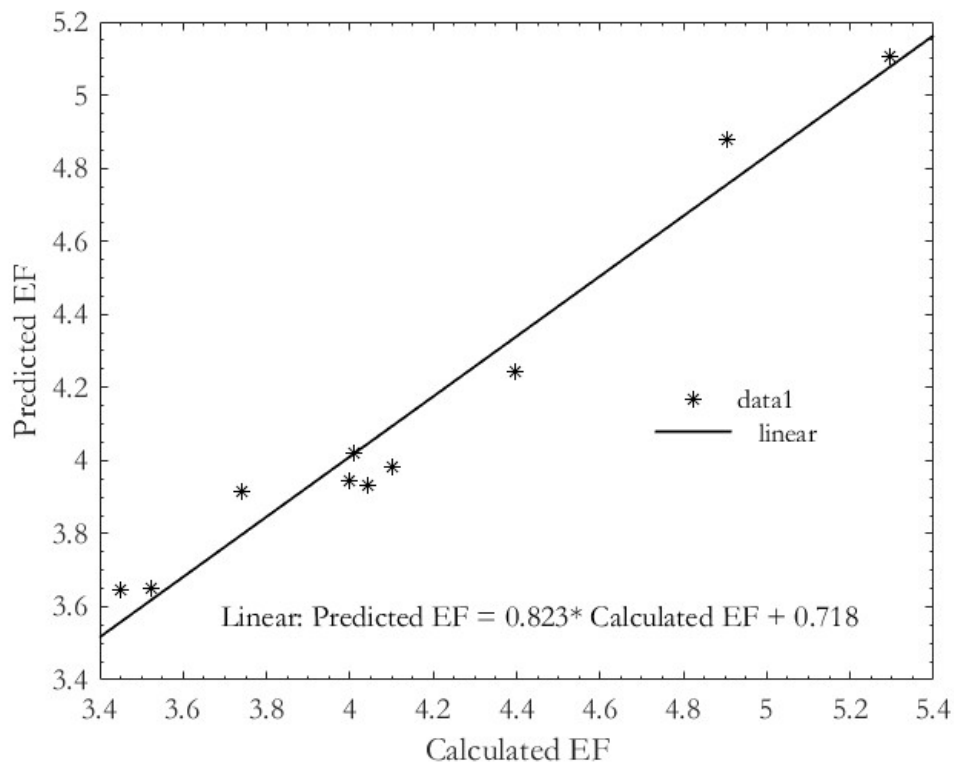


Figure 5:4: Calculated EF vs predicted EF using validating set data

5.6. COMPARISON OF MEASURED EF AND MODELLED EF USING ONE-WAY ANOVA

Table 5.3 below illustrates the ANOVA table for the calculated EF output and the modelled EF output using the input parameters from the train data set. On the ANOVA Table 5.3, the source consists of columns and errors whose sum of squares between groups is 0 and within groups is 11.424, respectively. The degree of freedom within columns is the subtraction of 1 from the number between groups, which is equal to 1. The degree of freedom of the error is equal to the degree of freedom within the groups and was equal to 28. The total degree of freedom is the sum of the degree of freedom between columns and errors and was 29.

The groups of calculated and modelled outputs showed the mean square of columns as a ratio of $(0/1)$, which is equal to 0, whereas the mean square of columns is the fraction of the sum of squares and the degree of freedom for error, which is $(11.424/28)$ and equal to 0.408. The fraction of the mean square of the columns and error was $(0/0.408)$, which is equal to 4.702×10^{-6} and equivalent to the F-statistic. The p-value is equivalent to the probability of the F-statistic and was 0.998. The p-value is greater than the threshold value of 0.05 (0.998) and demonstrates that there is no significant difference between the calculated EF (EF_{cal}) and the modelled EF (EF_{mod}).

Table 5.3: Statistics based on the predicted and modelled outputs with the multi-
nonlinear regression model

Source	Sum of Square (SS)	Degree of Freedom (df)	Mean Square (MS)	F	Prob >F
Columns	0	1	0.000	4.702×10^{-6}	0.998
Error	11.424	28	0.408		
Total	11.424	29			

An ANOVA plot in Figure 5.4 was also used to further explain the degree of accuracy between the calculated (determined) data values and predicted data values using the nonlinear regression model. The calculated and modelled values of the EF are both illustrated in Figure 5.4. The median value is represented by the red line in the figure, and the calculated and modelled EF were 4.329 and 3.716, respectively, while the maximum value of the calculated and modelled were 6.037 and 6.126, respectively, and the minimum values of the calculated and modelled EF were 3.666 and 3.761, respectively. The p-value from the one-way ANOVA plot was 0.998 and, hence, demonstrated no significant difference between the modelled and calculated values. Therefore, the developed model for the energy factor is accurately predicting the determined EF.

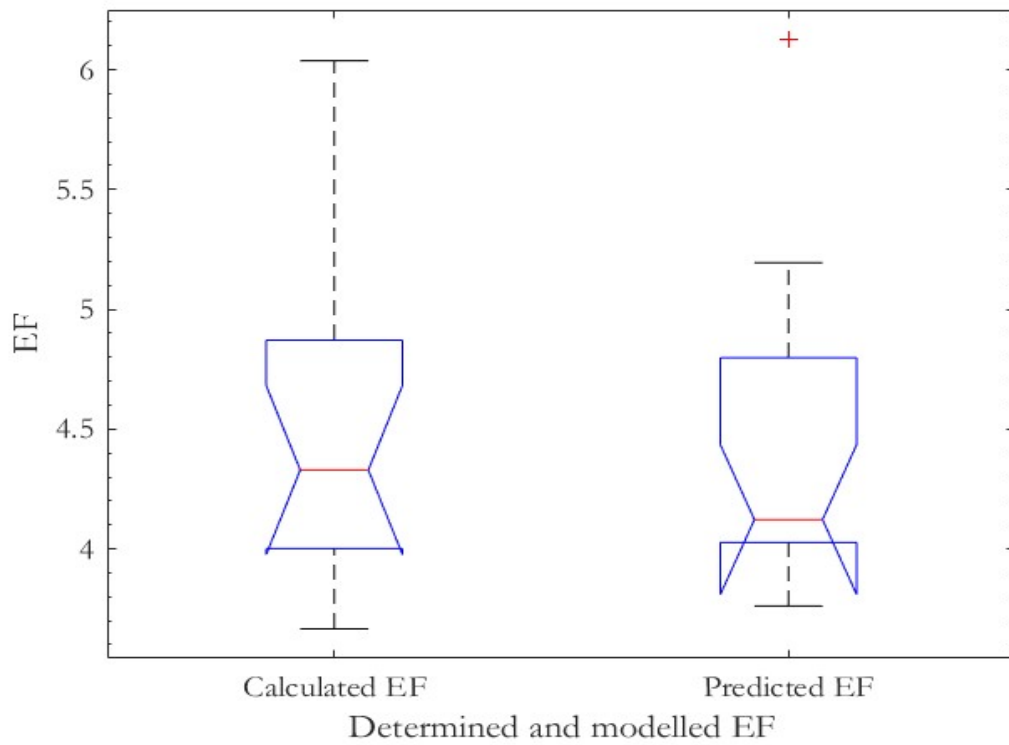


Figure 5:5: ANOVA plots of the predicted and modelled energy factors (test data set)

5.7. SUMMARY

In this chapter, the MNLR model was trained using the raw data set from the HSAASHP water heater collected from the installed data loggers. The values obtained for the determination of the coefficient, r^2 , root mean square, and p-value were within the range to indicate that the model is accurate and acceptable. The formula $y = \frac{\beta_1 X_2 - X_3 / \beta_5}{(1 + \beta_2 X_1 + \beta_3 X_2 + \beta_4 X_3)}$ was used to develop the model and it was validated using a different validated data set, the train values for the RMSE, r^2 , and the p-value between the measured EF and the modelled EF was 0.1180, 0.9643 and 0.998, respectively. The r^2 of 0.9644 suggests that 96% of the difference in the target variable is explained by the model. The

input parameters considered for this model were electrical energy, ambient temperature and relative humidity, and the reliefF algorithm illustrated that the electrical energy consumed is a primary parameter, while the ambient temperature and relative humidity were secondary parameters. The comparison of the measured and modelled EF outputs using the ANOVA plots with the train data set showed the p-value as 0.998 and the absolute difference between the calculated and predicted values for the minimum, median and maximum values were 0.095, 0.613 and 0.089, respectively which shows that there is strong agreement correlation between the modelled and measured EFs. In conclusion, the model demonstrated no significant differences as the predicted values closely matched the actual measured values for the EF, validating the model.

CHAPTER 6: CONCLUSION

6.1. FINAL CONCLUSIONS

This research, due to favourable results, managed to successfully address the immediate need for cost-effective and energy-efficient solutions for heating sanitary hot water in a South African university residence. The designed and installed HSAASHP water heater at the Mannheim Ladies' Residence proved to be extremely efficient and economically viable. The electrical energy consumption and operations were significantly reduced by replacing the inefficient 2 000 L, 24 kW electric boiler with SCs and an ASHP unit referred to as an HSAASHP water heater.

This research emphasizes the following key outcomes:

- **Energy efficiency:** The inefficient electrical energy consumption of the electric boiler before retrofitting ranged from 3 852.26 kWh to 16 844.96 kWh. After retrofitting, the electrical energy consumption decreased significantly, ranging from 809.3 kWh to 5 973.4 kWh. The HSAASHP system's ability to save energy was demonstrated by the reduction of the total electrical energy consumption from 151 128.9 kWh to 41 036.8 kWh during a one-year period.
- **Economic viability:** According to the techno-economic analysis, the PBP was just 2.19 years, and the break-even point was reached in two years. With a remarkable investment gain of R2 624 547.17 (139 101USD), profit of 87% and an annualized ROI of 14.39%, the HSAASHP water heater estimated NPV over a 15-year period was R3 027 461,79 (160 455,5 USD). These figures support the long-term financial gains from the HSAASHP water heater implementation.

- Accurate modelling: The MNLR model's r^2 value of 0.9641 illustrated that it was highly accurate, meaning 96% of the difference in the target variable of the model was elaborated by the model. The model further validated its reliability by confirming a good correlation between the expected and measured EF values.
- Sustainability: The HSAASHP water heater contributes to larger objectives of environmental sustainability and lower carbon emissions by using renewable energy sources and decreasing dependency on Eskom's coal-based grid.

In conclusion, according to this research, the HSAASHP water heater is an efficient water heating system for university residences and other comparable establishments, offering a consistent supply of hot water with improved energy efficiency throughout the year.

6.2. SUGGESTIONS FOR FURTHER RESEARCH

- The study is limited to one experiment, which is solely at the CUT residence. As the HSAASHP water heater has proven to be efficient and economically viable, it is suggested that universities should implement the same HSAASHP water heaters at their university residences which will help in reducing electricity costs especially in students' residences, which are the major consumers of electricity.
- To further optimize energy use, future research could investigate connecting the HSAASHP system with smart grid technologies, enabling demand-side

management and real-time monitoring. Grid reliability and energy efficiency could be improved by such integration.

- Further studies should be conducted on other MNL model input factors, such as water flow rates and pressure, to improve the model's predictive power and broaden its applicability in other contexts.

REFERENCES

- [1] O. J. Oladunni, K. Mpofu, and O. A. Olanrewaju, “Greenhouse gas emissions and its driving forces in the transport sector of South Africa,” *Energy Reports*, vol. 8, pp. 2052–2061, 2022, doi: 10.1016/j.egyr.2022.01.123.
- [2] J. Burton, A. Marquard, and B. McCall, “Socio-Economic Considerations for a Paris Agreement-Compatible Coal Transition in South Africa,” no. July, pp. 1–24, 2019, [Online]. Available: www.climate-transparency.org
- [3] H. R. Bohlmann, J. M. Horridge, R. Inglesi-Lotz, E. L. Roos, and L. Stander, “Regional employment and economic growth effects of South Africa’s transition to low-carbon energy supply mix,” *Energy Policy*, vol. 128, no. January, pp. 830–837, 2019, doi: 10.1016/j.enpol.2019.01.065.
- [4] M. Piercer, W (CSIR); Le Roux, “Statistics of utility-scale power generation un South Africa.” Accessed: Apr. 23, 2023. [Online]. Available: [chrome-extension://efaidnbmnnnibpcajpcgiclfndmkaj/https://www.csir.co.za/sites/default/files/Documents/Statistics of power in SA 2022-CSIR-%5BFINAL%5D.pdf](chrome-extension://efaidnbmnnnibpcajpcgiclfndmkaj/https://www.csir.co.za/sites/default/files/Documents/Statistics%20of%20power%20in%20SA%202022-CSIR-%5BFINAL%5D.pdf)
- [5] G. Nene, P. Mashau, and S. Mpanza, “Impact of coal prices changes on prices of electricity in South Africa,” *Bus. Manag. Rev.*, vol. 14, no. 01, pp. 10–12, 2023, doi: 10.24052/bmr/v14nu01/art-07.
- [6] P. A. Hohne, K. Kusakana, and B. P. Numbi, “Optimal energy management and economic analysis of a grid-connected hybrid solar water heating system: A case of Bloemfontein, South Africa,” *Sustain. Energy Technol. Assessments*, vol. 31, no. December 2018, pp. 273–291, 2019, doi: 10.1016/j.seta.2018.12.027.
- [7] P. G. Rousseau, J. P. Strauss, and G. P. Greyvenstein, “Demand side management

- for water heating installations in South African commercial buildings,” *Int. J. Energy Res.*, vol. 25, no. 4, pp. 291–317, 2001, doi: 10.1002/er.680.
- [8] S. Tangwe, N. Mzolo, M. Simon, and E. Meyer, “Modeling the demand of a calorifier to establish the baseline before retrofitting it with a commercial air source heat pump,” in *2014 International Conference on the Eleventh Industrial and Commercial Use of Energy*, 2014, pp. 1–8.
- [9] N. Maistry and T. M. McKay, “Promoting energy efficiency in a South African university,” *J. Energy South. Africa*, vol. 27, no. 3, pp. 1–10, 2016, doi: 10.17159/2413-3051/2016/v27i3a1553.
- [10] T. P. Gaonwe, K. Kusakana, and P. A. Hohne, “Walk-through Energy Audit and Savings opportunities: Case of Water Heaters at CUT Residential Buildings,” *2019 Open Innov. Conf. OI 2019*, pp. 434–439, 2019, doi: 10.1109/OI.2019.8908172.
- [11] Q. Catherine, J. Wheeler, R. Wilkinson, and G. de Jager, “Hot water usage profiling to improve geyser efficiency,” *J. Energy South. Africa*, vol. 23, no. 1, pp. 39–45, 2012, doi: 10.17159/2413-3051/2012/v23i1a3156.
- [12] B. K. Bose, “Global warming: Energy, environmental pollution, and the impact of power electronics,” *IEEE Ind. Electron. Mag.*, vol. 4, no. 1, pp. 6–17, 2010, doi: 10.1109/MIE.2010.935860.
- [13] S. Jaisankar, J. Ananth, S. Thulasi, S. T. Jayasuthakar, and K. N. Sheeba, “A comprehensive review on solar water heaters,” *Renew. Sustain. Energy Rev.*, vol. 15, no. 6, pp. 3045–3050, 2011, doi: 10.1016/j.rser.2011.03.009.
- [14] A. Naidoo, “The socio-economic impacts of solar water heaters compared across two communities: A case study of Cato Manor,” *Renew. Sustain. Energy Rev.*, vol. 119, no. October 2019, p. 109525, 2020, doi: 10.1016/j.rser.2019.109525.

- [15] E. D. Özdemir, S. D. Marathe, J. Tomaschek, A. Dobbins, and L. Eltrop, “Economic and environmental analysis of solar water heater utilisation in Gauteng Province, South Africa,” *J. Energy South. Africa*, vol. 23, no. 2, pp. 2–19, 2012, doi: 10.17159/2413-3051/2012/v23i2a3157.
- [16] M. Sikhonza, S. Tangwe, and M. Simon, “Statistical analysis of split type air source heat pump water heaters,” *2018 Int. Conf. Domest. Use Energy, DUE 2018*, pp. 1–8, 2018, doi: 10.23919/DUE.2018.8384388.
- [17] A. Amirirad, R. Kumar, A. S. Fung, and W. H. Leong, “Experimental and simulation studies on air source heat pump water heater for year-round applications in Canada,” *Energy Build.*, vol. 165, pp. 141–149, 2018, doi: 10.1016/j.enbuild.2018.01.052.
- [18] H. Willem, Y. Lin, and A. Lekov, “Review of energy efficiency and system performance of residential heat pump water heaters,” *Energy Build.*, vol. 143, pp. 191–201, 2017, doi: 10.1016/j.enbuild.2017.02.023.
- [19] S. loh Tangwe and M. Simon, “Quantification of the viability of residential air source heat pump water heaters as potential replacement for geysers in South Africa,” *J. Eng. Des. Technol.*, vol. 17, no. 2, pp. 456–470, 2019, doi: 10.1108/JEDT-05-2017-0042.
- [20] L. Zhu, J. Yu, M. Zhou, and X. Wang, “Performance analysis of a novel dual-nozzle ejector enhanced cycle for solar assisted air-source heat pump systems,” *Renew. Energy*, vol. 63, pp. 735–740, 2014, doi: 10.1016/j.renene.2013.10.030.
- [21] A. Nuntaphan, C. Chansena, and T. Kiatsiriroat, “Performance analysis of solar water heater combined with heat pump using refrigerant mixture,” *Appl. Energy*, vol. 86, no. 5, pp. 748–756, 2009, doi: 10.1016/j.apenergy.2008.05.014.
- [22] Z. Chen, C. Qin, and Q. Jin, “Experimental and theoretical study on a hybrid

- residential hot water system with solar and gas,” *J. Nat. Gas Sci. Eng.*, vol. 26, pp. 974–980, 2015, doi: 10.1016/j.jngse.2015.07.037.
- [23] S. L. Tangwe and K. Kusakana, “Quantitative Assessment of the Impact of Retrofitting an Electric Boiler with an Air Source Heat Pump Unit on a University Campus,” *Int. J. Simul. Syst. Sci. Technol.*, pp. 1–10, 2020, doi: 10.5013/ijssst.a.21.02.28.
- [24] M. Sikhonza, S. Tangwe, N. Mzolo, and C. Manyi-loh, “The development of a multiple linear regression model to predict the performance of a hybrid solar air source heat pump water heater,” in *AIUE Proceedings of the 2nd Energy and Human Habitat Conference 2021*, 2021, pp. 2–8.
- [25] S. C. S. Jucá, P. C. M. Carvalho, and F. T. Brito, “A low cost concept for data acquisition systems applied to decentralized renewable energy plants,” *Sensors*, vol. 11, no. 1, pp. 743–756, 2011, doi: 10.3390/s110100743.
- [26] O. Langniß and D. Ince, “Solar water heating,” *Sol. Energy*, no. June, pp. 18–21, 2004.
- [27] S. A. Raza, S. S. Ahmad, T. A. H. Ratlamwala, G. Hussain, and M. Alkahtani, “Techno-economic analysis of glazed, unglazed and evacuated tube solarwater heaters,” *Energies*, vol. 13, no. 23, pp. 1–18, 2020, doi: 10.3390/en13236261.
- [28] R. Lazzarin, “Heat pumps and solar energy : A review with some insights in the future,” *Int. J. Refrig.*, vol. 116, pp. 146–160, 2020, doi: 10.1016/j.ijrefrig.2020.03.031.
- [29] J. J. Ramírez-minguela, J. A. Alfaro-ayala, V. H. Rangel-hernández, and A. R. Uriberamírez, “Comparison of the thermo-hydraulic performance and the entropy generation rate for two types of low temperature solar collectors using CFD,” *Sol. Energy*, vol. 166, no. March, pp. 123–137, 2018, doi: 10.1016/j.solener.2018.03.050.
- [30] S. Ran, X. Li, W. Xu, and B. Wang, “A solar-air hybrid source heat pump for space

- heating and domestic hot water,” *Sol. Energy*, vol. 199, no. November 2019, pp. 347–359, 2020, doi: 10.1016/j.solener.2020.02.038.
- [31] M. R. Islam, K. Sumathy, and S. Ullah, “Solar water heating systems and their market trends,” *Renew. Sustain. Energy Rev.*, vol. 17, pp. 1–25, 2013, doi: 10.1016/j.rser.2012.09.011.
- [32] Z. Rahimi-Ahar, M. Khiadani, L. Rahimi Ahar, and A. Shafieian, “Performance evaluation of single stand and hybrid solar water heaters: a comprehensive review,” *Clean Technol. Environ. Policy*, vol. 25, no. 7, pp. 2157–2184, 2023, doi: 10.1007/s10098-023-02556-6.
- [33] B. Ali, K. Sopian, M. Al Ghouli, M. Y. Othman, A. Zaharim, and A. M. Razali, “Economics of domestic solar hot water heating systems in Malaysia,” *Eur. J. Sci. Res.*, vol. 26, no. 1, pp. 20–28, 2009.
- [34] G. Donev, W. G. J. H. M. Van Sark, K. Blok, and O. Dintchev, “Solar water heating potential in South Africa in dynamic energy market conditions,” *Renew. Sustain. Energy Rev.*, vol. 16, no. 5, pp. 3002–3013, 2012, doi: 10.1016/j.rser.2012.01.065.
- [35] J. Varghese and K. Manjunath, “Techno-economic analysis of an integrated collector storage solar water heater with CPC reflector for households,” *Int. J. Ambient Energy*, vol. 0750, 2018, doi: 10.1080/01430750.2017.1354327.
- [36] A. Dhiman and G. Sachdeva, *Comparative Analysis of the Payback Period for Different Types of Solar Energy Systems Used in India*. Springer Singapore, 2021. doi: 10.1007/978-981-16-0909-1_53.
- [37] M. Dehghan, C. F. Pfeiffer, and E. Rakhshani, “A Review on Techno-Economic Assessment of Solar Water Heating Systems in the Middle East,” *Energies*, vol. 14, no. 16, pp. 1–28, 2021.

- [38] S. L. Tangwe, “Demonstration of residential air source heat pump water heaters performance in South Africa: Systems monitoring and modelling,” University of Sunderland, 2018.
- [39] P. Carroll, M. Chesser, and P. Lyons, “Air Source Heat Pumps field studies : A systematic literature review,” *Renew. Sustain. Energy Rev.*, vol. 134, no. July, p. 110275, 2020, doi: 10.1016/j.rser.2020.110275.
- [40] Q. Wang, F. Liu, L. Hou, and J. Gao, “Simulative study on solar-assisted air source heat pump system,” *Adv. Mater. Res.*, vol. 671, pp. 2141–2144, 2013, doi: 10.4028/www.scientific.net/AMR.671-674.2141.
- [41] O. Kara, K. Ulgen, and A. Hepbasli, “Exergetic assessment of direct-expansion solar-assisted heat pump systems : Review and modeling,” *Renew. Sustain. Energy Rev.*, vol. 12, pp. 1383–1401, 2008, doi: 10.1016/j.rser.2006.12.001.
- [42] P. G. Rousseau and G. P. Greyvenstein, “Enhancing the impact of heat pump water heaters in the South African commercial sector,” *Energy*, vol. 25, pp. 51–70, 2000.
- [43] P. Laipradit, J. Tiansuwan, T. Kiatsiriroat, and L. Aye, “Theoretical performance analysis of heat pump water heaters using carbon dioxide as refrigerant,” *Int. J. Energy Res.*, vol. 32, no. June 2006, pp. 356–366, 2008, doi: 10.1002/er.
- [44] G. L. Morrison, T. Anderson, and M. Behnia, “Seasonal performance rating of heat pump water heaters,” *Sol. Energy*, vol. 76, no. 1–3, pp. 147–152, 2004, doi: 10.1016/j.solener.2003.08.007.
- [45] H. Sadeghi, A. Ijaz, and R. M. Singh, “Current status of heat pumps in Norway and analysis of their performance and payback time,” *Sustain. Energy Technol. Assessments*, vol. 54, no. April, p. 102829, 2022, doi: 10.1016/j.seta.2022.102829.
- [46] M. Song, J. Dong, C. Wu, Y. Jiang, and M. Qu, “Improving the frosting and

- defrosting performance of air source heat pump units: review and outlook,” *HKIE Trans. Hong Kong Inst. Eng.*, vol. 24, no. 2, pp. 88–98, 2017, doi: 10.1080/1023697X.2017.1313134.
- [47] S. L. Tangwe, M. Simon, and R. Mhundwa, “The performance of split and integrated types air-source heat pump water heaters in South Africa,” *J. Energy South. Africa*, vol. 29, no. 2, pp. 12–20, 2018, doi: 10.17159/2413-3051/2018/v29i2a4358.
- [48] C. Riedy, P. Ryan, G. Milne, P. Alviano, and S. Dwyer, “Hot water systems.” Accessed: Nov. 04, 2024. [Online]. Available: <https://www.yourhome.gov.au/energy/hot-water-systems>
- [49] S. loh Tangwe, M. S. Edson, and L. Meyer, “Design of a heat pump water heater performance monitoring system : to determine performance of a split type system,” *J. Eng. Des. Technol.*, vol. 14, no. 4, pp. 1–10, 2016.
- [50] J. Bursill and C. A. Cruickshank, “Heat Pump Water Heater Control Strategy Optimization for Cold Climates,” *J. Sol. Energy Eng.*, vol. 138, pp. 1–8, 2016, doi: 10.1115/1.4032144.
- [51] P. Gang, L. Guiqiang, and J. Jie, “Comparative study of air-source heat pump water heater systems using the instantaneous heating and cyclic heating modes,” *Appl. Therm. Eng.*, vol. 31, no. 2–3, pp. 342–347, 2011, doi: 10.1016/j.applthermaleng.2010.09.020.
- [52] Y. Noorollahi, H. G. Arjenaki, and R. Ghasempour, “Thermo-economic modeling and GIS-based spatial data analysis of ground source heat pump systems for regional shallow geothermal mapping,” *Renew. Sustain. Energy Rev.*, vol. 72, no. January, pp. 648–660, 2017, doi: 10.1016/j.rser.2017.01.099.
- [53] M. El Haj Assad, M. N. Almallahi, M. Alshabi, and H. Delnava, “Heating and

- Cooling By Geothermal Energy,” *2022 Adv. Sci. Eng. Technol. Int. Conf. ASET 2022*, pp. 1–7, 2022, doi: 10.1109/ASET53988.2022.9734943.
- [54] I. A. Gondal, “Prospects of shallow geothermal systems in HVAC for NZEB,” *Energy Built Environ.*, vol. 2, no. 4, pp. 425–435, 2021, doi: 10.1016/j.enbenv.2020.09.007.
- [55] K. J. Chua, S. K. Chou, and W. M. Yang, “Advances in heat pump systems: A review,” *Appl. Energy*, vol. 87, no. 12, pp. 3611–3624, 2010, doi: 10.1016/j.apenergy.2010.06.014.
- [56] T. Aprianti, E. Tan, C. Diu, G. Ryan, and H. T. Chua, “A comparison of ground and air source heat pump performance for domestic applications: A case study in Perth, Australia,” *Int. J. Energy Res.*, vol. 45, no. 15, pp. 20686–20699, 2021, doi: 10.1002/er.7133.
- [57] L. Buijze, L. Van Bijsterveldt, and H. Cremer, “Review of induced seismicity in geothermal systems worldwide and implications for geothermal systems in the Netherlands,” *Geol. en Mijnbouw/Netherlands J. Geosci.*, vol. 2019, 2020, doi: 10.1017/njg.2019.6.
- [58] C. Nsanzubuhoro, “Optimisation of feedwater heaters and geothermal preheater in fossil-geothermal Hybrid Power Plant,” 2019.
- [59] P. Farzanehkhameh, M. Soltani, and F. Moradi, “Optimization and energy-economic assessment of a geothermal heat pump system,” *Renew. Sustain. Energy Rev.*, vol. 133, no. July, p. 110282, 2020, doi: 10.1016/j.rser.2020.110282.
- [60] S. P. Lohani and D. Schmidt, “Comparison of energy and exergy analysis of fossil plant, ground and air source heat pump building heating system,” *Renew. Energy*, vol. 35, no. 6, pp. 1275–1282, 2010, doi: 10.1016/j.renene.2009.10.002.

- [61] S. J. Self, B. V Reddy, and M. A. Rosen, “Geothermal heat pump systems : Status review and comparison with other heating options,” *Appl. Energy*, vol. 101, pp. 341–348, 2013, doi: 10.1016/j.apenergy.2012.01.048.
- [62] M. Baneshi and S. A. Bahreini, “Impacts of hot water consumption pattern on optimum sizing and techno- economic aspects of residential hybrid solar water heating systems,” *Sustain. Energy Technol. Assessments*, vol. 30, no. September, pp. 139–149, 2018, doi: 10.1016/j.seta.2018.09.008.
- [63] A. Kumar, K. A. Goyal, and M. . Sodha, “Technoeconomic optimization of solar natural convection hybrid hot water systems,” *Int. J. Energy Res.*, vol. 12, no. February, pp. 661–678, 1988.
- [64] J. Wiehagen and T. Kenney, “Hybrid Domestic Hot Water System for Efficiency and Performance — Preliminary Design,” *Energy Eng.*, vol. 104, no. 6, pp. 37–41, 2009, doi: 10.1080/01998590709509519.
- [65] E. Dudkiewicz and N. Fidorów-Kaprawy, “Hybrid Domestic Hot Water System Performance in Industrial Hall,” *Resources*, vol. 9, no. 65, pp. 1–12, 2020.
- [66] R. A. Jordan, J. T. Yamasaki, V. S. Júnior, and E. C. B. Dória, “Hybrid solar heat pump system for water heating,” *Eng. Agric.*, vol. 39, no. 4, pp. 419–425, 2019, doi: 10.1590/1809-4430-Eng.Agric.v39n4p419-425/2019.
- [67] Y. Cui, J. Zhu, S. Zoras, Y. Qiao, and X. Zhang, “Energy performance and life cycle cost assessments of a photovoltaic / thermal assisted heat pump system,” pp. 1–35.
- [68] M. Azly, A. Aziz, S. Mat, and K. Sopian, “Technology Review of Solar Assisted Heat Pump System for Hot Water Production,” *Latest Trends Renew. Energy Environ. Informatics*, pp. 65–75, 2013.
- [69] T. Kim, B. Choi, Y. Han, and K. Hyung, “A comparative investigation of solar-

- assisted heat pumps with solar thermal collectors for a hot water supply system,” *Energy Convers. Manag.*, vol. 172, no. July, pp. 472–484, 2018, doi: 10.1016/j.enconman.2018.07.035.
- [70] T. P. Gaonwe, K. Kusakana, and P. A. Hohne, “A review of solar and air-source renewable water heating systems, under the energy management scheme,” *Energy Reports*, vol. 8, pp. 1–10, 2022, doi: 10.1016/j.egyr.2022.10.065.
- [71] M. S. Buker and S. B. Riffat, “Solar assisted heat pump systems for low temperature water heating applications: A systematic review,” *Renew. Sustain. Energy Rev.*, vol. 55, pp. 399–413, 2016, doi: 10.1016/j.rser.2015.10.157.
- [72] H. Li and H. Yang, “Study on performance of solar assisted air source heat pump systems for hot water production in Hong Kong,” *Appl. Energy*, vol. 87, no. 9, pp. 2818–2825, 2010, doi: 10.1016/j.apenergy.2009.06.023.
- [73] K. Sezen, A. D. Tuncer, A. O. Akyuz, and A. Gungor, “Effects of ambient conditions on solar assisted heat pump systems: a review,” *Sci. Total Environ.*, vol. 778, 2021, doi: 10.1016/j.scitotenv.2021.146362.
- [74] G. Panaras, E. Mathioulakis, and V. Belessiotis, “Investigation of the performance of a combined solar thermal heat pump hot water system,” *Sol. Energy*, vol. 93, pp. 169–182, 2013, doi: 10.1016/j.solener.2013.03.027.
- [75] E. Bellos, C. Tzivanidis, K. Moschos, and K. A. Antonopoulos, “Energetic and financial evaluation of solar assisted heat pump space heating systems,” *Energy Convers. Manag.*, vol. 120, pp. 306–319, 2016, doi: 10.1016/j.enconman.2016.05.004.
- [76] J. Long, K. Xia, H. Zhong, H. Lu, and A. Yongga, “Study on energy-saving operation of a combined heating system of solar hot water and air source heat pump,” *Energy Convers. Manag.*, vol. 229, no. August 2020, p. 113624, 2021, doi:

- 10.1016/j.enconman.2020.113624.
- [77] X. Meng, X. Zhou, and Z. Li, “Review of the Coupled System of Solar and Air Source Heat Pump,” *Energies*, vol. 17, no. 23, pp. 1–26, 2024, doi: 10.3390/en17236045.
 - [78] X. Wang, L. Xia, C. Bales, and S. Pan, “A systematic review of recent air source heat pump (ASHP) systems assisted by solar thermal, photovoltaic and photovoltaic/thermal sources,” *Renew. Energy*, vol. 146, pp. 2472–2487, 2020, doi: 10.1016/j.renene.2019.08.096.
 - [79] M. A. Obalanlege, J. Xu, C. N. Markides, and Y. Mahmoudi, “Techno-economic analysis of a hybrid photovoltaic-thermal solar-assisted heat pump system for domestic hot water and power generation,” *Renew. Energy*, vol. 196, pp. 720–736, 2022, doi: 10.1016/j.renene.2022.07.044.
 - [80] A. Cavalletti, “Monitoring and transient modelling of Solar assisted heat pump with hybrid Panels: limits and potentials applied to an existing plant,” 2023.
 - [81] P. A. Hohne, K. Kusakana, and B. P. Numbi, “Operation Cost Minimisation of Hybrid Solar/Electrical Water Heating Systems: Model Development,” *Adv. Sci. Lett.*, vol. 24, no. 11, pp. 8076–8080, 2018, doi: 10.1166/asl.2018.12495.
 - [82] O. P. Okubanjo Ayodeji A, Ofualagba Godswill, “Cost Optimization of Hybrid Solar/ Heat Pump Water Heating System : Model Formulation,” in *2022 IEEE Nigeria 4th International Conference on Disruptive Technologies for Sustainable Development (NIGERCON)*, Lagos, Nigeria, 2022, pp. 1–5.
 - [83] Z. Li and X. Huang, “Simulation analysis on operation performance of a hybrid heat pump system integrating photovoltaic / thermal and air source,” *Appl. Therm. Eng.*, vol. 200, no. October 2021, p. 117693, 2022, doi:

- 10.1016/j.applthermaleng.2021.117693.
- [84] A. Bani Yaseen, L. Al-Hyari, O. Almahmoud, and M. Hammad, “Performance of a new solar water heater design with natural circulation,” *Energy Sources, Part A Recover. Util. Environ. Eff.*, pp. 1–16, 2020, doi: 10.1080/15567036.2020.1785590.
 - [85] H. W. Coleman and K. K. Brown, *Impact of Uncertainty on Modeling and Testing*, vol. 1995, no. April. 1995.
 - [86] C. E. Manyi-Loh, M. Sikhonza, and S. Tangwe, “Linear regression analysis and techno-economic viability of an air source heat pump water heater in a residence at a university campus,” *Energies*, vol. 14, no. 8, 2021, doi: 10.3390/en14082280.
 - [87] H. T. Castrup, “Distributions for Uncertainty Analysis,” *Integr. Sci. Gr.*, no. May 2004, pp. 1–12, 2001, [Online]. Available: papers3://publication/uuid/FEC2A5ED-D3D6-4C5B-B02B-9D15DC0771C0
 - [88] M. B. Lyons, D. A. Keith, S. R. Phinn, T. J. Mason, and J. Elith, “A comparison of resampling methods for remote sensing classification and accuracy assessment,” *Remote Sens. Environ.*, vol. 208, no. February, pp. 145–153, 2018, doi: 10.1016/j.rse.2018.02.026.
 - [89] Z. Zheng, J. Zhou, F. Xu, and G. Deng, “Solar assisted air source heat pump systems for campus water heating in China: Economic optimization of solar fraction design,” *Appl. Therm. Eng.*, vol. 213, no. June, p. 118767, 2022, doi: 10.1016/j.applthermaleng.2022.118767.
 - [90] J. Cai, A. Morris, M. Cirillo, S. . Kramer, and J. Hiebert, “Theoretical framing as justifying,” *J. Res. Math. Educ.*, vol. 50, no. 3, pp. 218–224, 2019.
 - [91] S. Tangwe, P. Mukumba, and G. Makaka, “An Installed Hybrid Direct Expansion Solar Assisted Heat Pump Water Heater to Monitor and Modeled the Energy Factor

- of a University Students' Accommodation,” *Energies*, vol. 16, no. 3, 2023, doi: 10.3390/en16031159.
- [92] S. T. Loh, P. Mukumba, and G. Makaka, “Design and Employing of a Non-Linear Response Surface Model to Predict the Microbial Loads in Anaerobic Digestion of Cow Manure: Batch Balloon Digester,” *Sustain.*, vol. 14, no. 20, 2022, doi: 10.3390/su142013289.
- [93] P. A. Hohne, K. Kusakana, and B. P. Numbi, “Scheduling and economic analysis of hybrid solar water heating system based on timer and optimal control,” *J. Energy Storage*, vol. 20, no. May, pp. 16–29, 2018, doi: 10.1016/j.est.2018.08.019.
- [94] P. A. Hohne, K. Kusakana, and B. P. Numbi, “Optimal energy management and economic analysis of a grid-connected hybrid solar water heating system: A case of Bloemfontein, South Africa,” *Sustain. Energy Technol. Assessments*, vol. 31, no. May 2018, pp. 273–291, 2019, doi: 10.1016/j.seta.2018.12.027.
- [95] K. I. Olatayo, J. H. Wichers, and P. W. Stoker, “Energy and economic performance of small wind energy systems under different climatic conditions of South Africa,” *Renew. Sustain. Energy Rev.*, vol. 98, no. September, pp. 376–392, 2018, doi: 10.1016/j.rser.2018.09.037.
- [96] K. Kusakana, “The Impact of an Air to Water Heat Pump in the Residence of a University Campus,” *Int. J. Electr. Electron. Eng. Telecommun.*, vol. 11, no. 2, pp. 109–116, 2022, doi: 10.18178/IJEETC.11.2.109-116.
- [97] B. Yaniktepe, O. Kara, and C. Ozalp, “Technoeconomic Evaluation for an Installed Small-Scale Photovoltaic Power Plant,” *Int. J. Photoenergy*, vol. 2017, 2017, doi: 10.1155/2017/3237543.
- [98] M. Zamfir, M. D. Manea, and L. Ionescu, “Return on Investment – Indicator for

- Measuring the Profitability of Invested Capital,” *Valahian J. Econ. Stud.*, vol. 7, no. 2, pp. 79–86, 2016, doi: 10.1515/vjes-2016-0010.
- [99] M. Amorim, C. Ferreira, M. Vieira, and J. Carlos, *Engineering Systems and Networks: the way ahead for industrial engineering and operations management*. 2016.
- [100] Y. Yu, H. Yang, J. Peng, and E. Long, “Performance comparisons of two flat-plate photovoltaic thermal collectors with different channel configurations,” *Energy*, vol. 175, pp. 300–308, 2019, doi: 10.1016/j.energy.2019.03.054.
- [101] B. Abbasi, S. Li, and A. Mwesigye, “Energy, exergy, economic, and environmental (4E) analysis of SAHP water heaters in very cold climatic conditions,” *Renew. Energy*, vol. 226, no. March, p. 120391, 2024, doi: 10.1016/j.renene.2024.120391.
- [102] R. Simonetti, L. Molinaroli, and G. Manzolini, “Experimental performance evaluation of a solar-assisted heat pump driven by PV/T panels in real ambient conditions,” *Proc. ISES Sol. World Congr. 2019 IEA SHC Int. Conf. Sol. Heat. Cool. Build. Ind. 2019*, pp. 213–223, 2020, doi: 10.18086/swc.2019.05.07.
- [103] C. Manyi-Loh, “An Evaluation of the Energetic Performance of a Residential Hybrid Solar Assisted Air Source Heat Pump Water Heater,” *SSRN Electron. J.*, 2021, doi: 10.2139/ssrn.3900339.
- [104] M. Simon and E. Meyer, “Quantifying residential hot water production savings by retrofitting geysers with air source heat pumps,” *Proc. 23rd Conf. Domest. Use Energy, DUE 2015*, pp. 235–241, 2015, doi: 10.1109/DUE.2015.7102986.
- [105] M. Sikhonza, S. Tangwe, and M. Simon, “An efficient design of a data acquisition system to monitor the operating performance of a hybrid solar assisted air source heat pump water heater,” *Proc. 27th Int. Conf. Domest. Use Energy, DUE 2019*, pp. 126–132, 2019.

- [106] T. R. Brown and R. C. Brown, “Techno-economics of advanced biofuels pathways,” *RSC Adv.*, vol. 3, no. 17, pp. 5758–5764, 2013, doi: 10.1039/c2ra23369j.
- [107] C. D. Scown, N. R. Baral, M. Yang, N. Vora, and T. Huntington, “Technoeconomic analysis for biofuels and bioproducts,” *Curr. Opin. Biotechnol.*, vol. 67, pp. 58–64, 2021, doi: 10.1016/j.copbio.2021.01.002.
- [108] “South African rand to US dollars today.” Accessed: Jan. 13, 2025. [Online]. Available: <https://wise.com/gb/currency-converter/zar-to-usd-rate>
- [109] O. Reyes, C. Morell, and S. Ventura, “Scalable extensions of the ReliefF algorithm for weighting and selecting features on the multi-label learning context,” *Neurocomputing*, vol. 161, pp. 168–182, 2015, doi: 10.1016/j.neucom.2015.02.045.
- [110] Y. L. Gong, M. J. Hu, H. F. Yang, and B. Han, “Research on application of ReliefF and improved RVM in water quality grade evaluation,” *Water Sci. Technol.*, vol. 85, no. 3, pp. 799–810, 2022, doi: 10.2166/wst.2022.005.

APPENDICES

APPENDIX A: INPUT AND OUTPUT PARAMETERS PERFORMANCE OF THE HSAASHP WATER HEATER

Months	Ambient Temp	RH	E _{COP}	E _{sc}	COP	EF	Q	Season
Jan	27.175	45.92	784.1914	1 829.78	4.35	5.2	12 926.08	Summer
Feb	24.698	53.72	242.79	566.51	4.20	5.0	3 852.26	Summer
Mar	24.33	49.81	1143.844	2 668.97	3.95	4.7	17 065.98	Summer
Apr	17.9283	63.324	1182.42	2 758.98	3.70	4.4	16 514.46	Summer
May	13.9145	70.3	1536.017	3 584.04	2.8	3.5	16 844.96	Winter
Jun	10.4435	65.765	867.1071	2 023.25	2.6	3.0	8 324.41	Winter
Jul	10.4476	59.46	867.1071	2 023.25	2.5	3.1	8 439.84	Winter
Aug	13.2239	45.76	1792.02	4 181.38	2.4	3.0	16 844.98	Winter
Sep	16.846	44.26	1026.84	2 395.96	3.2	3.8	12 390.53	Summer
Oct	20.7584	50.52	1344.017	3 136.04	3.35	4.0	17 046.59	Summer
Nov	23.1203	54.392	1238.726	2 890.36	3.6	4.2	16 598.92	Summer
Dec	22.9329	66.73	285.96	667.24	4.0	4.7	4 279.87	Summer

APPENDIX B: PERFORMANCE OF THE HSAASHP WATER DURING THE SECOND PHASE OF OPERATION

Appendix B1: Solar Collectors

SD	V-Ph2	FR-SC	T _{in} -SC	T _{out} -SC	Q-SC	E-Sol	SF
	(L)	(Counts)	(°C)	(°C)	(kWh)	(kWh)	
1	2971	1212	57.37	57.85	22.262	25.826	0.862
2	3770	2036	54.32	54.70	29.661	46.201	0.642
3	4020	2616	54.34	54.64	28.240	43.581	0.648
4	3993	2526	53.95	54.17	30.448	42.113	0.723
5	5027	2564	53.51	53.82	29.222	46.091	0.634
6	4095	1381	54.87	55.16	19.360	22.330	0.867
7	3804	2522	54.91	55.32	26.460	47.082	0.562
8	2452	2406	53.33	53.75	26.714	46.785	0.571
9	4387	2600	54.54	54.79	30.416	45.061	0.675
10	4353	2600	53.71	54.07	27.111	44.961	0.603
11	4353	2600	53.79	54.07	27.111	44.961	0.603
12	3989	2346	54.33	54.56	27.166	35.098	0.774
13	2971	2368	55.24	55.37	36.632	48.391	0.757
14	5125	2604	54.67	54.81	35.901	48.319	0.743
15	3028	1864	54.46	54.58	36.903	46.713	0.790

Appendix B2: ASHP Unit

SD	V-Ph2	FR-HP	T_{in}-HP	T_{out}-HP	Q-HP	E-HP	COP
	(L)	(Counts)	(°C)	(°C)	(kWh)	(kWh)	
1	2971	62	55.35	59.93	66.69	19.80	3.368
2	3770	131	52.74	57.04	229.76	43.40	5.294
3	4020	48	52.86	55.93	52.10	20.70	2.517
4	3993	91	52.45	57.15	202.80	45.80	4.428
5	5027	94	52.02	56.89	106.50	29.90	3.562
6	4095	64	53.53	57.91	80.54	23.80	3.384
7	3804	50	53.16	57.67	53.32	17.90	2.979
8	2452	104	47.46	51.95	255.77	54.50	4.693
9	4387	109	53.02	56.80	156.70	36.40	4.305
10	4353	66	52.23	56.54	89.36	26.00	3.437
11	4353	66	52.27	55.57	77.82	25.70	3.028
12	3989	99	52.74	57.15	152.67	34.30	4.451
13	2971	84	51.99	55.06	47.59	15.20	3.131
14	5125	38	53.33	56.89	41.66	17.40	2.394
15	3028	129	49.85	52.94	165.74	39.20	4.228

APPENDIX C: OPERATING PERFORMANCE OF AN ELECTRIC BOILER AND HSAASHP WATER HEATER

Months	Boiler Et (2023) (kWh) baseline	Activities	HSAASHP (2023) (kWh)	Et EF	Seasons
Jan	12926.08	30%	2613.971	5.2	Summer
Feb	3852.26	25%	809.3	5	Summer
Mar	17065.98	100%	3812.814	4.7	Summer
Apr	16514.46	100%	3941.4	4.44	Summer
May	16844.96	100%	5120.057	3.5	Winter
Jun	8324.41	50%	2890.357	3	Winter
Jul	8439.84	50%	2890.357	3.1	Winter
Aug	16844.98	100%	5973.4	3	Winter
Sep	12390.53	75%	3422.8	3.8	Summer
Oct	17046.59	100%	4480.057	4.0	Summer
Nov	16598.92	100%	4129.086	4.2	Summer
Dec	4279.87	25%	953.2	4.7	Summer
Total	151128.9		41036.8		

APPENDIX D: TECHNO-ECONOMIC ANALYSIS OF A HSAASHP WATER HEATER

Saving/kWh	No of years	Year	tariff	FV sav/R	NPV sav/R	CUMSUM NPV	
	0	2023					400011,7
110092,1	1	2024	3,15	346790,1	301556,622	301556,622	
110092,1	2	2025	3,6225	398808,6	390032,892	691589,514	
110092,1	3	2026	4,095	450827,1	449310,726	1140900,24	1000
110092,1	4	2027	4,095	450827,1	450599,034	1591499,27	
110092,1	5	2028	4,5675	502845,7	502807,485	2094306,76	
110092,1	6	2029	5,5125	606882,7	606875,789	2701182,55	1000
110092,1	7	2030	5,985	658901,2	658900,093	3360082,64	
110092,1	8	2031	6,4575	710919,7	710919,554	4071002,19	
110092,1	9	2032	6,93	762938,3	762938,224	4833940,42	1000
110092,1	10	2033	7,4025	814956,8	814956,766	5648897,18	
110092,1	11	2034	7,875	866975,3	866975,287	6515872,47	
110092,1	12	2035	8,3475	918993,8	918993,805	7434866,27	1000
110092,1	13	2036	8,82	971012,3	971012,322	8405878,6	
110092,1	14	2037	9,2925	1023031	1023030,84	9428909,43	
110092,1	15	2038	9,765	1075049	1075049,36	10503958,8	1000