Design of an Improved Solar Powered Water Desalination Plant

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Submitted in fulfilment of the academic requirements for the degree of Master of Science in Mechanical Engineering, College of Agriculture, Engineering and Science, University of KwaZulu-Natal

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Publication 1 (Published): IJMET 2019

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Publication 2 (Published): IJMET 2019

Devesh Singh and Freddie L. Inambao, "Design Theory and Computational Analysis of a Solar Still". *International Journal of Mechanical Engineering and Technology*. 10(11), 2019, pp. 72-95. http://www.iaeme.com/IJMET/issues.asp?JType=IJMET&VType=10&IType=11

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The research, writing and compilation of these publications were carried out by the candidate (lead author) under the supervision of Prof. F. L. Inambao (corresponding author).

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Prof. Freddie L. Inambao

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Abstract

South Africa and the greater African continent are predicted to suffer from future water shortages due to a rapidly growing population and inadequate conservation of water resources. Research has shown that over the last decade desalination has become a reliable and effective means of producing potable water. This research study aimed to increase the performance characteristics of the solar powered desalination test rig that exists at the Discipline of Mechanical Engineering workshop, University of KwaZulu-Natal. The project objectives were to improve system performance and thermal efficiency of the boiler still of the test rig through various design and operational changes. System performance refers to volumetric output productivity of the boiler still whereas thermal efficiency refers to the various still temperatures.

Based on the review of relevant literature a methodology composed of a qualitative and quantitative approach was drawn up. The qualitative approach comprised a feasibility study using a survey, market analysis, quality function deployment (QFD) and failure modes and effects analysis (FMEA). An analytical, computational and experimental model alongside computer aided design (CAD) made up the quantitative approach. The feasibility study (sample size 100) found that 85 % of respondents believed desalination was the solution to future water shortages that South Africa may face. The QFD and FMEA both noted the importance of operating the boiler still in a specific total dissolved solids range to enhance productivity and reduce system fouling. The proposed boiler still design is a double slope solar still that will operate within specified ranges for input water total dissolved solids, basin depth and roof slope. The analytical and computational models noted a 114.13 % and 90.77 % increase respectively in new still productivity when compared to the experimental productivity of the existing single slope boiler still.

The double slope still design reduced the shadow effect experienced by single slope stills. Maintainability of the system was improved through a modular sheet metal and glass boiler still design. Reverse osmosis was noted as the preferred desalination technique through the research survey.

Considering that productivity of solar boiler stills are largely dependent on still area, it is suggested that further research be carried out into the incorporation of parallel stills and preheat/energy recovery systems in series.

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List of Acronyms and Abbreviations

3D	Three Dimensional
C	Criticality
CAD	Computer Aided Design
CFD	Computational Fluid Dynamics
FMEA	Failure Modes and Effects Analysis
QFD	Quality Function Deployment
RPN	Risk Priority Number
TDS	Total Dissolved Solids

Nomenclature

Chapter 2

Symbol	Description	Unit
$\dot{m}$	Mass transfer rate	kg/s
$\dot{V}$	Volumetric flow rate of purified water	m^3/s
$\dot{Q}$	Rate of heat transfer	J/s
A	Area	m^2
C	Average concentration	mg/L
Cp	Concentration of reverse osmosis permeate water	None
c_p	Number of cell pairs	None
e	Current efficiency	None
E	Voltage	V
F	Faraday's constant	None
FF	Membrane fouling factor	None
G	Incident solar radiation	W/m^2
h_c	Heat transfer coefficient	$W/m^2.K$
I	Electrical current	A
K	Membrane permeability for water	m/bar.s
p	Pressure	mmHg/Pa
pf	Polarisation factor	None
q	Heat transfer	W
R	Resistance	Ω
T	Temperature	K
TCF	Water permeability temperature correction factor	None
U	Overall loss coefficient	$W/m^2.K$
	Greek Letters	
$\Delta\bar{P}$	Average pressure applied across the membrane	bar
$\Delta\bar{\pi}$	Average osmotic pressure applied across the membrane	bar
ΔH	Change in enthalpy	J/mol
ΔN	Change in normality	None
η	Efficiency	None
ε	Effectiveness for simultaneous heat and mass exchange	None
	Subscripts	
a	Ambient	
A	For water	
b	Basin	
B	For salt	
d	Distillate	
e	Evaporation	
g	Glass/ground	
mem	Membrane	
p	Purified water	

w	Water	

Chapter 6

Symbol	Description	Unit
n	Sample Size	None
Z	Confidence level	%
p	Estimated prevalence	%
e	Margin of error	%

Chapter 7

pH	Potential of Hydrogen	None
S	Severity	None
D	Detectability	None
O	Occurrence	None

Chapter 8

Symbol	Description	Unit
A	Area	m^2
C	Heat capacity	J/K
h	Heat transfer coefficient	$W/m^2.K$
H	Monthly average of daily radiation	$kJ/m^2.day$
h_{fg}	Latent heat of evaporation	$W/m^2.K$
I	Solar Radiation Intensity	W/m^2
o	Optical efficiency	None
P	Partial pressure	mm of Hg
q	Heat transfer rate	W
T	Temperature	K
U	Heat transfer coefficient between two mediums	$W.m^2.K$
K_T	Clearness index	None
	Greek Letters	
s	Sunset hour angle	Degree
β	Slope angle	Degree
γ	Surface azimuth angle	Degree
δ	Declination angle	Degree
ε	Absorptance	None
ϵ	Emittance	None
θ	Inclination angle	Degree
φ	Latitude	Degree
	Subscripts	
c	Convective	

d	Diffuse
e	Evaporation
g	Glass cover
o	Between glass cover and environment
r	Radiation
s	Sky
t	Between water and glass cover
w	Water in basin
z	Zenith

Chapter 9

Symbol	**Description**	**Unit**
Br	Ratio of buoyancy	None
C	Dimensionless concentration	None
P	Pressure	Pa
c_v	Molar specific heat at constant volume	J. mol.K
Pr	Prandtl number	None
R	Gas constant	J / mol.K
g	Gravitational acceleration	m/s^{-2}
Ra	Rayleigh number	None
i	Internal energy	J
Re	Reynolds Number	None
L	Length	M
S_i	Heat Sink	None
T	Temperature	K
Le	Lewis number	None
	Greek Letters	
α	Thermal diffusivity	m^2/s
β	Thermal expansion coefficient	K^{-1}
θ	Dimensionless temperature	kg/m^3
κ	Thermal conductivity	W/m.K
μ	Dynamic viscosity	$N.s/ m^2$
ρ	Density	None
υ	Kinematic viscosity	m^2/s
Φ	Heat source	None
	Subscripts	
g	Glass	
w	Water	

CHAPTER 1: INTRODUCTION

1.1 Background of solar powered water desalination

South Africa and the greater African continent are largely water scarce regions with much of the continental land being semi-arid to arid. Africans rely heavily on seasonal rain and borehole water for supply of freshwater. Increased temperatures, drought and erratic weather conditions have led to an ever growing need to research, develop and invest in alternative methods to attain and produce potable water. Solar powered water desalination is a process in which energy is harnessed from the sun to be used as the driving forcing to carry out water desalination. Desalination has a proven track record of being a reliable and safe method to produce potable water. The challenge that arises on the African continent is the lack of a dependable and continuous source of electricity, especially in underdeveloped nations. Solar energy is the ideal candidate to capitalise on the abundant solar irradiation available in African regions. One such plant is being developed in the Western Cape (Figure 1-1), South Africa. This plant produces 100 kl of potable water per day at a cost significantly less than diesel powered counterparts [1].

Figure 1-1: Witstand solar powered water desalination plant

1.2 Problem statement

At the University of KwaZulu-Natal, Discipline of Mechanical Engineering, there exists a solar powered desalination plant test rig. The test rig was designed, manufactured and tested by Group 15 as part of the mechanical engineering courses: Design and Research project 1 & 2

(EN4MEPD/DP) in 2018, as seen in Figure 1-2. The test rig fulfilled the requirements of the problem statement proposed to Group 15. However, a number of design and performance recommendations were noted in Group 15's design and research project report [2]. The most notable was to improve the boiler of the test rig. The boiler still was not optimally designed to maximise the evaporation rate of saline liquids while condensation of potable water was hindered. The problem then arises regarding the design and analysis of an improved boiler to refine the performance characteristics of the test rig and build on the shortcomings of the existing design.

Figure 1-2: Solar powered desalination plant test rig at Mechanical Engineering Workshop, UKZN

1.3 Research questions

These are the research questions that have been developed with respect to the design of an improved boiler for a solar powered water desalination plant:

1) What physical design change(s) can be made to improve current boiler still performance?
2) How can a research methodology be developed to provide a more holistic design and analysis approach?
3) Which desalination technique is preferred by the general population of South Africa?

1.4 Hypotheses

The hypotheses below are "educated guesses" developed by the individual based on the research of relevant source material, consultation with the project supervisor and industry experts. These seek to investigate a possible solution to the research questions listed in Section 1.3.

1) The boiler performance can be increased through a double slope still design which reduces the shadow effect.
2) Deriving a methodology composed of both a qualitative and quantitative approach.
3) Solar distillation is the preferred desalination technique by South Africans.

1.5 Aim and Objectives

1.5.1 Aim

The aim of the research project was to increase the performance characteristics of the solar powered desalination test rig that exists at the Discipline of Mechanical Engineering workshop, University of KwaZulu-Natal.

1.5.2 Objectives

The following objectives sought to enable the achievement of the aim of the improvement project, namely:

1) Increase system performance by readdressing boiler still design
2) Enhance thermal efficiency through different material selection
3) The system should require little to no user input
4) Provide direct comparison between existing still and improved still
5) New boiler setup should be able to be integrated with existing test rig

1.6 Layout of Study

1.6.1 Scope

Key areas which the project falls within are:

1) Renewable and alternative energy
2) Water treatment and potable water production
3) Heat and mass transfer
4) Thermodynamics
5) Mechanical design
6) Environmental science
7) Meteorology

1.6.2 Layout

1) Chapter 1: Introduction –The background, problem statement objectives, scope and research work carried out as part of the MSc. Engineering degree.

2) Chapter 2: Solar Desalination: A Critical Review – The literature review relevant to this dissertation. It reviews the need for research into alternative water purification methods in general, desalination methods in particular, their working principles and mathematical modelling, and the economics of thermal and membrane-based desalination.
3) Chapter 3: Methodology –The methodological approach used during the study. Qualitative and quantitative research approaches are described, their advantages and disadvantages listed, and the various aspects of each approach discussed. Lastly, a methodological process flow diagram is shown to represent the overall manner in which the study was carried out.
4) Chapter 4: Feasibility Study – This chapter presents a feasibility study that was carried out, in which 100 participants completed a research questionnaire regarding water supply and alternative means of producing potable water in South Africa. The results and their implications for the survey are discussed.
5) Chapter 5: Quality Function Deployment –This chapter presents a QFD that was carried out as part of the qualitative approach of the system design. The completed QFD is shown in Appendix B and an analysis of the outcomes carried out with design recommendations made. The results of the QFD were examined.
6) Chapter 6: Market Analysis – This chapter describes the market analysis carried out during the study. The generated information could provide valuable insights into a possible benchmark for design and performance characteristics.
7) Chapter 7: Failure Modes and Effects Analysis – The chapter presents and analyses the results of the FMEA. The results were considered during the mechanical design phase.
8) Chapter 8: Design Theory and Analytical Analysis of a Solar Still – This chapter reviews the theory behind still design, and the mathematical models used to analyse system performance. The system performance results obtained through the numerical solution of the mathematical model using MATLAB are for a double slope solar still operating in Durban, South Africa.
9) Chapter 9: Design Theory and Computational Analysis of a Solar Still – This chapter provides the theory behind computational modelling of the solar still. The design theory behind a Computational Fluid Dynamics simulation is provided and simplified for a heat transfer model. The simulation process for an ANSYS® CFD model is included and the results of the computational model are evaluated.
10) Chapter 10: Design Theory and Experimental Analysis of a Solar Still – In this chapter the experimental approach was used to verify the performance characteristics of the current solar powered desalination plant test rig and results are discussed.

11) Chapter 11 Comparison of Quantitative Results – The chapter presents analysis and comparison of results obtained through the analytical, computational and experimental models.
12) Chapter 12: Conclusion, recommendations and future research

1.6.3 Target audience

The target audience for this dissertation is as follows:

1) Students concerned with similar projects and research
2) Lecturers, professors and external professionals tasked with project moderation
3) Industry members interested in scope of project
4) Organizations involved in water treatment and potable water production
5) Government officials tasked with proposing green initiatives
6) Members of the general public interested in specific components or the project scope in its entirety

1.7 Discussion

Water scarcity is a major concern for South Africa and the African continent. The need for research and development in alternative methods of water production has been spurred on, in recent years, by drought, global warming and extreme weather patterns. Desalination has shown itself to be able to produce safe and clean drinking water reliably and effectively. However, largescale desalination plants, as seen in Figure 1-1, often come with huge price tags. The use of household desalination devices could serve as an unconventional solution to the usual borehole and rainwater alternatives. Numerous African countries are without dependable and continuous electricity supply thus making standard desalination less desirable. As such, design and development of small-scale low cost solar powered water desalination plants for household use has become all the more relevant in the present day.

The problem statement indicates that there is a solar powered desalination plant test rig at the UKZN Mechanical Engineering workshop. This desalination test rig formed part of research carried out by a final year Design and Research Project group in 2018, as illustrated in Figure 1-2. The overall design fulfilled the objectives of the project although the boiler still design was noted as a possible are for improvement in future research. The aim of the current research was to design a new boiler still to refine performance characteristics of the existing design to increase the distillation rate. Achievement of the project aim was broken down into five objectives; improve system performance by readdressing boiler still design, enhance thermal efficiency through different material selection, ensure minimal need for user input, providing a direct system performance characteristic comparison and lastly, the new boiler design must be able to be incorporated into the existing test rig. Performance was characterised by an increase in boiler still temperatures and productivity.

Three research questions were drawn up and hypotheses provided for each. The first question related to what physical design change(s) could be made to the existing boiler to improve still performance. It was hypothesised that a double slope boiler still design would reduce the shadow effect and thus increase boiler performance. This was proven to be correct after an analytical and computational model both produced improved performance characteristics compared to the current boiler still design. The second research question probed the derivation of a more holistic research methodology. It was hypothesised that the inclusion of a qualitative approach to system design and analysis would prevent certain neglect of certain areas. This hypothesis was accepted as the qualitative approach provided a better understanding of the need for such devices in South Africa, which would make it a success in terms of large-scale production and the limitations of existing designs. The final question considered the desalination technique preferred by South Africans. It was hypothesised that solar distillation would be the most favoured technique however this hypothesis was rejected. A research survey was carried out which queried this and various other related issues. The majority of the respondents noted reverse osmosis as being the preferred method of desalination.

1.8 Summary of chapter

This chapter provided an introduction to the design and research thesis regarding the improvement of the existing solar powered water desalination plant at the Mechanical Engineering workshop at UKZN. The introduction provided the setting of the current research and the need for further study was justified. The problem statement was presented along with the aim and objectives. Research questions to be tackled during the research and their respective hypotheses were outlined. Lastly, the layout of study was presented providing insight into the scope, layout and target audience for this thesis.

1.9 References

[1] Herman, K. South Africa unveils first solar powered desalination plant. [Online] 2018. [Cited: August 21, 2019.] https://www.pumps-africa.com/south-africa-unveilsfirst-solar-powered-desalination-plant/.

[2] Cassim, B., Ramnarayan, A. and Goga, A. *Solar powered water desalination plant.* Durban: University of KwaZulu-Natal, 2018.

CHAPTER 2: SOLAR DESALINATION: A CRITICAL REVIEW

This chapter reviews the need for research into alternative water purification methods in general, desalination methods in particular, and their working principles and mathematical modelling. The economics of thermal and membrane based desalination is noted. The article has been published in the International Journal of Mechanical Engineering and Technology, IAEME Publications.

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SOLAR DESALINATION: A CRITICAL REVIEW

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ABSTRACT

Rapid population growth and insufficient conservation of water resources in water scarce regions are but two reasons for the predicted water shortages that are likely to plague future generations. Desalination, over the last two decades, has seen major strides made in the production of potable water in large scale projects. Through continuous research and development new and improved methods have been found and implemented across the world. The viability of desalination as a reliable alternative potable water source has been proven on numerous occasions through various studies, projects and devices. This paper reviews the need for research into alternative water purification methods in general, desalination methods in particular, their working principles and mathematical modelling. The economics of thermal and membrane based desalination is noted.

Key words: Solar, Water desalination, Water purification, Potable water

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1. INTRODUCTION

The global population rapidly increases by approximately 80 million people per year [1] and is estimated to reach 9.1 billion by the year 2050 [2]. Fifty percent of the total drinking water consumed is groundwater [3], while globally 2.5 billion individuals rely only on groundwater to meet their basic water requirements [4]. It has been reported by UN-Water [5] and Calder et al. [6] that 1.2 billion of the global population reside in water scarce regions. Over the last two decades, at least half of the countries with a low Human Development Index have started funding, researching, developing and managing water resources and alternative water harvesting methods [5]. Figure 1 depicts the global stress on groundwater supply [7]. As noted from Figure 1, annual depletion of groundwater is among the highest within northern and southern Africa and the Middle East.

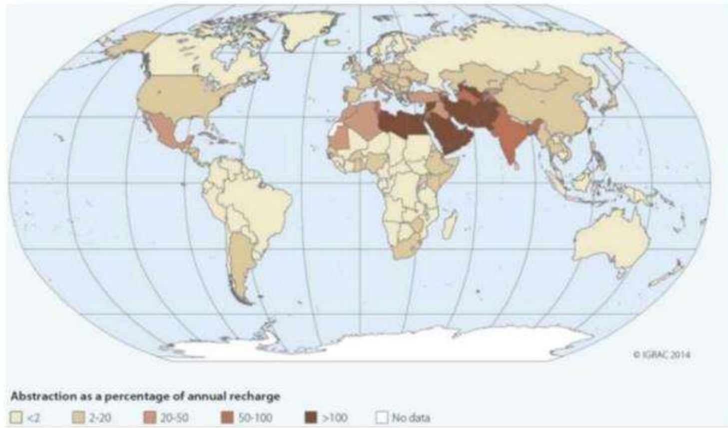


Figure 1 Groundwater development stress [7]

1.1 Need for research and development

There are three dimensions of sustainable water development, namely i) poverty, ii) economic and iii) environmental. As of 28th July 2010, the United Nations General Assembly Resolution 64/292 recognized access to safe, clean and drinkable water and sanitation as a fundamental human right [8]. Although the eradication of extreme poverty and hunger has been the primary Millennium Development Goal shared by the world, in 2012 it was reported that 1.2 billion people still live in extreme poverty without access to clean drinking water [9]. Figure 2 is a graphical representation of global water scarcity, revealing the dire need for water harvesting, purification and distillation systems in these regions. It is imperative to grasp how different sectors of an economy are linked to water security [10]. Only through investment in water infrastructure, management and security can the full potential of a country's economic development be utilized. Research and development into low cost alternative solutions to water scarcity can have far reaching benefits for a country's citizens through stimulation of economic growth and an improved standard of living, especially in rural areas [11]. The challenge is to develop environmentally sustainable solutions that have a low or no carbon footprint through the design, manufacturing and operational stages of its lifespan, and that can be utilized in rural areas by individuals who do not have access to electricity.

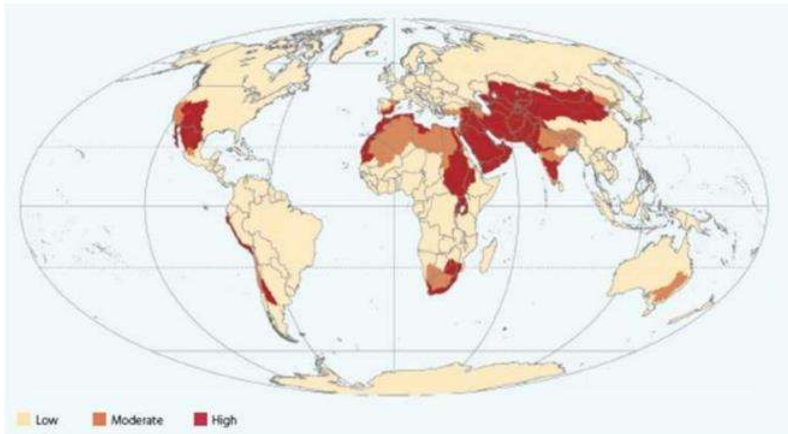


Figure 2 Water scarcity globally by major basin [10]

1.2 Shortage of water in South Africa

South Africa has been ranked as the 30th driest country in the world [12]. South Africa is a water-stressed country with dynamic and erratic climate and rainfall fluctuations. The ratio of withdrawal to supply is extremely high (> 80%) [13], as seen in Figure 3. This broadly means that for every 100 litres available more than 80 litres are used. This, however, is an average across the country as in some parts of South Africa, the demand is now far above supply, leading to water restrictions and shortages.

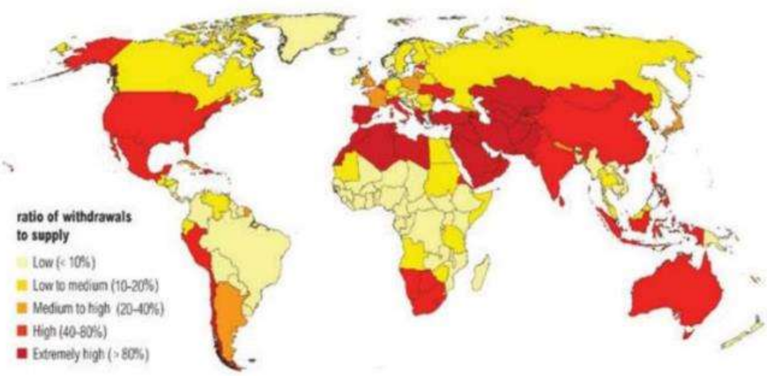


Figure 3 Water withdrawal to supply ratio globally [13]

The percentage makeup of water supply can be seen in the pie chart in Figure 4 [14]. Most notably, surface water makes up more than three quarters of the water supply. Groundwater still remains a significantly under utilised resource due to lack of knowledge, affordability and means to distill the groundwater. Groundwater can provide a suitable means to allocate freshwater to rural and undeveloped communities across South Africa. As observed in the pie chart displayed in Figure 5, rural households only acccount for 4 % of the water usage in South Africa [15]. This 4 % is accessed through communal taps, boreholes or rivers. The latter two require filtration and/or treatment. Boiling is the only means of distillation in most rural households.

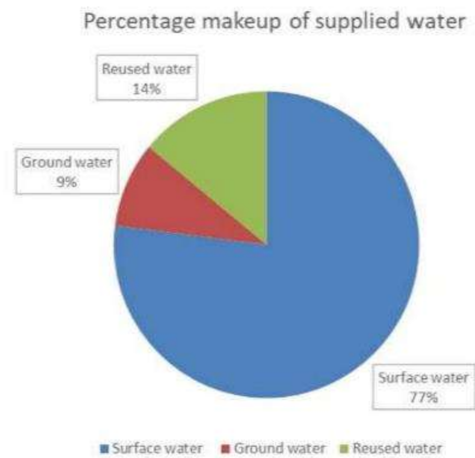


Figure 4. Pie chart of percentage makeup of supply water in South Africa [14]

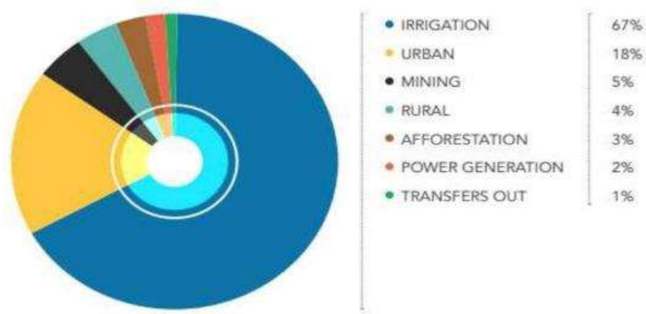


Figure 5. Percentage water used by each sector in South Africa [15]

1.3 Water Purification

Ground, river and seawater are all in unsuitable states to be safely consumed [16]. In most cases, river or ground water can be shared by communities, industries and the agricultural sector. These sectors all use and contribute to the health of the aquatic ecosystem [17]. The physio-chemical characteristics of the water in developing countries largely constitute unwanted dissolved microorganisms, chemical compounds, pollutants, infectious agents and sewage [18], not all of which may be evident through visual or taste inspection. Even short or medium term consumption of untreated water can result in mild to serious health concerns including bacterial, viral and parasitic infections [19]. The consumption of seawater has the reverse effect of normal water intake leading to dehydration [20] and even disease [21]. Thus, there is a need for proper water purification for those who do not have access to potable water. Water purification ranges from removal of dirt and debris to chemical treatment [22]. There are numerous methods for processing contaminated water to bring it to a state that is safe for consumption. The most commonly used water purification methods that have proven to produce the best outcomes given the circumstances are the following [23]:

- Distillation – boiling water and collecting the condensed stream for consumption [24].
- Desalination – separation of salts and other dissolved minerals from water via various means resulting in freshwater [25].
- Mechanical filtration – the use of a physical barrier to remove impurities and contaminants from water [20].
- Chemical treatment – the addition of chemical compounds to neutralise other chemicals, kill biological contaminants, remove minerals or gases resulting in potable water [26].
- Boiling.

Each of the above-mentioned methods target a specific set of contaminants and range in efficency, cost and reliability.

2. WATER DESALINATION

2.1. What is Solar Desalination?

Solar desalination can be defined as the process of harnessing the solar energy supplied by the sun to removed dissolved impurities found within water. These may include sodium in seawater and other minerals from wastewater [27].

2.2. Methods of Desalination

Several methods of desalination exist. Each method brings a varied approach to the desalination process. Figure 6 is a map of the various desalination methods that are used. The two main categories of desalination processes are phase change (thermal processes) and single phase (membrane processes) [28].

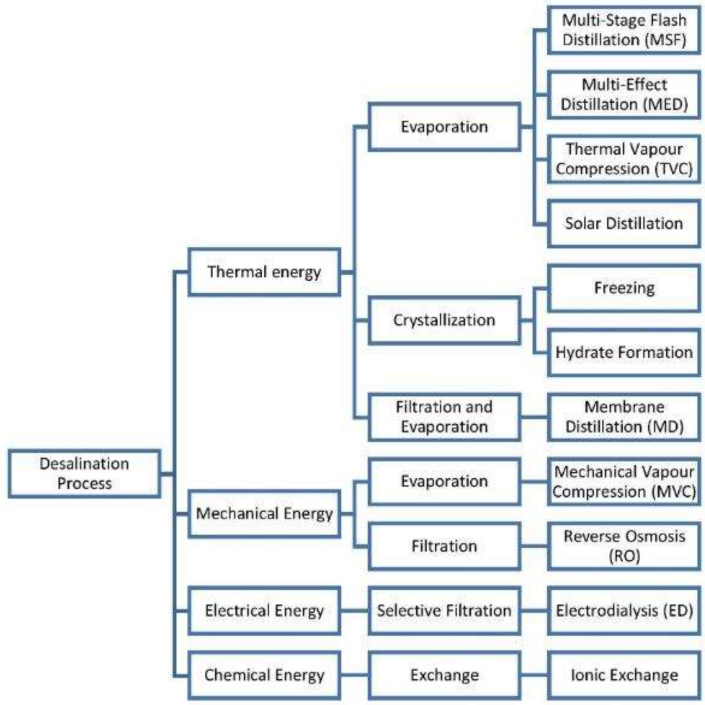


Figure 6 Various desalination methods

Figure 7 is a graphical representation of the percentage utilization globally of the different desalination technologies used [29]. If the utilization is below 1 % it is not represented in the pie chart as it can be regarded as negligible. As can be seen in the pie chart, reverse osmosis (RO) constitutes approximately 52 % of global desalination, with thermal processes making up a further 22 % of the technologies utilized.

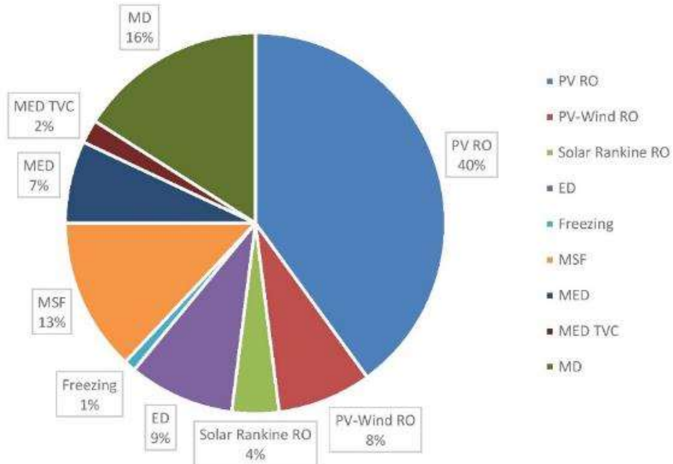


Figure 7 Pie chart of the percentage utilization of each type of desalination technology [29]

The description, working principles and various sub-categories of the common desalination processes are discussed below.

2.2.1. Solar Distillation

Solar stills employ solar powered water distillation and are a tried and tested water purification technology. They are capable of supplying potable water free of dirt and debris (filtration), do not result in high salinity (desalination), and remove most major biological contaminates (chemical treatment or boiling) [30]. Stills range in size, makeup, method of operation and efficiency, and may be either passive or active. Passive stills rely solely on solar energy to cause evaporation whilst active stills utilize a combination of solar and waste energy from industrial machinery. The stills can be used singly for individuals or collectively in solar powered water distillation farms to provide potable water for many households in a community. Figure 8 depicts the working principles of a passive solar powered water distillation system [31].

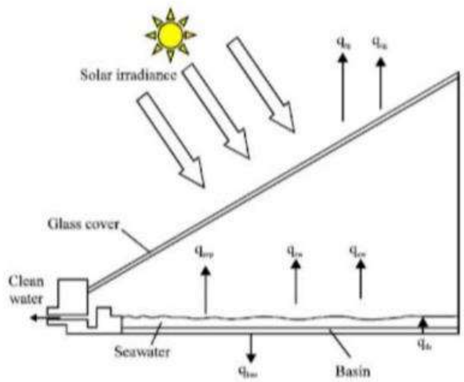


Figure 8 Passive solar powered water distillation system working diagram [31]

Untreated water enters the still into a collector basin. Solar energy passes through a transparent cover. The solar energy causes the water to evaporate. The steam then condenses on the glass and flows down into a distillate trough. The still needs to be airtight to prevent loss of evaporate which can reduce efficiency [32]. Passive stills have developed significantly over the last three decades. Various solar still designs are now available to suit the application circumstances and overcome efficiency challenges. The various designs include the following [33, 34]:

- Single-effect still – the simplest type of still that utilises one interface to permit solar energy and collect condensate. The overall layout can be seen in Figure 8. Single-effect stills are most common but are often plagued with issues such as low thermal efficiency and leakage because stills are not airtight [35].
- Multi-effect still – generally, a device with two or more stages. It has increased thermal efficiency and exploits latent heat already available in the system due to condensation for additional distillation [36].
- Basin still – the device is constructed with an inclined transparent cover over a shallow blackened basin which contains the impure water [32, 37], as seen in Figure 9.

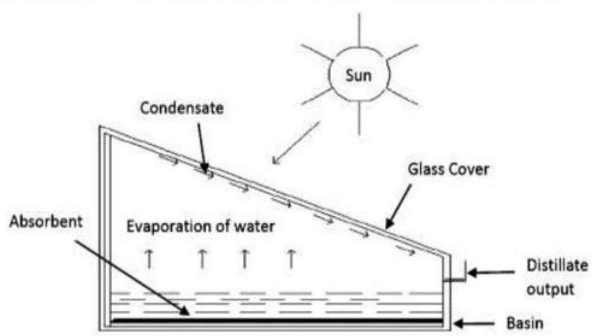


Figure 9 Basin solar still schematic [37]

- Wick – a wick still corresponds to the design of a standard basin still, however, it has a wick material e.g. jute or charcoal floating in the water [37], as seen in Figure 10. The wick material absorbs water using capillary action and aids in evaporation [38].

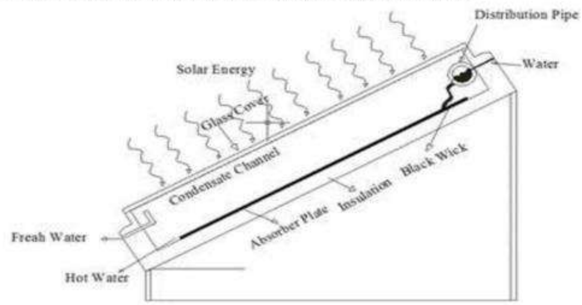


Figure 10 Wick solar still schematic [37]

- Diffusion – Tanaka and Nakatake [39] explain that the device is constructed from a series of parallel partitions which are closely spaced and in contact with saline-soaked wicks. It is a multi-effect still. The device aims to decrease the number of diffusion gaps, thereby increasing distilled water productivity. Figure 11 represents a diffusion still schematic. It varies slightly from the original design initially proposed by Tanaka and Nakatake [39].

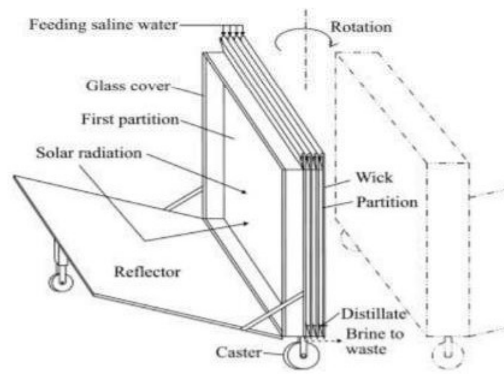


Figure 11 Diffusion solar still schematic [39]

- Spherical – the basin is placed within a sphere that has a transparent covering, at least on the top hemisphere [33], as seen in Figure 12. This design aims to eliminate any wall shadows that may normally fall onto the basin using conventional stills [40].

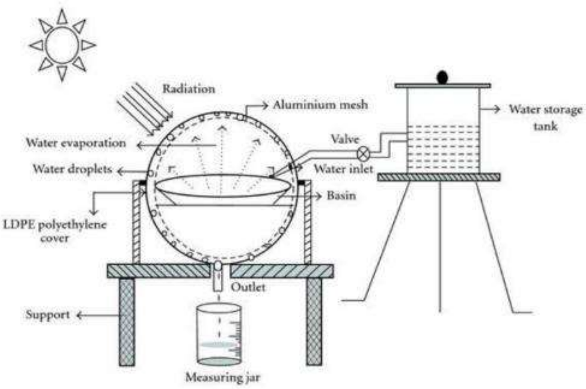


Figure 12 Spherical solar still schematic [33]

- Parabolic – a variation on conventional solar stills, these stills aim to concentrate the solar irradiation on the still basin using a reflective parabolic shaped collector [41]. Figure 13 is a schematic of a parabolic solar powered water distillation system; as observed in the diagram, the basin recieves solar radiation from both above and below [33].

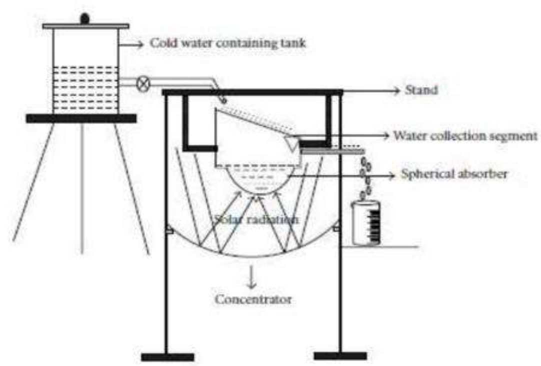


Figure 13 Parabolic solar still schematic [33]

- Tubular – tubular solar stills consist of a trough, frame and tubular casing. The tubular casing allows solar radiation to pass through while also channelling the condensate [42]. As seen in Figure 14, the tubular solar still is essentially one-half pipe (trough) inside another pipe (casing) [33].

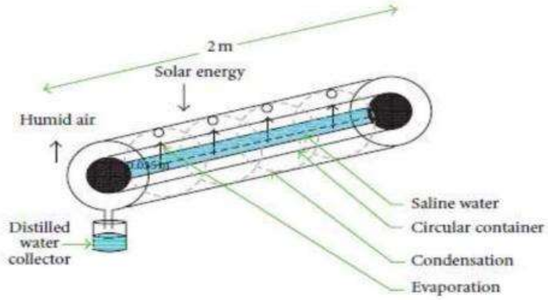


Figure 14 Tubular solar still schematic [33]

Table 1 provides a summarised description of the different still geometries taken from research available. As can be seen, the multistage solar still provides the best output production per square area per day. The double effect still provides a fair trade-off between complexity and efficiency.

Table 1 Summary of production output per still type found in current research

Still type	**Output production ($L/m^2/day$)**	**Description**	**Details**	**Reference**
Spherical	2.8 – 5.7	N/A	N/A	[43]
Conventional	2	Winter	N/A	[44]
	5	Summer		
Double slope	4	Annual average	N/A	[45]
Single effect	4.15	N/A	N/A	[46]
Double effect	6.1			
Multistage solar still with expansion nozzle, recovery features, and a vacuum pump	9	N/A	Three stage system.	[47]
Using violet dye/charcoal	5.3	N/A	Addition of dye/charcoal leads to 17% improvement.	[48]
External solar heater (using a heat transfer fluid)	2	Conventional	Water is heated in basin by heat transfer liquid in separate circuit.	[49]
	2.75	Modified		
Multistage still with an effective vacuum pump	18	P = 0.2 bar	Yield is inversely proportional to water height in basin.	[50]
	10	P = 1.0 bar		

The advantages of desalination through solar powered distillation are as follows:

- Requires energy from the sun which is free [51].
- Minimal major maintenance [51].
- Can distil both freshwater and seawater [52].
- Relatively low start-up cost compared to other desalination methods [53].

The disadvantages associated with solar powered distillation are:

- Poor operational efficiency especially during winter months 54].
- Low volumetric output of potable water [55].
- Does not remove all bacteria and chemical components found in input water [56].

Mathematical Modelling of a Generic Solar Distillation System

In order to maximise production output, the volume of water that evaporates within the still needs to be increased, thus leading to improved distilled condensate collection. Still volumetric output is directly proportional to the amount of solar radiation absorbed by the still. Energy losses are disregarded or can be quantified through experimental methods. Apart from convection and radiation, there is a transfer of energy between the basin and cover. The mathematical modelling of the still and its performance is shown below [57, 58].

The heat transfer coefficient h_c can be found as follows:

$$h_c = 0.888\left[T_b - T_g + \left(\frac{p_{wb}-p_{wg}}{2016-p_{wb}}\right)T_b\right]^{\frac{1}{3}} \quad (1)$$

Heat transfer between the cover and the basin is given by:

$$q_{c,b-g} = h_c(T_b - T_g) \quad (2)$$

The rate of mass transfer (evaporation heat transfer):

$$\dot{m}_d = 9.15 \times 10^{-7} h_c(p_{wb} - p_{wg}) \quad (3)$$

Evaporation and condensation heat transfer can be found by:

$$q_e = \dot{m}_d h_{fg} \quad (4)$$

Heat loss to the ground:

$$q_k = U_g(T_b - T_a) \quad (5)$$

Still efficiency is given by:

$$\eta_i = \frac{q_e}{G} \quad (6)$$

The inclusion of loss of water condensate through drip back into basin:

$$\eta_i = \frac{\dot{m}_p h_{fg}}{G} \quad (7)$$

By maximising the rate of mass transfer the amount of condensate is also therefore maximised. This can be accomplished by increasing the basin temperature, decreasing basin depth or reducing heat losses from the still.

2.2.2. Reverse Osmosis

The parameter total dissolved solids (TDS), measured in mg/L, quantifies the concentration of dissolved minerals in water [59]. According to the World Health Organization a TDS concentration of 500 mg/L is required for potable water [60]. Water with a TDS level above 500 mg/L is regarded as brackish or seawater [61].

Reverse osmosis (RO) is a water treatment process in which fresh potable water is produced through a process in which a saline liquid is forced through a semi-permeable membrane due to high differential pressure [62]. This occurs in the opposite direction of natural osmosis, therefore it is referred to as reverse osmosis. The basic process flow diagram of a RO device is shown in Figure 15.

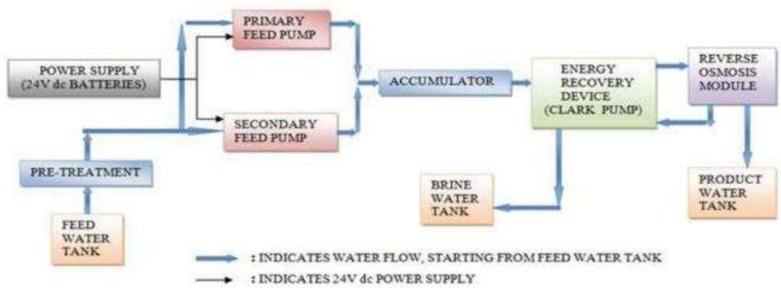


Figure 15 Basic reverse osmosis process flow diagram [63].

The reverse osmosis process follows the steps outlined below [64]:

- Pre-treatment – feed water is fed through multistage filters to remove debris, suspended solids and sand [65]. The filtration process removes particles as small as 10 microns [66]. This prevents damage to the high-pressure pumps and the semi-permeable membrane [67].
- Pressurization – centrifugal pumps increase the pressure to between 50 bars and 80 bars, depending on the salinity of the pre-treated water [68].
- Filtration – the semi-permeable membrane inhibits the movement of dissolved minerals across the membrane but allows the water to flow through [69].
- Chemical dosing – the filtered water is now chemical dosed to prevent the growth of microorganisms and for pH correction [69].
- Discharge – the brine collected during the filtration process is discharged and deposited back into the ocean in most cases [70].

Figure 16 is a diagrammatic process flow chart that shows the steps mentioned above in the relevant order [71].

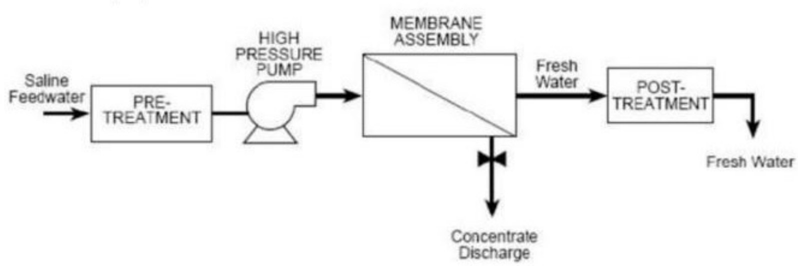


Figure 16 Steps of reverse osmosis process [71]

The advantages of desalination through RO are as follows:

- Can produce high volumetric output rates [72].
- Removes a large percentage of TDS, bacteria and chemicals through the filtration and chemical dosing steps [73].
- Efficient in energy consumption as there is no phase change of liquid [74].
- Maintenance of device can take place while device is still operational [73].

The disadvantages associated with RO desalination are:

- Requires high input pressure [75].
- High start-up costs [76].
- The selectively permeable membrane is susceptible to clogging and fouling, RO cannot take place if this occurs [76].

Mathematical Modelling of a Generic Reverse Osmosis System

The desalinated water flow rate across the selectively permeable membrane is given by Lienhard et al. [54]:

$$\dot{V}_p = K_A A_{mem}(TCF)(FF)(\Delta\bar{P} - \Delta\bar{\pi}) \quad (8)$$

These membranes aren not 100 % effective and allow some TDS to pass through; the concentration of the TDS salts within the desalinated water is show by Lienhard et al. [54] as:

$$C_p = \frac{K_B A_{mem}(pf)(TCF)C_{fe}}{\dot{V}_p} \quad (9)$$

2.3. Humidification-Dehumidification

Air has the ability to form a mixture with various other quantities such as water vapour [77]. Increasing the temperature of 1000 g of dry air from 303 K to 353 K leads to a new vapour composition of approximately 50 % [78]. Figure 17 is a basic process flow diagram for Humidification-Dehumidification (HDH) desalination [79]. The aim of the HDH desalination process is to simulate the natural water cycle but in a shorter period of time [28]. When air flow encounters a saline solution e.g. brine, the air will exchange heat for a quantity of vapour [80]. This vapour filled mixture is then allowed to have contact with a cooling surface thus causing condensation of distillate water [81]. The process is a continuous one. Condensate is prevented from mixing with the brine by increasing the brine temperature through latent heat recovery in a secondary heat exchanger [82]. The quantity of distilled water may vary from 5 % to 20 % of the brine water in circulation within the HDH desalination system [83]

The system seen in Figure 17 is an elementary process which operates under ambient conditions. The primary energy is harnessed from solar thermal energy to produce the water vapour. It requires a low grade of solar energy available and is effective for small to medium scale desalination projects.

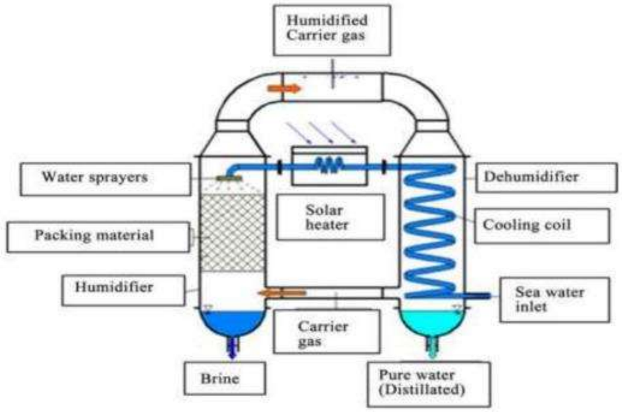
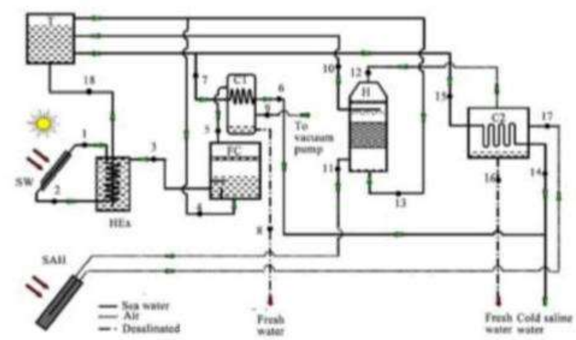


Figure 17 Humidification-dehumidification process flow [79]

More sophisticated HDH hybrid systems have been developed over the last decade. These devices employ the use of single stage flash evaporation units as seen in Figure 18 [84]. Research at the Massachusetts Institute of Technology shows that the inclusion of a single stage flash evaporator could yield increased distilled water recovery rates by an average of 9.1 % [85].



1.	T:	Mixing tank	5.	C1:	Flashing unit condenser
2.	SWH:	Solar water heater	6.	FC:	Flashing chamber
3.	Hex:	Heat exchanger	7.	H:	Humidifier
4.	SAH:	Solar air heater	8.	C2:	Dehumidifier

Figure 18 Hybrid single stage flash evaporating HDH desalination system [84]

Table 2 provides a summarised description of the different HDH systems arising from a review of the available literature.

Table 2 Summary of production output per HDH system type found in current research

Description	Output Production ($L/m^2/day$)	Gained Output Ratio (GOR)	Heating Mode	Reference
Solar area 6 m^2. No energy recovery.	3	GOR < 0.5	Water heating	[86]
Forced circulation of air, multi-pass shell and tube condenser, and wooden shaving packing in the humidifier.	12	GOR < 4	Water heating	[87]
Thermal storage, natural air draft, 38 m^2 collector area.	13	GOR = 3 – 4.5	Water heating	[88]
Packed-bed humidifier, air-cooled dehumidifier	9	N/A	Water and air heating	[89]
2 m^2 solar collector area, humidifier and condenser specific areas are 14 m^2/m^3 and 8 m^2/m^3.	8	GOR < 2	Water heating	[90]
Natural and forced air flow, heat recovery in the condenser.	Up to 5 kg/h	GOR < 4	Air heating	[91]
Five heating-humidification stages. Forced air circulation. Total collectors area ≈ 127 m^2.	4 (total 516 L/day)	N/A	Air heating	[92]
Single-stage, double-pass solar collector, pad humidifier and finned tube dehumidifier and 0.5 m^3 water storage tank. No heat recovery. Water may be heated in the storage tank to increase production significantly.	4 kg/m^2 - day (increased to 10 kg/m^2 - day upon operating the water heater)	N/A	Air heating	[93, 94]

The advantages of desalination through the HDH method are as follows:

- Ability to utilize low grade thermal energy [95].
- Moderate start-up and operational costs [96].
- Flexibility in output rate [97].

The disadvantages associated with the HDH method desalination are:

- If it is a solar HDH system, desalination after sunset is not feasible [98].
- Low energy recovery without Multi-Stage Flash Unit [79].
- Carrier gas (air) has low vapour content [79].

Mathematical Modelling of a Generic Humidification-Dehumidification System

The aim of the HDH process is to maximize the Gained Output Ratio (GOR). This is accomplished by trying to increase the rate of condensate produced while decreasing the heat energy input into the system. The equations below model a generic system [91].

The humidifier energy balance is given by:

$$\dot{m}_a\left[h_{a,in}(t) - h_{a,out}(t)\right] = \dot{m}_{w,in}h_{w,in}(t) - \dot{m}_{w,out}(t)h_{w,out}(t) \quad (10)$$

The dehumidifier energy balance can be shown by:

$$\dot{m}_a\left[h_{a,out}(t) - h_{a,in}(t)\right] = \dot{m}_{w,in}c_{p,w}\left[T_{w,out}(t) - T_{w,in}(t)\right] + \dot{m}_c(t)h_c(t) \quad (11)$$

Effectiveness for simultaneous heat and mass exchange is:

$$\varepsilon = \frac{\Delta H}{\Delta H_{max}} \quad (12)$$

$\Delta H_{max,w} < \Delta H_{max,a}$ for the humidifier.

$$\varepsilon = \frac{\Delta H_w}{\Delta H_{max,w}} = \frac{\dot{m}_{w,in}h_{w,in} - \dot{m}_{w,out}h_{w,out}}{\dot{m}_{w,in}h_{w,in} - \dot{m}_{w,out}h_{w,out}^{ideal}} \quad (13)$$

$$\varepsilon = \frac{\Delta H_a}{\Delta H_{max,a}} = \frac{\dot{m}_a h_{a,out} - \dot{m}_a h_{a,in}}{\dot{m}_a h_{a,out}^{ideal} - \dot{m}_a h_{a,in}} \quad (14)$$

The Gained Output Ratio or system performance index can be thus given as:

$$GOR = \frac{\dot{m}_{product}h_{fg}}{Q_{in}} \quad (15)$$

2.3.1. Electrodialysis

The favourable transportation of ions through an ion exchange membrane due to the action of an electric field is known as Electrodialysis (ED) [99]. This process of desalination uses a low concentration saline solution to produce concentrated brine and distilled water [100]. As shown in Figure 19, the saline solution is feed from the top and the two products exit through the bottom [101].

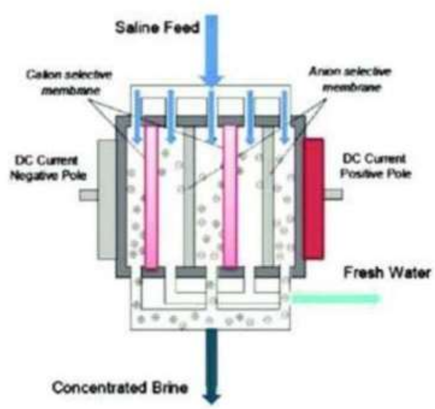


Figure 19 Electrodialysis desalination process schematic [101]

A differential voltage is established between the anode and cathode when an ionic solution is passed through the cell, as seen in Figure 20 [102]. The cations, which are positively charged, gravitate toward the cathode while the negatively charged anions move toward the anode. The positive anion-exchange membrane retains the cations and the negatively charged cation exchange membrane retains the anions. This leads to an ion concentration increase in alternating sections. The concentrated solution is now a brine product and the depleted solution is distilled water [103].

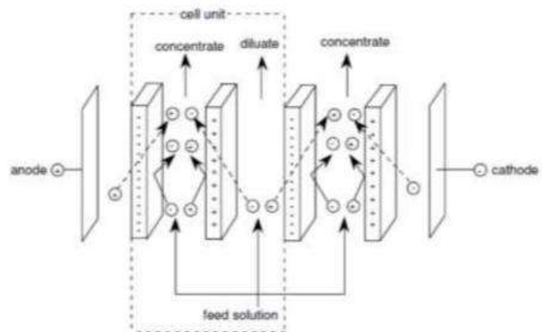


Figure 20 Illustration of the electrodialysis process [102]

It has been found that ED is more economic for saline solutions with concentrations below 5 g/L than is RO [104]. There are cases in which solutions with concentrations of up to 30 g/L have been successfully desalinated through the ED process [105], however it is recommended to be used for solutions with concentrations of 6 g/L or below [106].

Mathematical Modelling of a Generic Electrodialysis System

The mathematical modelling of an ED cell is described below. The aim of the model will be to maximise the flow of desalinated water (Q_d). Faradays law can be utilised to quantify the flow of charge required to transfer salt in order to demineralize a stream of brackish water /seawater [107]:

$$I = \frac{FQ_d \Delta N}{c_p e} \quad (16)$$

The voltage required can be found using Ohm's law, which dictates the relationship between current, resistance and voltage [107]:

$$E = I \times R \quad (17)$$

The resistance of the solution is given by Sharbat [107]:

$$R = \frac{U}{I} = constant \quad (18)$$

The advantages of desalination through ED are as follows:

- Phase change does not occur as such so there are relatively low energy requirements [102].
- Low input pressure is required [108].
- Can desalinate water of high TDS [100].

The disadvantages associated with ED desalination are:

- Does not remove organic matter from the water, filtration is required [108].
- Complex control system required to maintain efficient operation [100].
- Fouling of permeable membranes can occur [109].

3. ECONOMICS OF THERMAL AND MEMBRANE DESALINATION

Table 3 and Table 4 list the cost of production for thermal and reverse osmosis desalination per 1000 litres in dollars [110]. As can be noted from the tables, the average cost for thermal desalination is lower than that of RO. Reverse osmosis becomes more economical for seawater desalination for volumes greater than 15 000 m^3/day.

Table 3 Thermal desalination cost per 1000 litres produced [110]

Desalination Method	Output Production (m^3/day)	Cost per m^3 (Dollars US)
Multi Effect Distillation	< 100	2.5 – 10
	12000 – 55000	0.95 – 1.95
	> 91000	0.52 – 1.01
Multi-Stage Flash	23000 – 528000	0.52 – 1.75
Vapour Compression	1000 – 1200	2.01 – 2.66

Table 4 Reverse Osmosis desalination cost per 1000 litres produced [110]

Input Water	Output Production (m^3/day)	Cost per m^3 (Dollars US)
Brackish	< 20	5.63 – 12.9
	20 – 1200	0.78 – 1.33
	40000 – 46000	0.26 – 0.54
Sea	< 100	1.5 – 18.75
	250 – 1000	1.25 – 3.93
	15000 – 60000	0.48 – 1.62
	100000 – 320000	0.45 – 0.66

4. CONCLUSION

Approximately 15.38 % of the global population reside in water scarce regions. The withdrawal ratio is extremely high for the northern and southern Africa regions, the Middle-East and south east Asia. South Africa has been classified as the 30th driest country in the world. Water purification involves the processing of water that is not suitable for consumption, using various methods so that the water can be regarded as potable. Distillation and desalination are two major water purification methods. Solar desalination is a process in which solar energy is harnessed to remove dissolved impurities found in water. Distillation, RO, HDH and ED are four methods of desalination. Reverse osmosis is the most widely utilized desalination method as it makes up 52 % of global desalination. Reverse osmosis and ED are regarded as single phase (membrane based) processes. Distillation and HGH are phase change (thermal based) processes. Twenty two percent of global desalination processes are thermal based processes. Through the study of the economics of thermal and membrane desalination, it was found that thermal desalination had a lower average cost than reverse osmosis. While reverse osmosis became more economical for desalination volumes exceeding 15000 m^3/day.

5. ACRONYMS

ED – Electrodialysis
GOR – Gained Output Ratio
HDH – Humidification-Dehumidification
RO – Reverse Osmosis
TDS – Total Dissolved Solids

6. NOMENCLATURE

Symbols
A = Area (m^2)
C = Average concentration (mg/L)
C_p = Concentration of reverse osmosis
c_p = Number of cell pairs
E = Voltage (V)
e = Current efficiency
F = Faraday's constant
FF = Membrane fouling factor
G = Incident solar radiation (W/m^2)
h_c = Heat transfer coefficient (W/m^2. K)
I = Electrical current (A)
K = Membrane permeability for water (m/bar. s)
p = Pressure (mmHg/Pa)
pf = Polarization factor
Q = Flowrate (L/s)
q = Heat transfer (W)
$\dot{m}$ = Mass transfer rate (kg/s)
$\dot{Q}$ = Rate of heat transfer (J/s)
T = Temperature (K)
TCF = Water permeability temperature correction
R = Resistance (Ω)
U = Overall loss coefficient (W/m^2. K)
$\dot{V}$ = Volumetric flow rate of purified water (m^3/s)
Greek Letters
η = Efficiency
$\Delta\bar{P}$ = Average pressure applied across the membrane (bar)
$\Delta\bar{\pi}$ = Average osmotic pressure applied across the membrane (bar)
ε = Effectiveness for simultaneous heat and mass exchange
ΔH = Change in enthalpy, J/mol
ΔN = Change in normality
Subscripts
A = for water
a = ambient

B = for salt
b = basin
d = distillate
e = evaporation
g = glass/ground
p = purified water
mem = membrane
w = water

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2.1 Discussion

More than 1.2 billion people live in water scarce regions across the world [1]. Funding, research and development into alternative water resources has begun by countries with a low Human Development Index. With South Africa being ranked the 30th driest country in the world [2], and the recent drought that affected the Western Cape in 2018, a significant mind shift is occurring with many realizing alternative water sources are required.

Common water purification techniques include distillation, desalination, filtration, chemical treatment and boiling. Over the last two decades desalination has risen in popularity; however, reservations still exist due to the bulk of desalination processes being very energy intensive. Since 2008 electricity supply in South Africa has been extremely unstable. Solar desalination relies on the solar energy harnessed from the sun to enable the desalination process. The four main methods of desalination are thermal, mechanical, electrical and chemical. The most common method is reverse osmosis (mechanical) constituting 52% of global desalination systems currently installed [3]. This chapter reviews the four main methods of desalination and the working principles, types, pros and cons, governing equations and productivity are described.

Solar distillation involves the evaporation of saline water and condensation of distilled water enabled by solar radiation. Solar radiation provides the energy to allow for the phase change from water to water vapour. Solar stills range from simple single slope stills to complex multistage stills. Multistage stills record average production rates of 18 L/m^2/day [4] but are much more expensive to manufacture and require significantly more energy input. Single and double slope stills are simpler to manufacture and are a cost-effective alternative to complex still designs although offering greatly reduced output rates. This can be overcome with addition of energy storage, air preheaters and external reflectors. The major advantage of solar stills is the ability to produce distilled water from both fresh and seawater. This is somewhat offset by poor operational performance during winter months.

Reverse osmosis produces potable water through pre-treatment and mechanical filtration of saline water through a semi-permeable member [5]. Reverse osmosis systems are able to handle water with high total dissolved solids (TDS) while also removing a large percentage of bacteria and chemicals [6]. The startup costs for these systems are extremely high and often pay-off periods are in excess of a decade [7].

The humidification-dehumidification method simulates the natural water cycle in a controlled environment to produce distilled water [8]. These systems can produce anything between 3 L/m^2/day to 13 L/m^2/day depending on the system setup [9, 10]. Humidification-dehumidification often cannot occur after sunset even though it is capable of utilising very low grade thermal energy [11].

Electrodialysis entails the favourable movement of ions across a differential permeable membrane [12]. A differential voltage is set up between an anode and cathode while an ionic solution (seawater in this case) is passed through the cell. Electrodialysis requires a great deal of electricity to power the system but is also capable of desalination water of extremely high TDS [13].

Solar distillation and reverse osmosis have both been shown to be reliable, cost effective and effective methods to desalinate water based on the respective production rates, pros and cons, cost factors and use globally. The cost per cubic metre of potable water produced by reverse osmosis significantly reduces from 18.75 $/m^3$ to 0.45 $/m^{3,}$ for seawater, with an increase of 100 m^3/day to 100 000 m^3/day of water desalinated [14]. Reverse osmosis is therefore better suited to largescale projects as solar distillation cost per cubic metre desalinated remains consistent in the ± 2 $/m^3$ range [14]. Solar distillation is therefore more applicable to household desalination plants.

2.2 Summary of chapter

A review of literature was carried out to introduce the need for research into water due to the current water shortages plaguing the global population and survey the current methods of water purification. The process of water solar desalination is summarised and the different desalination techniques are discussed. The economics of the different desalination systems are tabled.

2.3 References

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CHAPTER 3: METHODOLOGY

3.1 Introduction

A research methodology is the chosen systematic approach of study by a researcher into a given topic. The methodology attempts to identify, define and select processes/methods to analysis a problem and allow one to critically assess the reliability and validity of the study. The methodology of a study can be decided upon through research into similar topics, qualitative and quantitative research modes and consultation with design experts. This chapter describes the methodological approach to be used during the study. Qualitative and quantitative research approaches are described, their advantages and disadvantages listed, and the specific types of each approach discussed. Lastly, a methodological process flow diagram is shown to represent the overall manner in which the study will be carried out.

3.2 Qualitative approach

A definition of qualitative research provided by [1] is "a form of systematic empirical inquiry into meaning". This relates to the collection of data through a systematic, inductive approach based on epistemological and ontological assumptions [2]. Data is analysed through flexible interpretation and with assumptions in place [3]. Sources include observations, interviews, opinions and words [4].

The advantages of a qualitative research approach include:

- Data can be analysed with greater detail as there are generally less time constraints involved in qualitative research, while quantitative research often deals with time dependency testing [5].
- Is based on human experience, interpretation and observation [6]. This enables the researcher to understand the target market or gain valuable industry insight [7].
- Due to the fluid nature of research, qualitative methods enable the design and redesign of the research structure [8]. Through design structure iteration, the researcher is allowed sufficient freedom to decide on a structure that is consistent for their needs [9]. An example is increasing sample size in a survey when skewed results are attained.

The disadvantages of a qualitative research approach are listed as:

- Data attained can be highly subjective [10]. By the use of inappropriate sampling, choice of interviewees and predisposed notions on topics the assessment of contextual data can lead to misleading results [11].
- Qualitative research findings are often difficult to present in an easily observable manner like a graph of quantitative results [12].

- Qualitative research may not always be accepted as the primary source of results but rather as a supplementary to quantitative research [12].

Four qualitative research methods were chosen; feasibility study, Quality Function Deployment (QFA), market analysis and Failure Modes and Effects Analysis (FMEA). These methods are depicted in Figure 3-1 and discussed below in order to describe the outcome and result that can be obtained from these qualitative techniques.

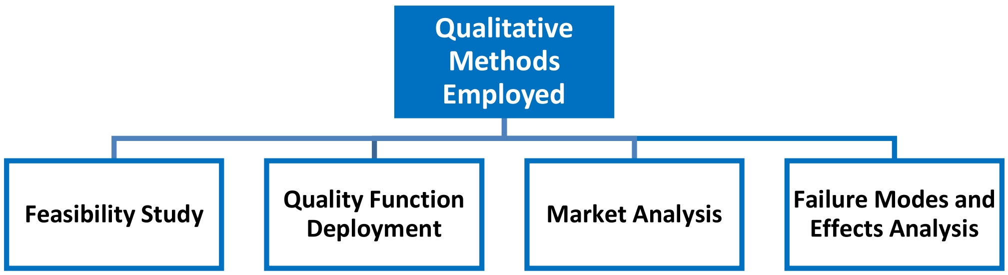

Figure 3-1: Qualitative methods employed

3.2.1 Feasibility study

This feasibility study refers to the viability of providing solar powered water desalination systems to the everyday municipal water consumer. Feasibility studies answer the questions: "Can this be done?" and "Should this be done?" [13]. The method involved a survey of members of the population to ascertain their opinions and views on the use of desalinated water as opposed to municipal water, the need for alternative water supply methods and willingness to invest in such technologies. Figure 3-2 is a radial diagram that lists the subsections a feasibility study may include. Note however, that this study was not limited to these constituents.

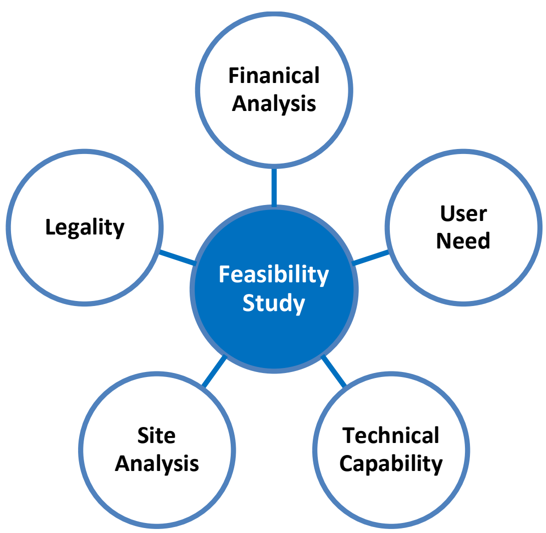

Figure 3-2: Fundamental feasibility study constituents

The main focus of the feasibility study to be carried out was user willingness and need, financial and site analysis.

3.2.2 Quality function deployment

QFD is a systematic method in which the customers' needs are identified such that product specifications can be tailored to meet these requirements [14]. The diagram in Figure 3-3 is a graphical representation of the QFD often referred to as the House of Quality [15].

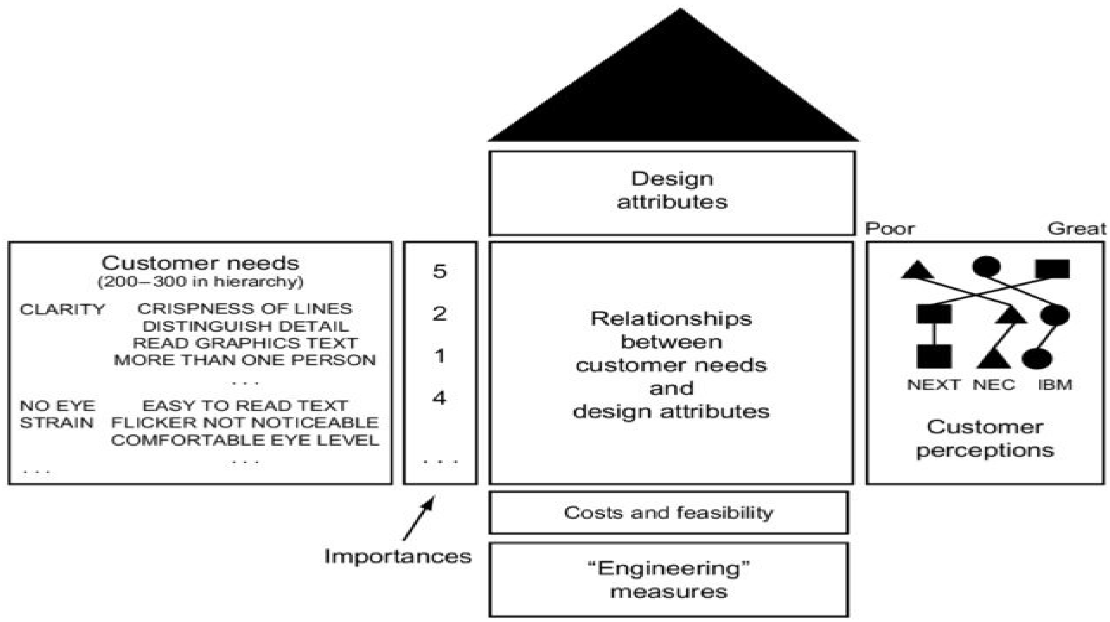

Figure 3-3: QFD House of Quality

The QFD is completed by the project designer. Certain needs can be prioritised by the designer as it is his/her opinion what the consumer values. The QFD will be used to identify the requirements of the customer in conjunction with the results attained through the feasibility study.

3.2.3 Market analysis

The market analysis generally forms a part of the feasibility study however it can be a standalone technique to both qualitatively and quantitatively assess the market that a system intends on entering. A common tool utilised to study a market is a SWOT (strengths, weaknesses, threats, opportunities) analysis, shown in Figure 3-4 [16].

Figure 3-4: Generic SWOT analysis

An in-depth SWOT analysis can be used to strategically enable an individual to develop a system that targets specific market segments built on competitor shortcomings and identify proven operational techniques [17].

3.2.4 Failure modes and effects analysis

FMEA is a qualitative approach to assess quantitative quantities that may affect a system. A FMEA aims to be proactive in identifying possible failure modes and their probable effects on the system [18]. The results of a FMEA can be used to optimise the design, decide on mitigating methods and provide future design recommendations. Figure 3-5 is the process used during an FMEA [19].

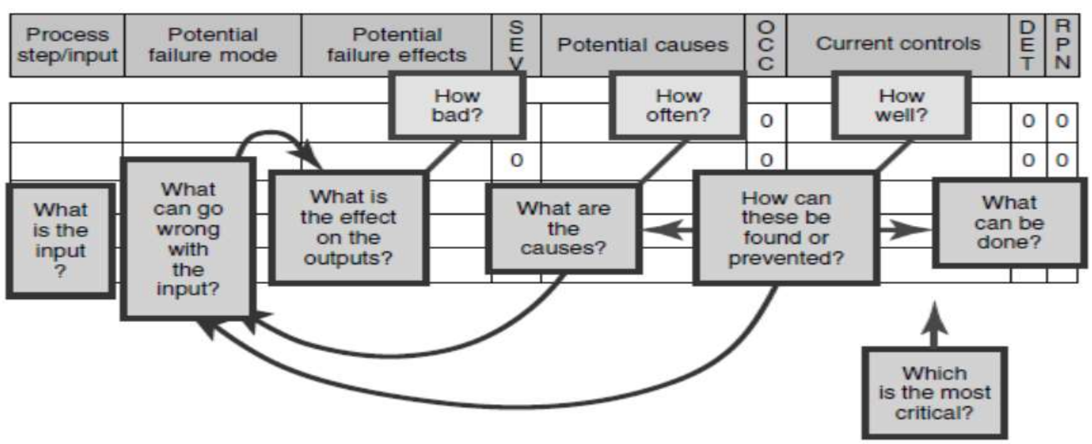

Figure 3-5: Failure Modes and Effects Analysis logical flow diagram

FMEA is a vital tool in the design of a system as it can help a creator meet operational, maintenance and cost targets [20].

3.3 Quantitative approach

Research by [21] describes quantitative research as the use of mathematical methods to analyse data collected and thus explain and gain an understanding of a specific phenomenon. The aim of this type of research is to quantify using numerical values the constraints, performance and specifications, amongst others, of a system [22]. Sources of quantitative data are attained through analytical, experimental, computational and even qualitative analysis [23].

The advantages of a quantitative research approach include:

- Time to analyse data can be reduced by the use of statistical software [24].
- Control variables/groups can be utilised to provide a comparison and aid in results validity [22].
- Can be used to discern key performance indices in technical research. This can allow individuals to easily recognise whether objectives were met and if the project was a success or failure.
- Quantitative methods can be designed to remove the influence of human behaviour, interaction and subjectivity [25], allowing an individual to model ideal situations.

The disadvantages to a quantitative research approach are listed as:

- The phenomenon is not always observed under natural circumstances, which can negatively affect results [26].
- As the approach is predetermined in structure, linearity and inflexibility it does not always allow for creative and imaginative thinking [27]. As such, the data collected is set to either accept or reject the predetermined notion [28].
- In the technical environment quantitative results are more readily accepted.

Three quantitative research methods were chosen: analytical modelling, Computer Aided Design (CAD) and computational modelling. These methods are depicted in Figure 3-6 and discussed below with the intention of describing the outcome and result that can be obtained from these quantitative techniques.

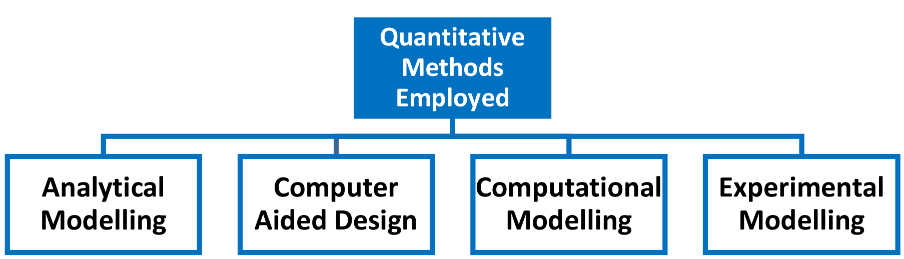

Figure 3-6: Quantitative methods to be employed

3.3.1 Analytical modelling

Analytical modelling involves the use of mathematical models to explain, understand, simulate and predict the behaviour of a system, process or function [29]. Analytical modelling can be categorised into three main techniques [30]:

- Regression analysis – a regression analysis allows the researcher to understand the relationship between a dependent and one or more independent variable(s) [31].
- Grouping methods – is an approach in which results or observations are grouped or categorised [32].
- Multiple equation models – extends the observable path of regression analysis through analysing multiple variables simultaneously [33].

3.3.2 Computer aided design

CAD is a software tool that can be used to model a system in two or three dimensions in a homogenous coordinate system by producing drawings such as orthographic and sectional views, assembly and isometric drawings and other graphical representations [34]. The CAD models produced in this study will be utilised in the computational model by importing the geometry.

3.3.3 Computational modelling

Computational models make use of mathematical and physical principles through computer science to study, analyse, simulate and understand the behaviour of systems [35].

The ANSYS® computational software utilises the iterative algorithm shown in Figure 3-7 to solve the governing equations of a fluent system [36]. Using computational software to solve fluent problems one can attain information such as system pressures, fluid velocities and operating temperatures.

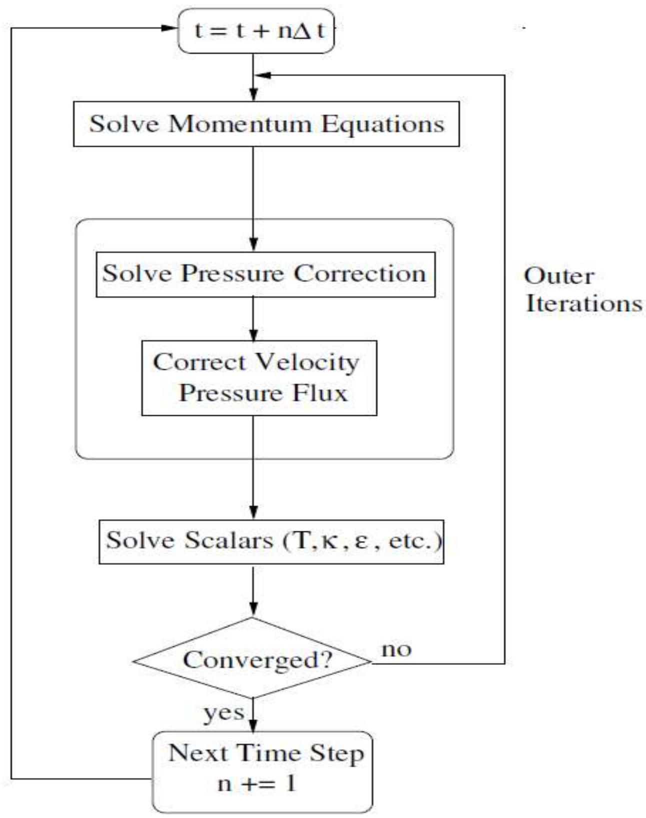

Figure 3-7: Example of computational software solving algorithm

Results obtained through computational analysis can provide a worthy data set to compare to values acquired via analytical modelling.

3.3.4 Experimental modelling

Experimental modelling is a scientific or structured procedure in which the environmental conditions of a system are controlled through certain treatments while an experimental variable(s) is observed [37]. Often the aim of experimental modelling is to test hypotheses, demonstrate a known behaviour or verify system performance. There are four main types of experiments that are carried out to achieve the above-mentioned description [38]:

1) True experiments
2) Quasi-experiments
3) Single-subject experiments
4) Non-experiments

The main issue that arises during the experimentation process is the impact of error and uncertainty on the results ascertained. Figure 3-8 describes the types of error that often affect experimental modelling [39]. Error should be mitigated where possible to enhance the validity of the results attained.

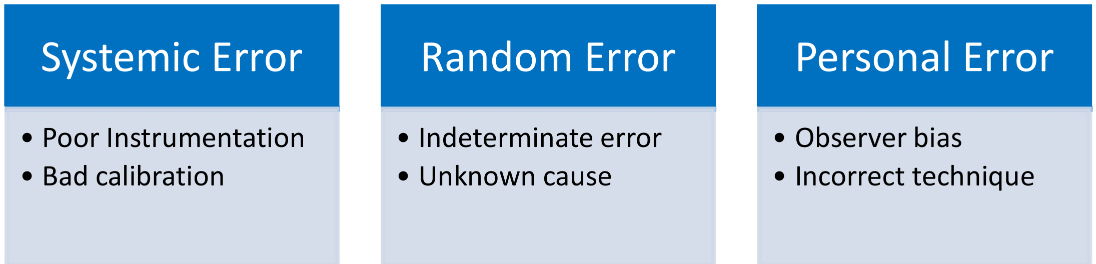

Figure 3-8: Types of experimental error

3.4 Methodology process flow

The following methodology (Figure 3-9) was used in the research, design, analysis and evaluation of the solar powered water desalination system. Both the qualitative and quantitative approaches will be listed and discussed hereafter. These formed a guideline for the research carried out.

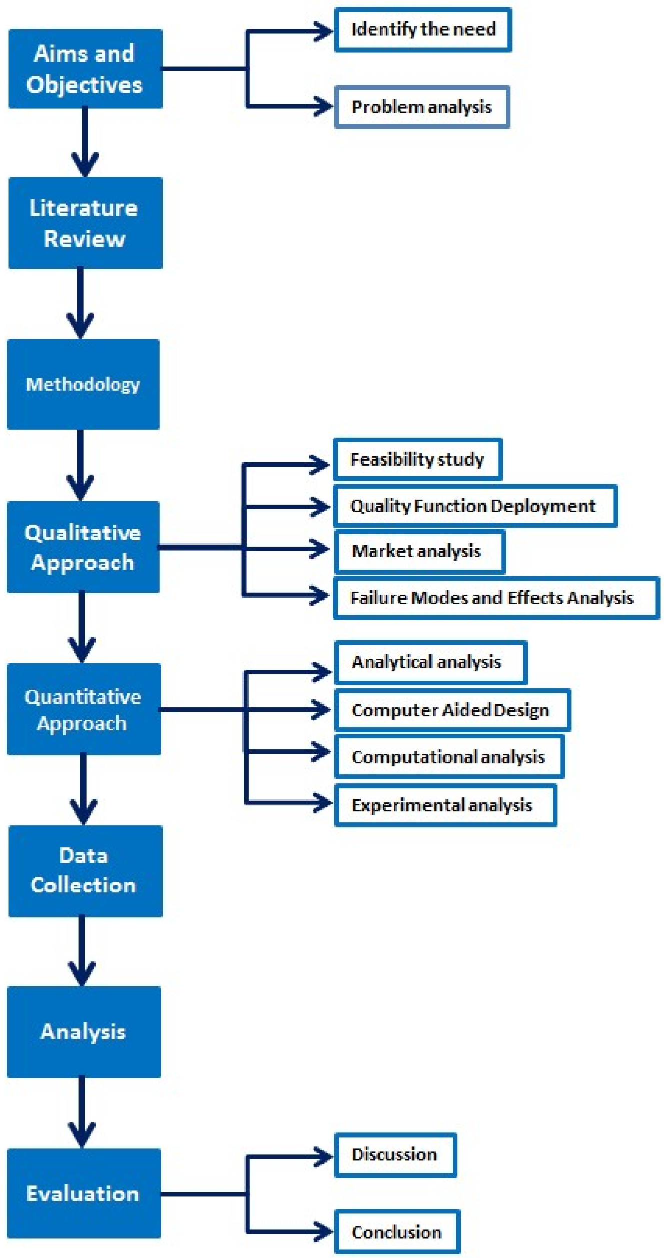

Figure 3-9: Research methodology flowchart

3.5 Discussion

The research methodology constructed enforces a better balance between qualitative and quantitative research styles. Generally, engineering research is heavily quantitative and rarely utilises a qualitative approach to aid in the research and design process. The methodology in this study made use of a four-part qualitative approach and a four part quantitative approach. The qualitative approach made use of three conventional qualitative engineering tools. The quantitative approach utilised various modelling and design techniques to obtain results.

The qualitative approach consisted of a feasibility study, QFD, market analysis and FMEA. The feasibility study was carried out in the form of a research questionnaire supplied to members of the general public. The aim of the feasibility study was to classify public opinion on "can", "should" and "how" research and design be accomplished. The QFD made use of the researcher's opinion on customers' needs when calculating the importance of certain design features and requirements. The results of a QFD play a role during the mechanical design process when selecting system characteristics such as material, size and set up. Market analysis is a tool often used in the engineering design process as it allows for a benchmark for design to be established. The researcher can qualitatively compare the proposed design concept with systems that have already been manufactured and tested and these devices can be encompassed in the QFD process, as required. An FMEA is a deductive approach to design. The researcher can theorise possible failure modes of the design concept and then systematically categorises the importance of such a failure. The objective is to either mitigate the failure mode through design changes or establish the likelihood and factor this into a maintenance strategy.

Analytical, computational and experimental modelling alongside CAD makes up the quantitative approach of the research methodology. Often, only a select few of these research tools are utilised. However, it is important to provide a comparison of results as each modelling technique comes with its associated strengths and weaknesses. An analytical model serves to solve the relevant governing equations of a system via various means. These governing equations can be categorised through a regression analysis, grouping method or multiple equations model. The analytical model approximates system conditions and attempts to factor in unideal factors e.g. wind on a solar still slope. CAD enables the visualisation of the system so that it can be utilised as a geometry for the computational model. Computational modelling integrates computer science, physical science and engineering to simulate the behaviour characteristics of systems. It provides an amalgamation of analytical modelling and CAD. The system governing equations are solved after various conditions are proposed and the behaviour results output both visually and numerically. An experimental analysis allows the researcher to set up a structured procedure while the behaviour of the system is observed under specific conditions. In this case, the solar powered water desalination plant test rig was utilised in the experimentation process to serve as a benchmark to which current and proposed system output results could be compared.

3.6 Summary of chapter

A description of the methodology to be utilised during the study was presented. Qualitative and quantitative research approaches were discussed along with their advantages and disadvantages. The various types of qualitative and quantitative research approaches to be used were mentioned. Lastly, the methodology employed was discussed.

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CHAPTER 4: FEASIBILITY STUDY

4.1 Introduction

A feasibility and customer opinion study was carried out. As part of the qualitative approach to the methodology, members of the general population were asked to complete a survey. The survey included basic information about the individual, their knowledge on water usage and scarcity in the region, alternative means of water supply and implementation within South Africa and lastly, their views on the viability of desalination systems for everyday use.

4.2 Sample size

When carrying out a survey one of the main factors that affects the reliability of results is the sample size of a survey which is the minimum number of individuals required to participate to yield a reliable result. In statistical analysis there is a generalised method to calculate this sample size, as given by [1]:

$$n = \frac{Z^2 \times p(1-p)}{e^2} \tag{4-1}$$

Where:

$n = Sample\ size$

$Z = Confidence\ level$

The confidence level is generally chosen as 95%. As such the corresponding Z-score can be taken from Table 4-1 [2].

Table 4-1: Confidence level: Z-score

Confidence Level	Z-score
90%	1.645
95%	1.96
98%	2.326
99%	2.576

$p = Estimated\ prevalence$

This is given as 50 % or 0.5.

$e = Margin\ of\ error$

Margin of error is chosen by the researcher. A smaller margin of error generally results in a more reliable set of results. A margin of error between 5 % to 10 % is acceptable [3]. Margin of error (e) was therefore taken as 10 %.

Given that:

$Z = 1.96$

$p = 50\ \% = 0.5$

$e = 7.5\ \% = 0.075$

Based on these figures, the sample size for the survey can be calculated using Equation (4-1). This sample size will be the minimum number of individuals that need to complete the survey for results to be deemed reliable.

$$n = \frac{(1.96)^2 \times 0.5(1 - 0.5)}{(0.10)^2} = 96.04$$

The result from the calculation shown above outputs a value of 96.04 which was rounded off to the next integer. The sample size therefore was set at 97 individuals and 100 completed the survey.

4.3 Research survey

The self-administered research survey that was designed, compiled and sent to individuals can be found in Appendix B.1. The online platform Google Forms was utilised to distribute the survey. The questionnaire consisted of 29 questions in total under the following headings:

1) Personal information
2) State of water resources
3) Alternative sources of water
4) Future of desalination

4.4 Results

The section provides the results obtained from the 100 respondents that completed the survey. The results for the feasibility study survey are structured as follows:

1) Question
2) Table with numerical results summary
3) Figure with graphical representation of results

Age of respondents

Question: Age

Table 4-2: Summary of ages of respondents

Age	Number	Age	Number	Age	Number	Age	Number
18	1	27	6	36	0	45	0
19	1	28	4	37	2	46	0
20	5	29	3	38	1	47	0
21	6	30	3	39	0	48	1
22	9	31	4	40	1	49	0
23	19	32	2	41	0	50	1
24	12	33	2	42	0		
25	6	34	3	43	1	56	1
26	6	35	0	44	0		
Average age of respondents				26.48 ≈ 26			

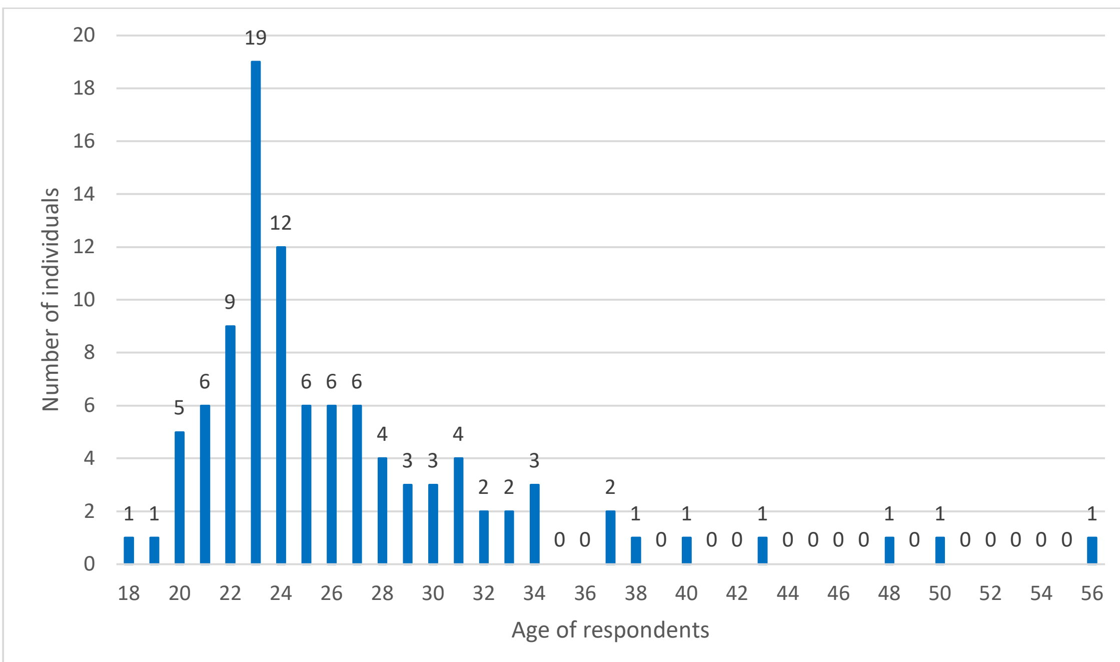

Figure 4-1: Number of respondents in each age group

Educational qualification

Question: Highest qualification completed

Table 4-3: Summary of highest qualification of respondents

Highest qualification	Number/Percentage of respondents
Grade 12	22
Higher certificate / Diploma	11
Bachelor's degree (Including Honours)	55
Post graduate degree (Masters/PhD)	12

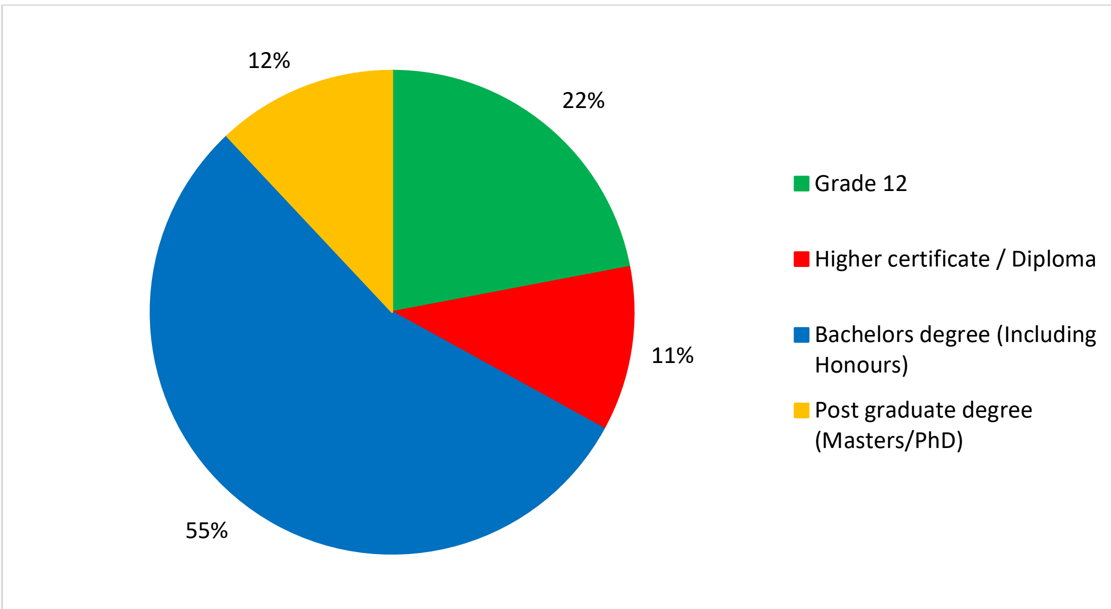

Figure 4-2: Highest educational qualifications of respondents

Geographic location

Question: City of residence

Table 4-4: Summary of geographic location of respondents

City	Number/Percentage of respondents
Cape Town	5
Johannesburg	18
Durban	51
Pietermaritzburg	2
Vanderbijlpark	6
Germiston	1
Vereeniging	5
Pretoria	3
Klerksdorp	1
Newcastle	2
Vaalpark	2
Meyerton	1
Heidelberg	1
Alberton	1
Potchefstroom	1

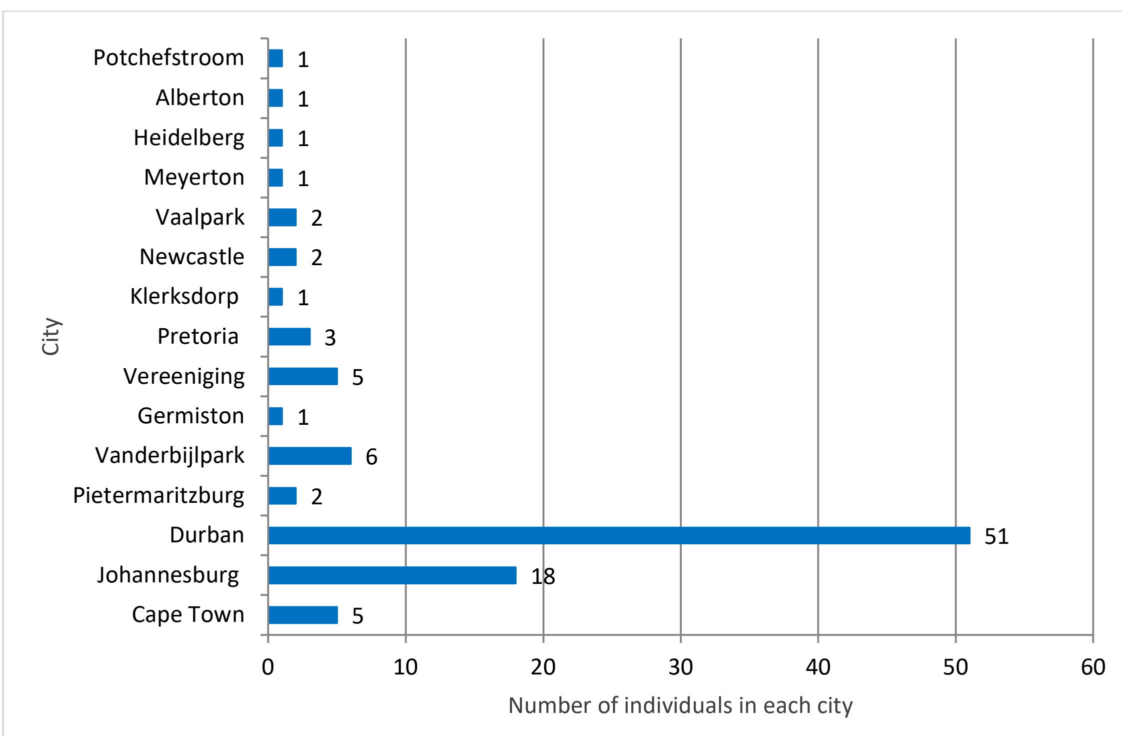

Figure 4-3: Geographic distribution of respondents

Household size

Question: Number of individuals in your household

Table 4-5: Summary of household size

Number of individuals in respondent's household	Number/Percentage of respondents
1	15
2	20
3	18
4	23
5	17
6	4
7	1
8	1
9	1
Average household size	3.34 ≈ 4

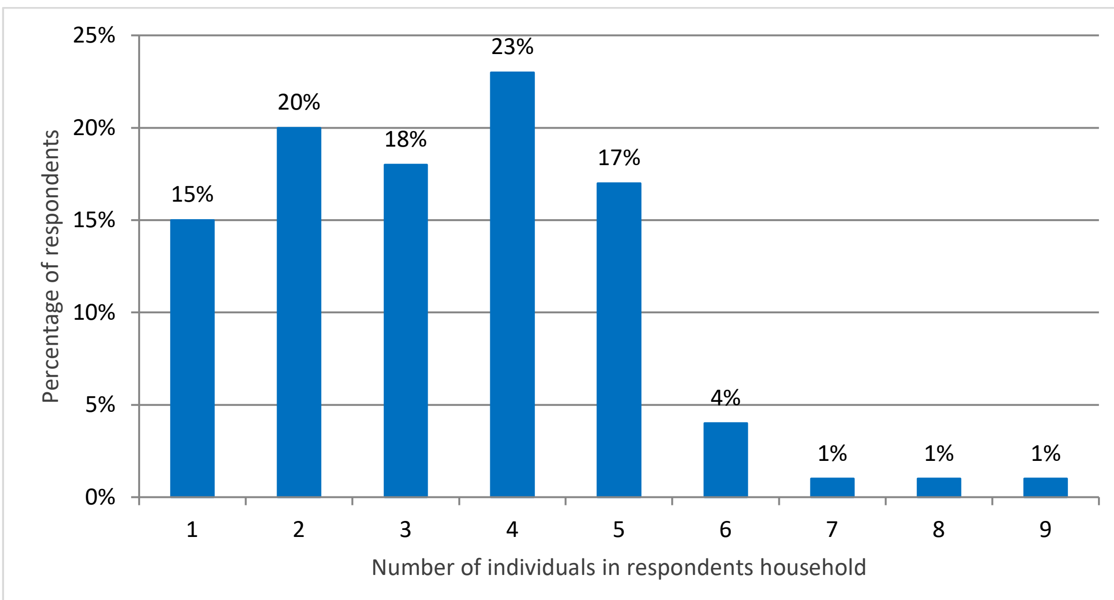

Figure 4-4: Number of individuals in respondent's household

Understanding of potable water

Question: What is your understanding of what potable water is?

Table 4-6: Summary of respondents' understanding of potable water

Understanding	Description on graph	Number/Percentage of respondents
Good understanding	Yes	49
Wrong understanding	No	14
Unclear understanding	Ambiguous	18
Does not know – No answer	Do not know	19

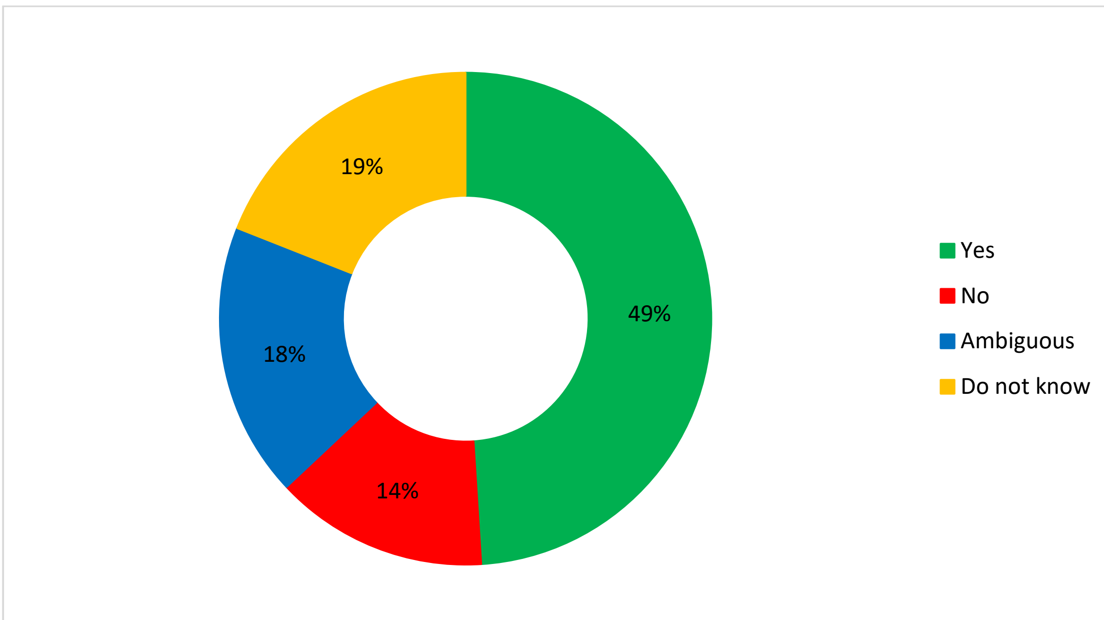

Figure 4-5: Respondents understanding of what potable water is

Source of drinking water

Question: What is the primary source of drinking water at your residence?

Table 4-7: Summary of sources of water at respondents' residences

Source of water	Number/Percentage of respondents
Municipality	91
Bottled water	6
Rainwater	1
Borehole	1
River/Lake	1

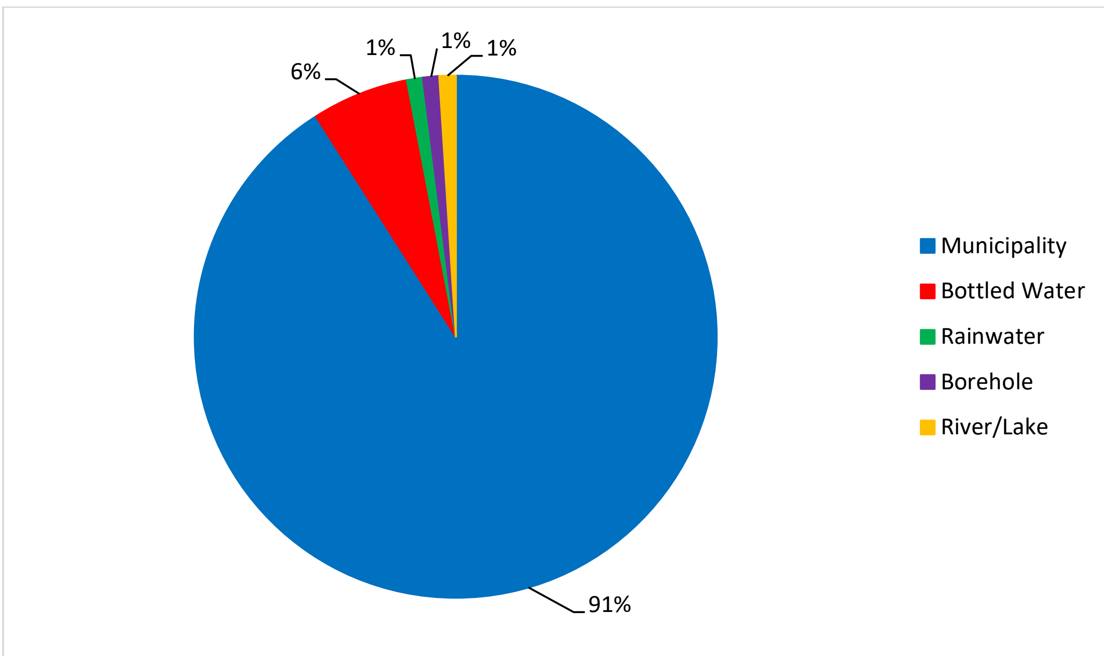

Figure 4-6: Respondents' current source of water

Perception of safety of municipal water

Question: On a scale of 1 to 10 - how safe for consumption is the water supplied by your municipality?

Table 4-8: Summary of municipal water safety rating by respondents

Rating	Description	Number/Percentage of respondents
1	Not safe for consumption	0
2		0
3		0
4		2
5		4
6		8
7		12
8		30
9		24
10	Extremely safe for consumption	20
Average rating of municipal water safety		8.16 ≈ 8

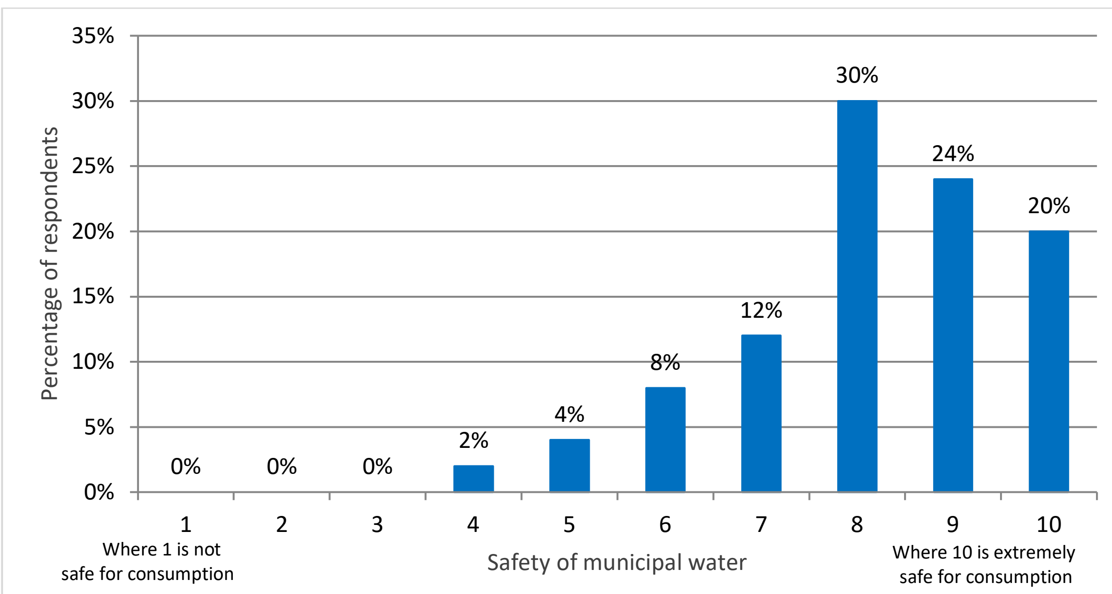

Figure 4-7: Respondents opinion on how safe municipal water

Scarcity of water resources in our country

Question: On a scale of 1 to 10 - how scarce are water resources in South Africa?

Table 4-9: Summary of water resources scarcity ratings by respondents

Rating	Description	Number/Percentage of respondents
1	Extremely scarce	1
2		1
3		12
4		27
5		23
6		11
7		13
8		5
9		5
10	Not scarce at all	2
Average rating of scarcity of water resources		5.24 ≈ 5

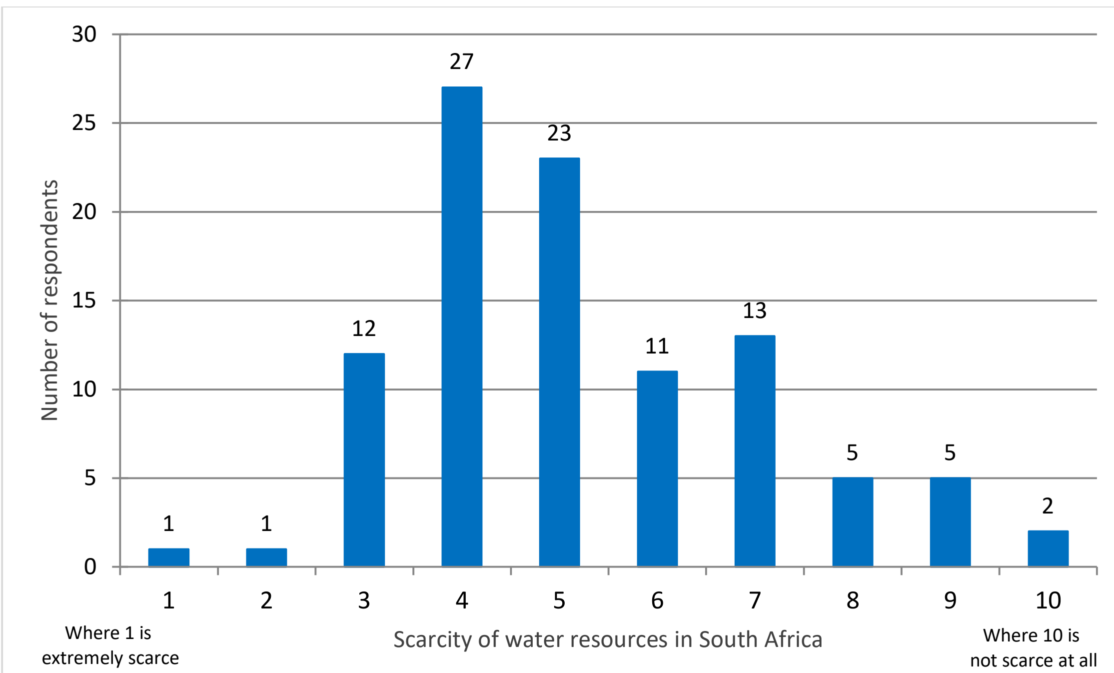

Figure 4-8: How scarce respondents believe water resources are in South Africa

Daily water consumption

Question: How many litres of water do you drink per day?

Table 4-10: Summary of water consumption by respondents per day

Range of water consumption per day	Number/Percentage respondents
Less than 1 litre	11
1 litre - 1.99 litres	50
2 litres - 2.99 litres	33
3 litres - 3.99 litres	5
Greater than 4 litres	1

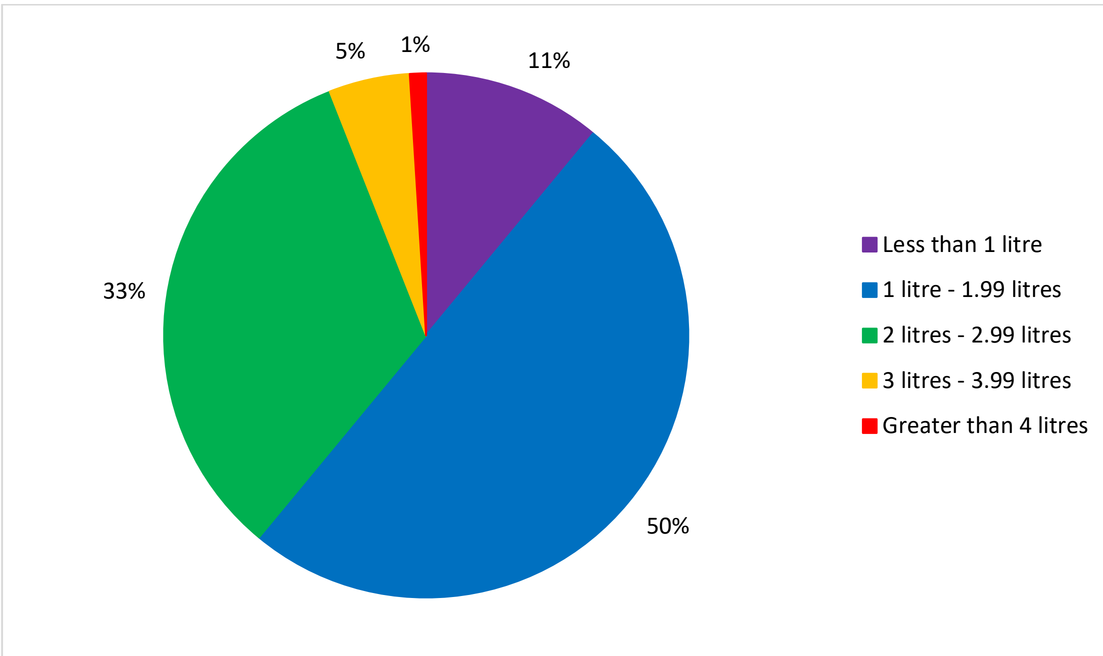

Figure 4-9: Individuals' estimate of daily consumption of water

Daily water usage

Question: How many litres of water, would you estimate, do you use per day in total to complete everyday tasks?

Table 4-11: Summary of water usage by respondents per day

Range of water usage per day	Number/Percentage respondents
Less than 10 litres	6
10 litres - 24.99 litres	27
25 litres - 49.99 litres	21
50 litres - 74.99 litres	21
75 litres - 99.99 litres	11
More than 100 litres	14

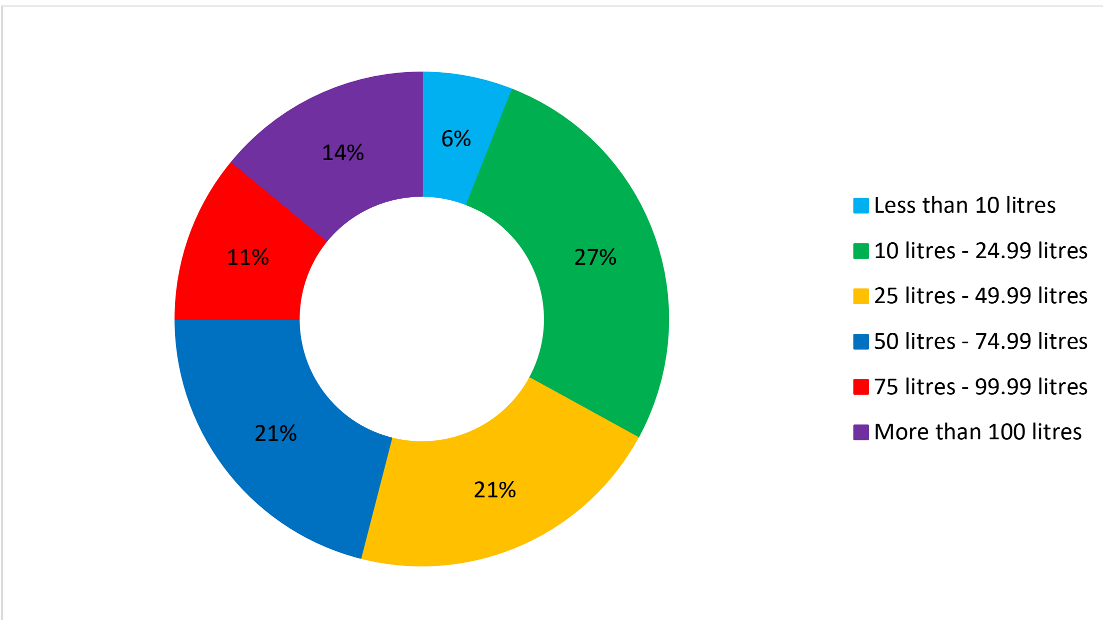

Figure 4-10: Respondents' estimate of daily water usage exclude water consumed

South Africans with access to safe drinking water

Question: What percentage of South Africa's population has access to a supply of safe drinking water?

Table 4-12: Summary of respondents' perception of percentage of South African's with access to safe drinking water

Range of individuals access to safe drinking water	Number/Percentage respondents
Less than 30%	13
30% - 49.99%	37
50% - 69.99%	29
70% - 89.99%	17
90% - 94.99%	3
More than 95%	1

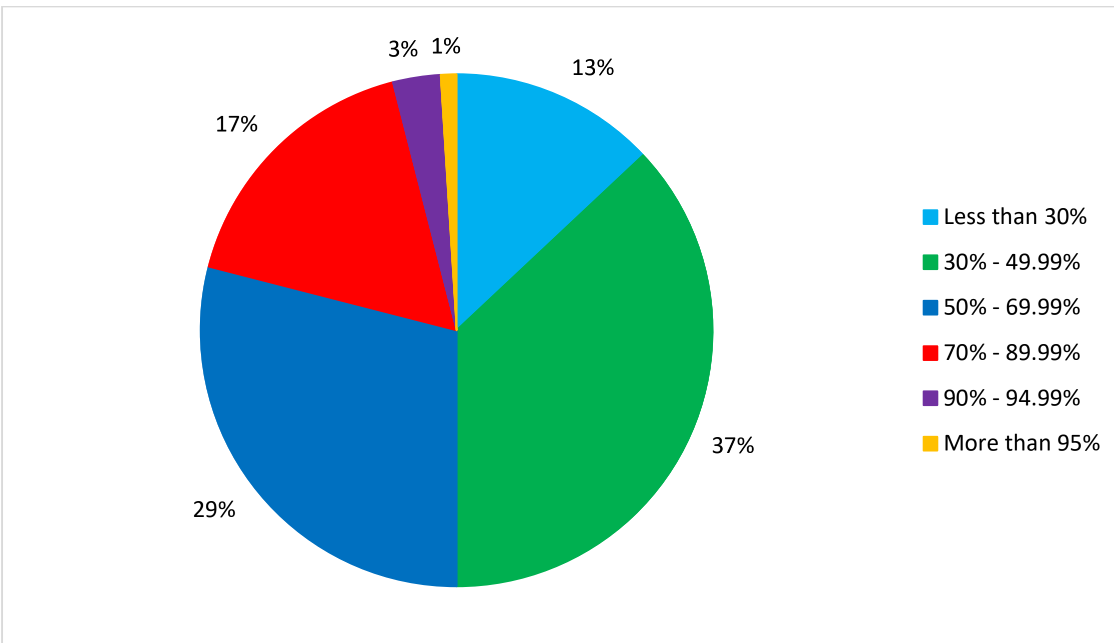

Figure 4-11: Respondents' belief on number of South African with access to safe drinking water

Conservation of water

Question: On a scale of 1 to 10 - how much do you attempt to conserve water during your daily activities?

Table 4-13: Summary of respondents' attempts to save water

Rating	Description	Number/Percentage of respondents
1	Not conservative at all	2
2		1
3		4
4		4
5		17
6		16
7		23
8		21
9		6
10	Extremely conservative	6
Average rating of water conservative		6.56 ≈ 7

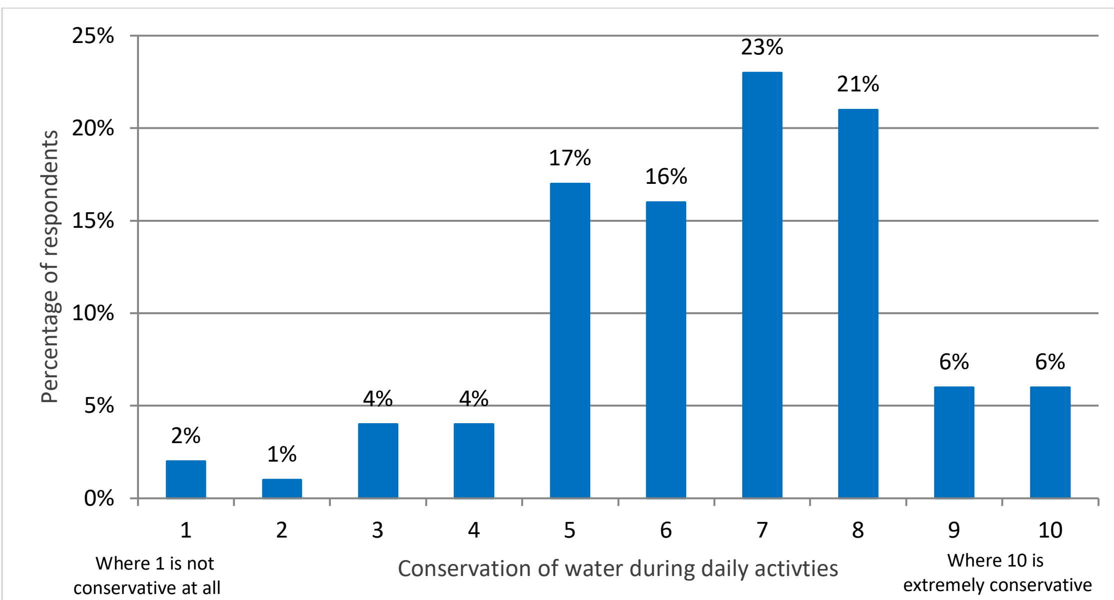

Figure 4-12: Respondents' conservation of water during daily activities

Measures to ensure water conservation

Question: Do you believe that there are sufficient measures in place to ensure the delivery of safe drinking water for current/future generations in South Africa?

Table 4-14: Summary of respondents' perception of measures to ensure water conservation for the future

Answer	Number/Percentage of respondents
Yes	16
No	84

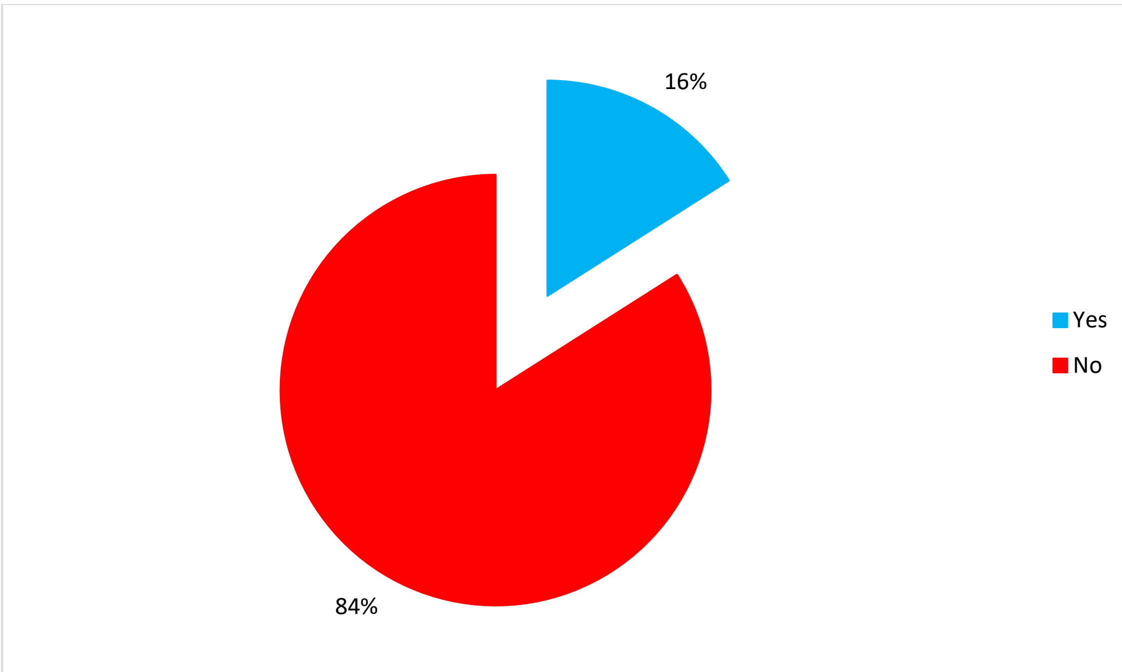

Figure 4-13: Respondents' belief that there are sufficient measures in place to ensure conservation of water resources

Best alternative to municipal water

Question: Which means of water supply is the best alternative to the municipal water supply?

Table 4-15: Summary of respondents' preferences for alternative water supply

Water production method	Number/Percentage of respondents
Rainwater	24
Borehole	35
Reclaimed/grey water	4
Desalination	24
River/Lake	8
Atmospheric water generation	5

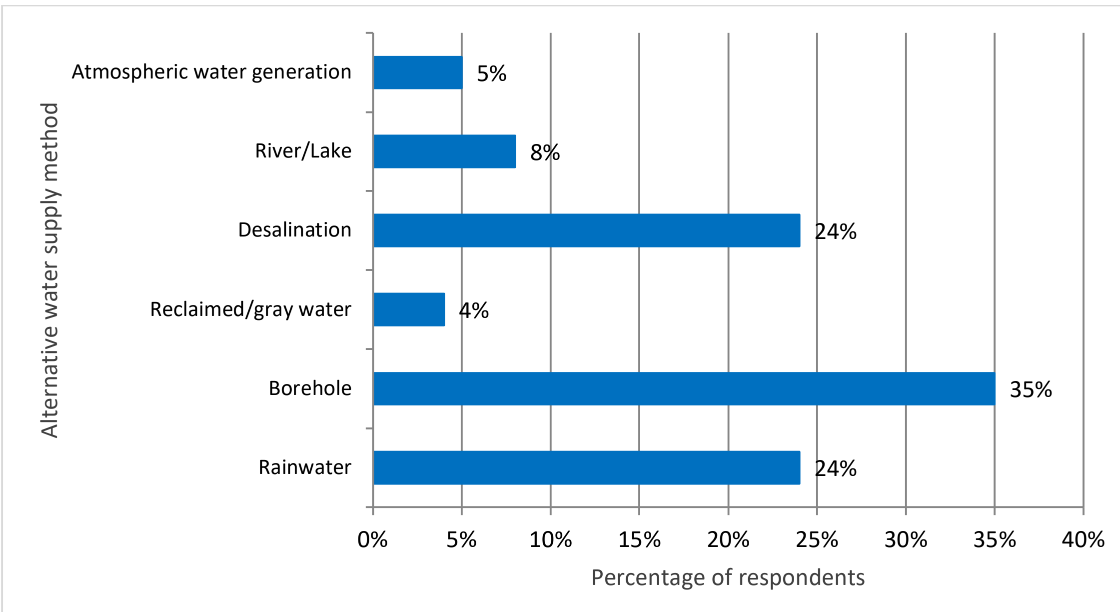

Figure 4-14: Respondents' preferred alternative means of water supply

Potable water production method

Question: Which method of potable water production do you prefer?

Table 4-16: Summary of respondents' preferred potable water production method

Potable water production method	Number/Percentage of respondents
Filtration	34
Ultraviolet irradiation	10
Boiling	27
Chemical treatment	29

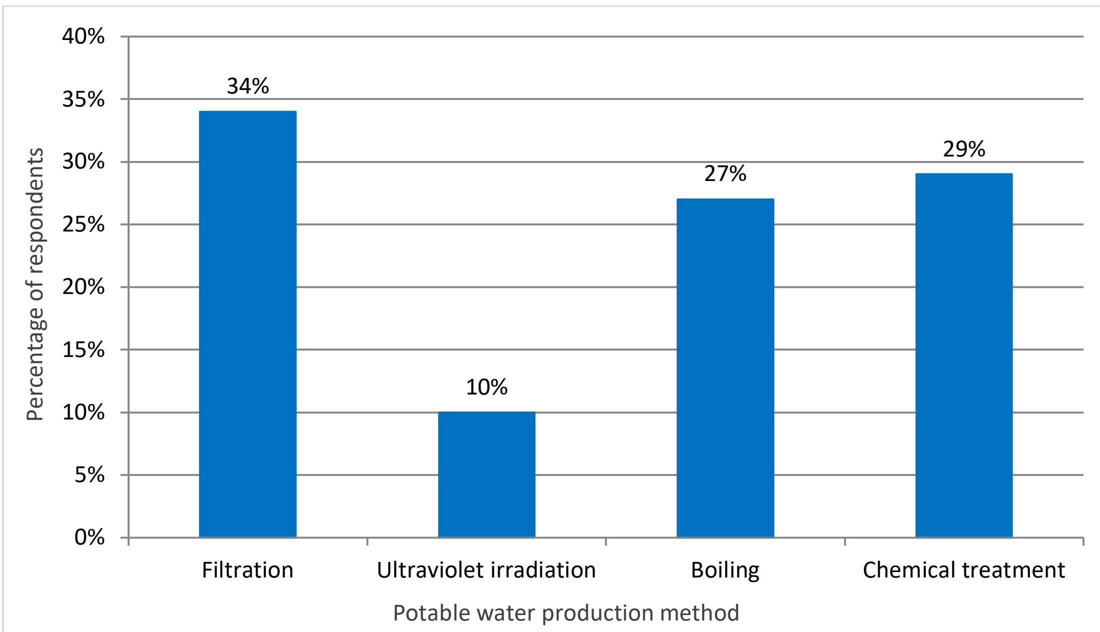

Figure 4-15: Individuals' preferred potable water production method

Understanding of desalination

Question: What is your understanding of desalination?

Table 4-17: Summary of respondents' understanding of desalination

Understanding	Description on graph	Number/Percentage of respondents
Good understanding	Yes	56
Wrong understanding	No	7
Unclear understanding	Ambiguous	17
Does not know – No answer	Do not know	20

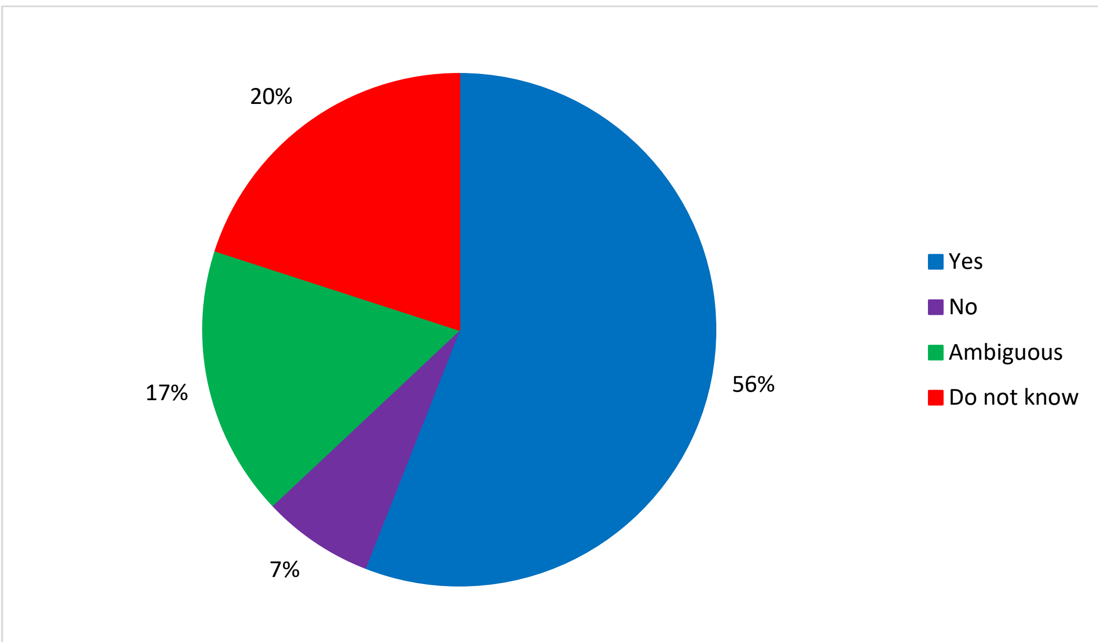

Figure 4-16: Respondents' understanding of what desalination is

Most effective and efficient desalination technique

Question: Which do you believe is the most effective and efficient method of desalination?

Table 4-18: Summary of respondents' belief regarding the most effective and efficient desalination method

Desalination method	Number/Percentage of respondents
Electrodialysis	6
Solar distillation	12
Humidification-dehumidification	1
Reverse osmosis	32
Do not know	49

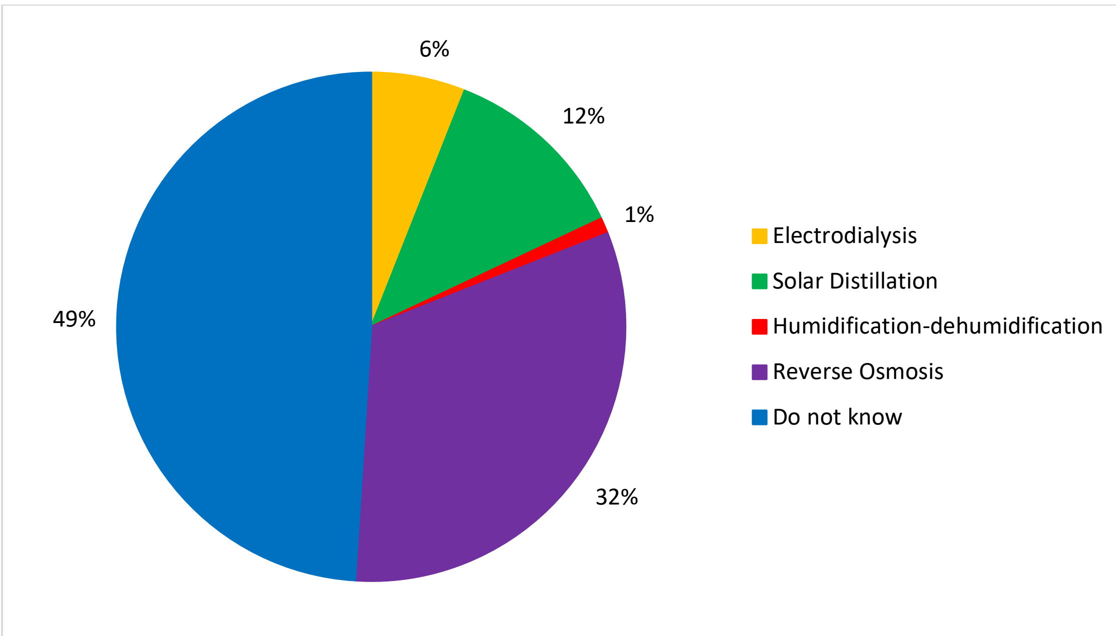

Figure 4-17: Individuals' preferred desalination method

Awareness of desalination plants in South Africa

Question: Are there any large-scale desalination plants in South Africa supplying drinking water to the general population?

Table 4-19: Summary of respondents' awareness of largescale desalination plants in South Africa

Awareness	Number/Percentage of respondents
Yes	20
No	21
Do not know	59

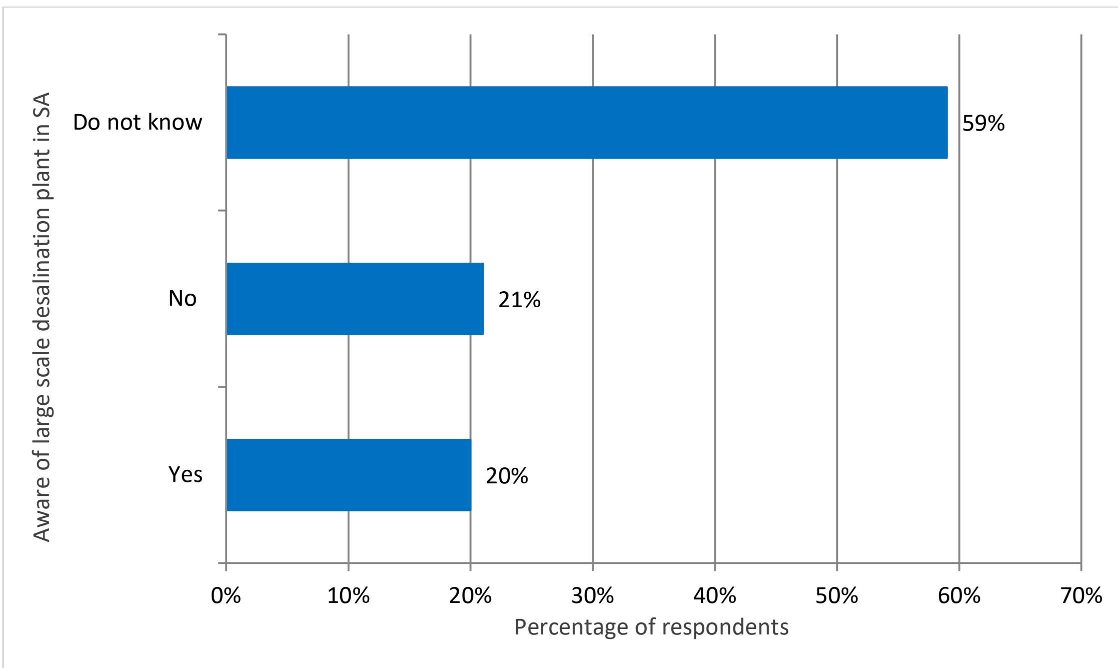

Figure 4-18: Awareness of large-scale desalination plants in South Africa

Investment in alterative water sources

Question: Do you believe there is sufficient investment in finding and implementing alternative means of supplying water in South Africa?

Table 4-20: Summary of respondents' perception of investment in alternative water sources

Answer	Number/Percentage of respondents
Yes	12
No	88

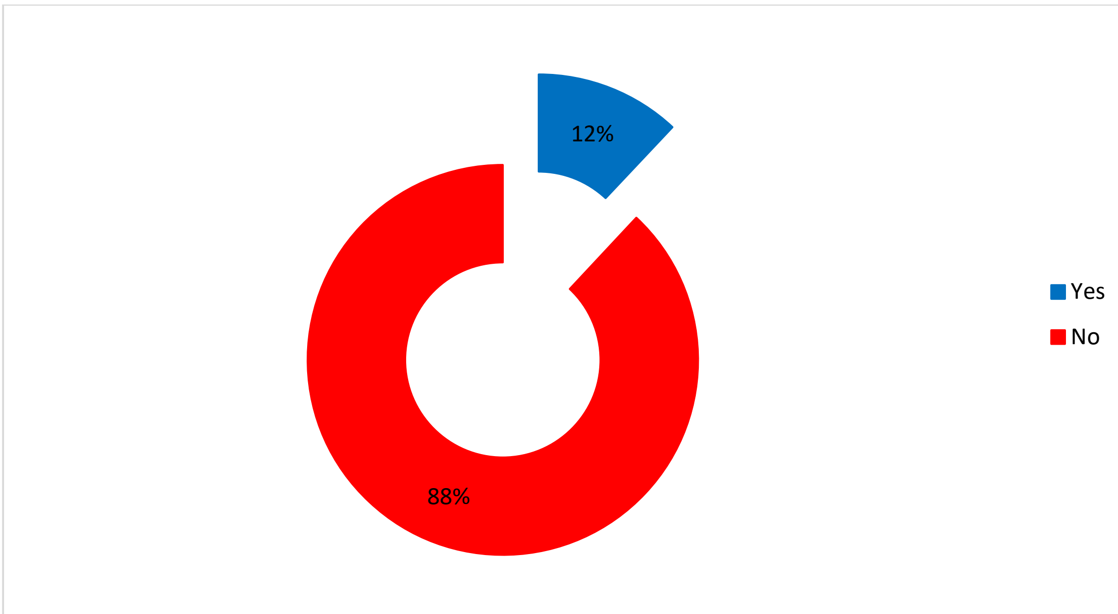

Figure 4-19: Opinions on investment in alternative water sources in South Africa

Willingness to purchase alternative water production devices

Question: If given the opportunity, would you purchase a desalination device for your household/business to become partially or completely independent of the municipal water supply?

Table 4-21: Summary of respondents' willingness to purchase desalination devices

Answer	Number/Percentage of respondents
Yes	80
No	20

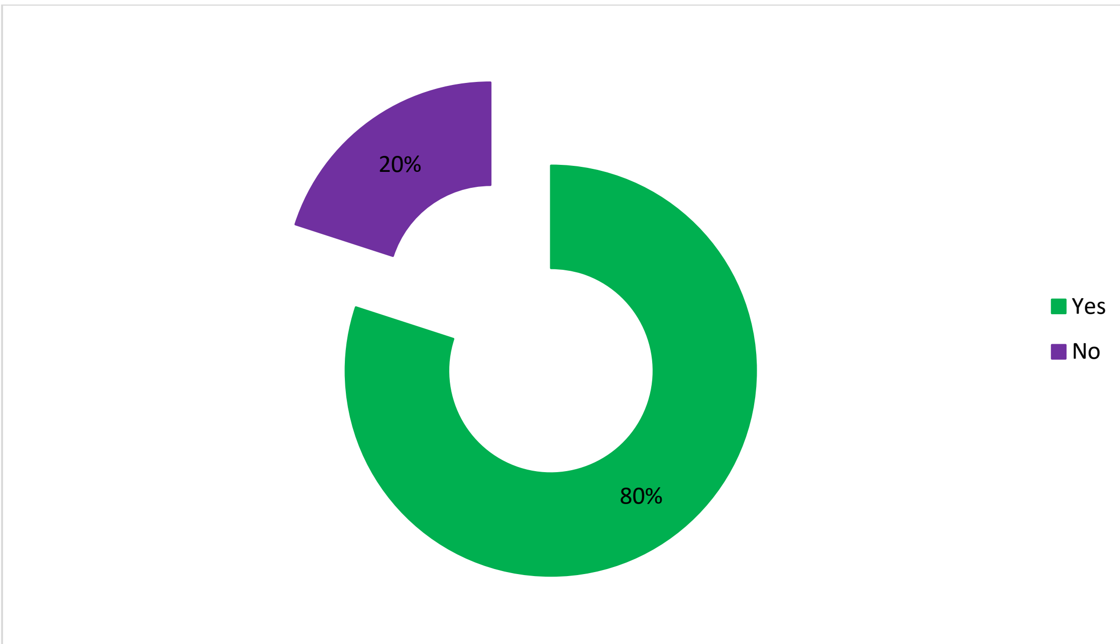

Figure 4-20: Respondents willingness to purchase desalination devices

Factors guiding purchase of desalination device

Question: What would be the deciding factor guiding your above decision?

Table 4-22: Summary of deciding factor guiding decision purchase of desalination device

Deciding factor	Number/Percentage of respondents
Input energy requirements	5
Start-up costs	42
Size, noise and aesthetics	4
Maintenance requirements	14
Output water quality	24
Volumetric output	3
All of the above	2
Other	6

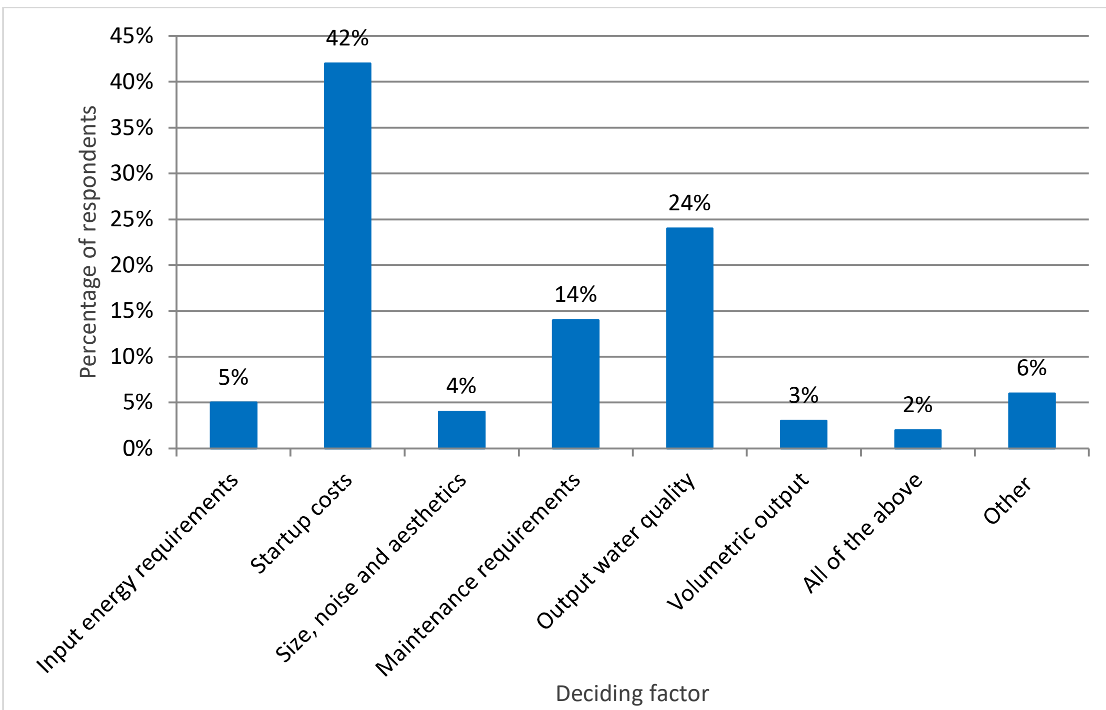

Figure 4-21: Deciding factor guiding decision on alternative water production device purchase

Desalination is the answer to future water shortages

Question: Do you believe desalination is the answer to current/future water shortage issues that may arise in South Africa?

Table 4-23: Summary of respondents' perception on desalination as the solution of future water shortages

Answer	Number/Percentage of respondents
Yes	85
No	15

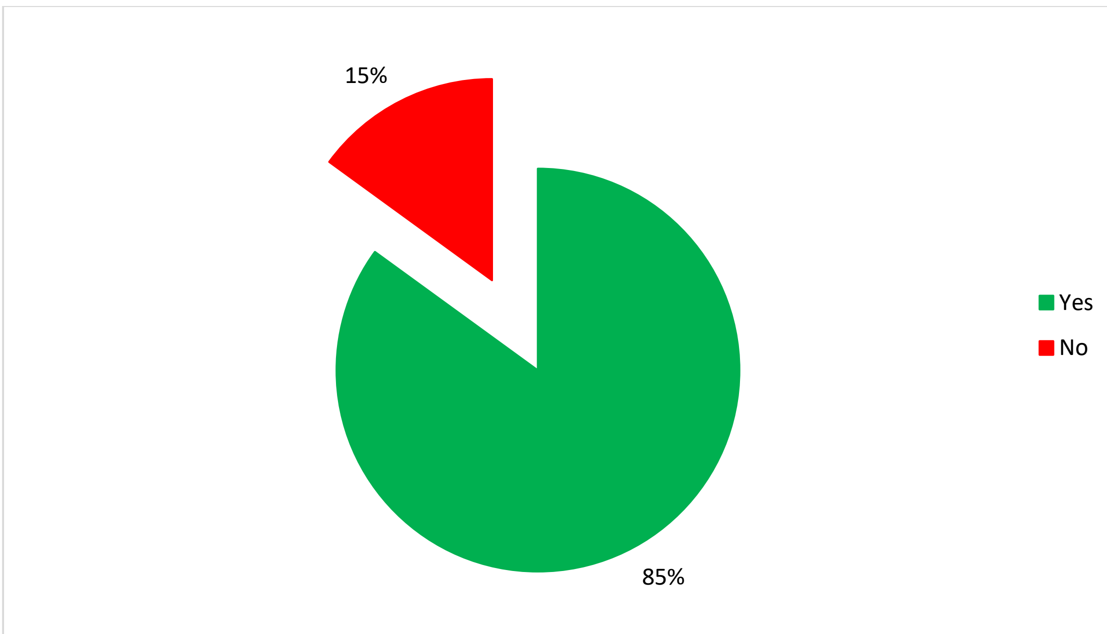

Figure 4-22: Individuals' belief that desalination is the future for alternative water production

Powering desalination devices

Question: What alternative energy source, do you believe is the best means of powering desalination systems?

Table 4-24: Summary of respondents preferred source of power for desalination device

Source of power	Number/Percentage of respondents
Solar	79
Wave	11
Wind	4
Geothermal	1
Other	5

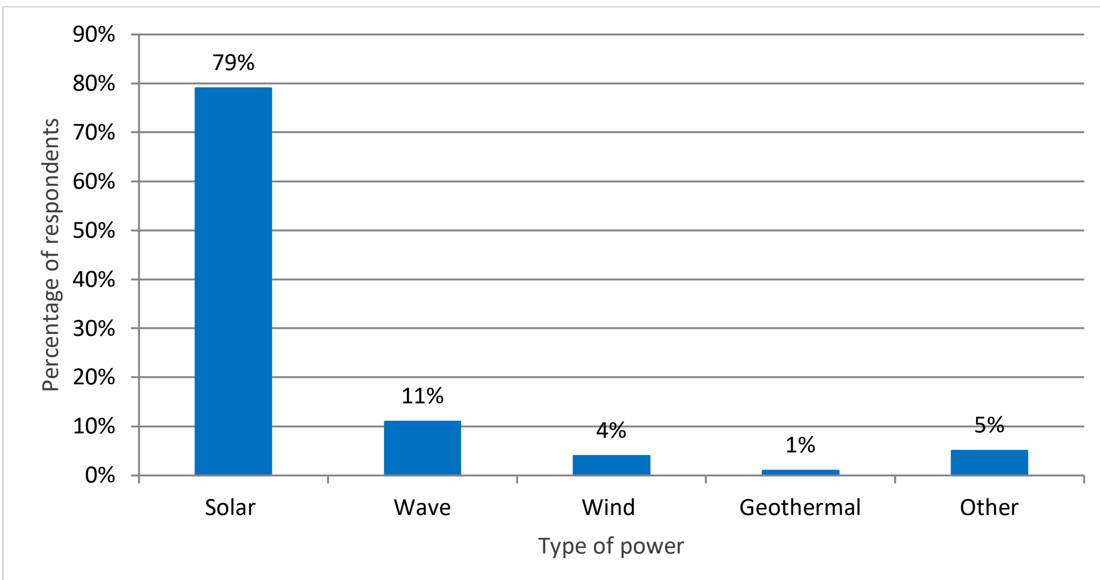

Figure 4-23: Method respondents believe is best to power desalination device

Solar energy in South Africa

Question: If solar energy was used to power a desalination system, do you believe South Africa receives sufficient solar irradiation on average per year to make the process viable?

Table 4-25: Summary of respondents' belief of the applicability of solar energy in South Africa

Applicability of solar energy	Number/Percentage of respondents
Yes	74
No	9
Do not know	17

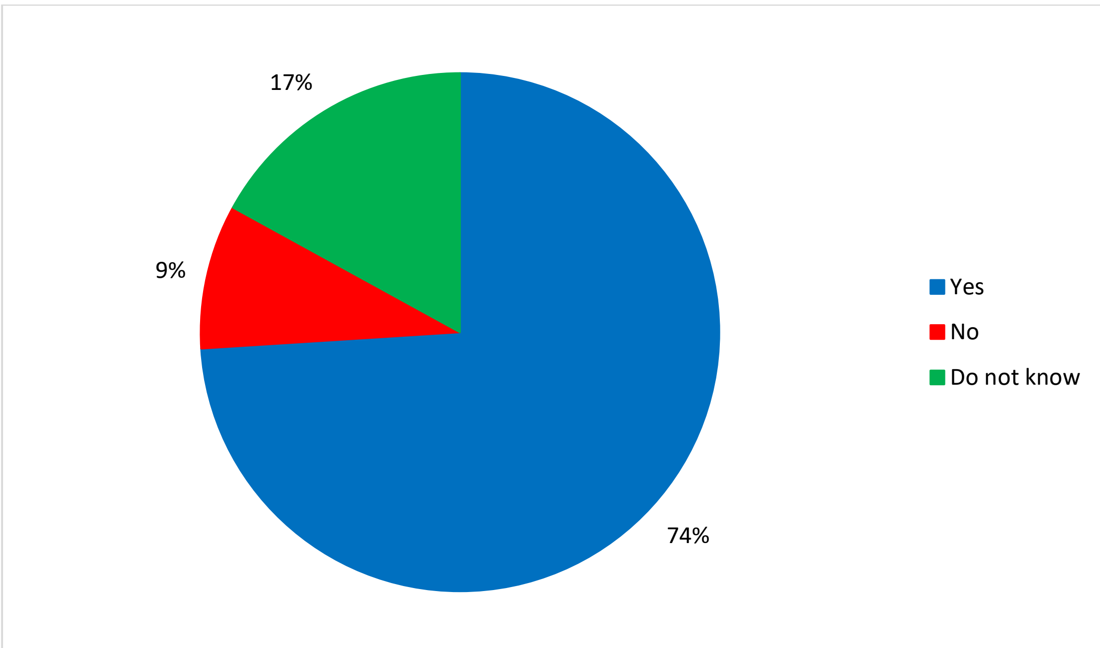

Figure 4-24: Applicability of solar energy in South Africa

4.5 Discussion

The survey was taken on the online platform Google Forms to aid in the data collection process. The sample size for the feasibility study was calculated to be 97 individuals with a margin of error of 10 %, confidence level of 95 % (as listed in Table 4-1) and estimated prevalence of 50 %. The research questionnaire consisted of 29 questions heading the headings: personal information, state of water resources, alternative sources of water and future of desalination. In total, 100 respondents completed the feasibility study questionnaire via the online platform Google Forms. The average age of the respondents was approximately 27 years old (Table 4-2), with more than 66 individuals having attained a bachelor's degree or above Figure 4-2. The majority (74 %) of the survey takers were either located in Durban, Johannesburg or Cape Town (Figure 4-3 and

Table 4-4). The mean household size was approximately four individuals (Table 4-5). Of the 100 responders, 49 had a good understanding of what potable water is while 14 and 19 individuals respectively either had the wrong understanding or did not know what potable was (Figure 4-5). 91 % of people relied on the municipality for the drinking water (Figure 4-6) with others depending on other means such as rainwater, borehole water and river water (Table 4-7). 98 % agreed that water supplied by their municipality was safe for consumption (Figure 4-7). 83 respondents used 1 litre to 2.99 litres for drinking per day (noted in Figure 4-9), and 69 % used between 10 litres and 74.99 litres of water per day in total to complete everyday tasks (Table 4-11). Most individuals believed that a small percentage of South Africans have access to safe drinking water, with 66 % estimating this to be between 30 % and 69.99 % (Figure 4-11). However, this is not the case, as in 2017 the Department of Water and Sanitation published a figure of 88.6 % having access to water [4]. On average, most respondents rated their water conservation at a 7 (Figure 4-12), where 1 was not conservative at all and 10 was extremely conservative. Alarmingly, 84 of out 100 persons perceived that there aren't sufficient measures in place to ensure the delivery of safe drinking water for current/future generations in South Africa (Table 4-14). Desalination placed second to borehole water as the preferred alternative to municipal water (Figure 4-14). The largest proportion of respondents (34 %, Table 4-16) elected filtration as the preferred means of potable water production. 56 % of survey takers had a good knowledge of what desalination was, although 27 % did not know or had the wrong understanding of desalination (Figure 4-16). Reverse osmosis and solar distillation are believed to be the two most efficient and effective desalination methods (Table 4-18). Impressively, 85 % of respondents believed that desalination was the answer to future water shortages (Figure 4-22), and 80 % expressed an interest in purchasing a desalination device (Table 4-21) for either their household or business with 42 % noting start-up cost as the biggest deciding factor on whether they would purchase the device or not (Figure 4-21). Solar energy was the most popular choice to power such desalination devices, amassing 79 % of positive responses (Table 4-24). Using the feasibility study as a guide, it would appear that there is a great desire amongst citizens to become independent of municipal water supply and desalination devices powered by solar energy are their preferred alternative method of producing potable water.

4.6 Summary of chapter

A feasibility study was carried out, in which 100 participants completed a research questionnaire regarding water supply and alternative means of producing potable water in South Africa. There were 29 questions and the results were summarised and graphed. The implications of these results were discussed.

4.7 References

[1] Israel, G. D. *Determining sample size.* Miami : University of Flordia, 1992.

[2] Louangrath, P. *Common statistical tables.* Bangkok: Bangkok University, 2015.

[3] Conroy, R. Sample size - A rough guide. [Online] 2000. [Cited: 04 15, 2019.] https://www.semanticscholar.org/paper/Sample-size-A-rough-guide-Conroy/4781878153e13322c028c7d8970e7f52fbaa102a#citing-papers.

[4] SAHRC, 2018. *Water and Sanitation Research Brief ,* Braamfontein: South African Human Rights Commission.

CHAPTER 5: QUALITY FUNCTION DEPLOYMENT

5.1 Introduction

QFD is a tool for customer inspired product development. It enables the engineer to design a product bearing in mind the end users' needs. Technical decisions can be made using the results of a QFD. The QFD was completed on a template which was sourced online [1]. The QFD that was carried out for the solar still can be seen in Appendix B.2. The following steps were used to complete the QFD, as depicted in Figure 5-1.

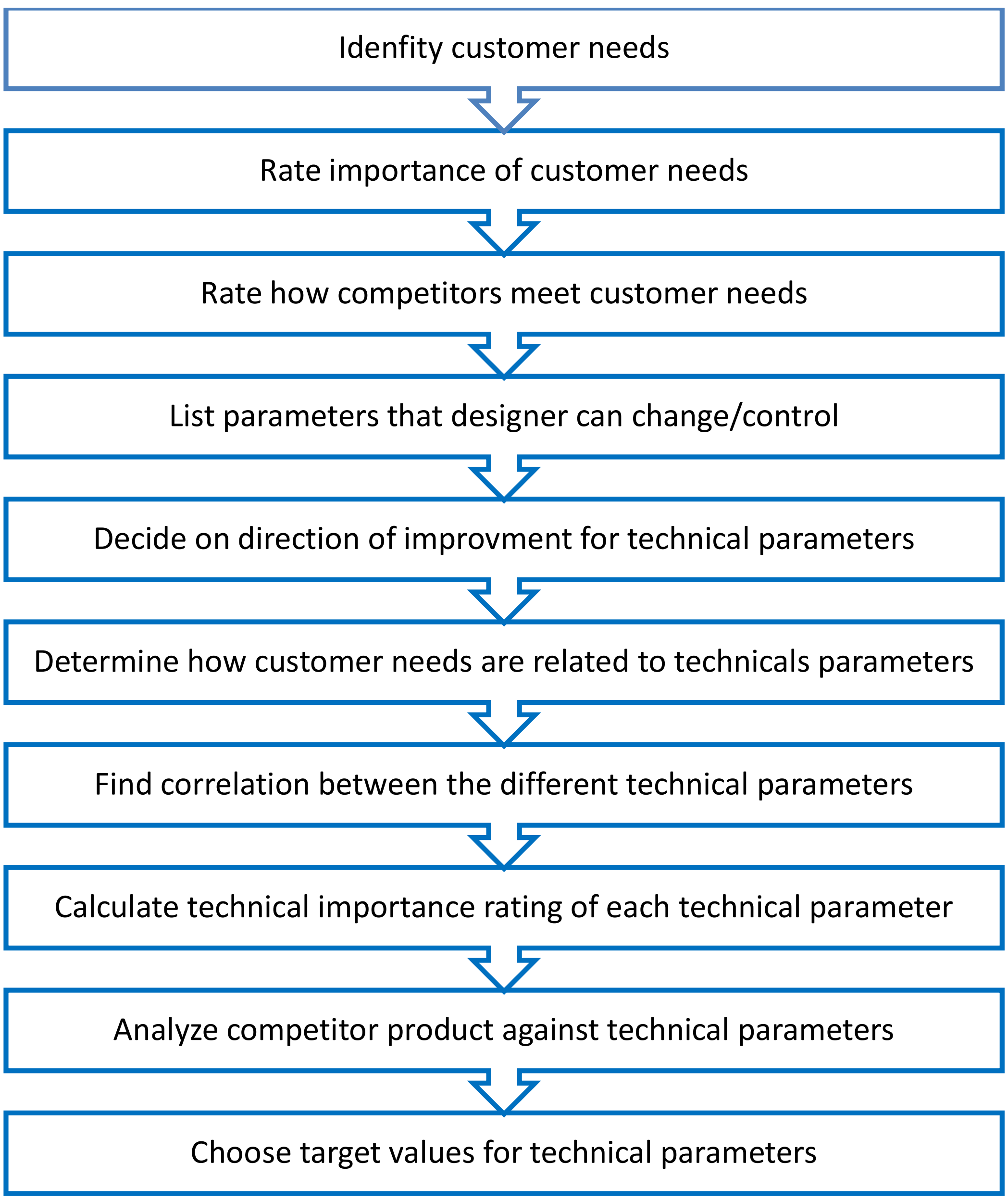

Figure 5-1: Quality Function Deployment steps

5.2 Results

QFD enables the user to gain insight into what the customer wants and how design parameters can be tailored to maximise desired needs while minimising negative system specifications. The customer requirements are the needs of the consumer; the relative weight of each need dictates the most important requirements. The relevant results from this study are illustrated in Table 5-1 and Figure 5-2.

Table 5-1: QFD customer requirements weighting

Customer Requirements (Explicit and Implicit)	Customer Importance	Relative Weight (%)
Start-up costs	10	11
Volumetric output	9	10
Input energy requirements	4	4
Size	3	3
Noise	5	5
Maintenance requirements	6	6
Maintenance costs	8	9
Water taste	8	9
Device working life	5	5
Autonomy	3	3
Safety of output water	8	9
Thermal efficiency	2	2
Aesthetics	4	4
Reliability (365 days a year)	6	6
Consistency of volumetric output	6	6
Pretreatment of input water	7	7

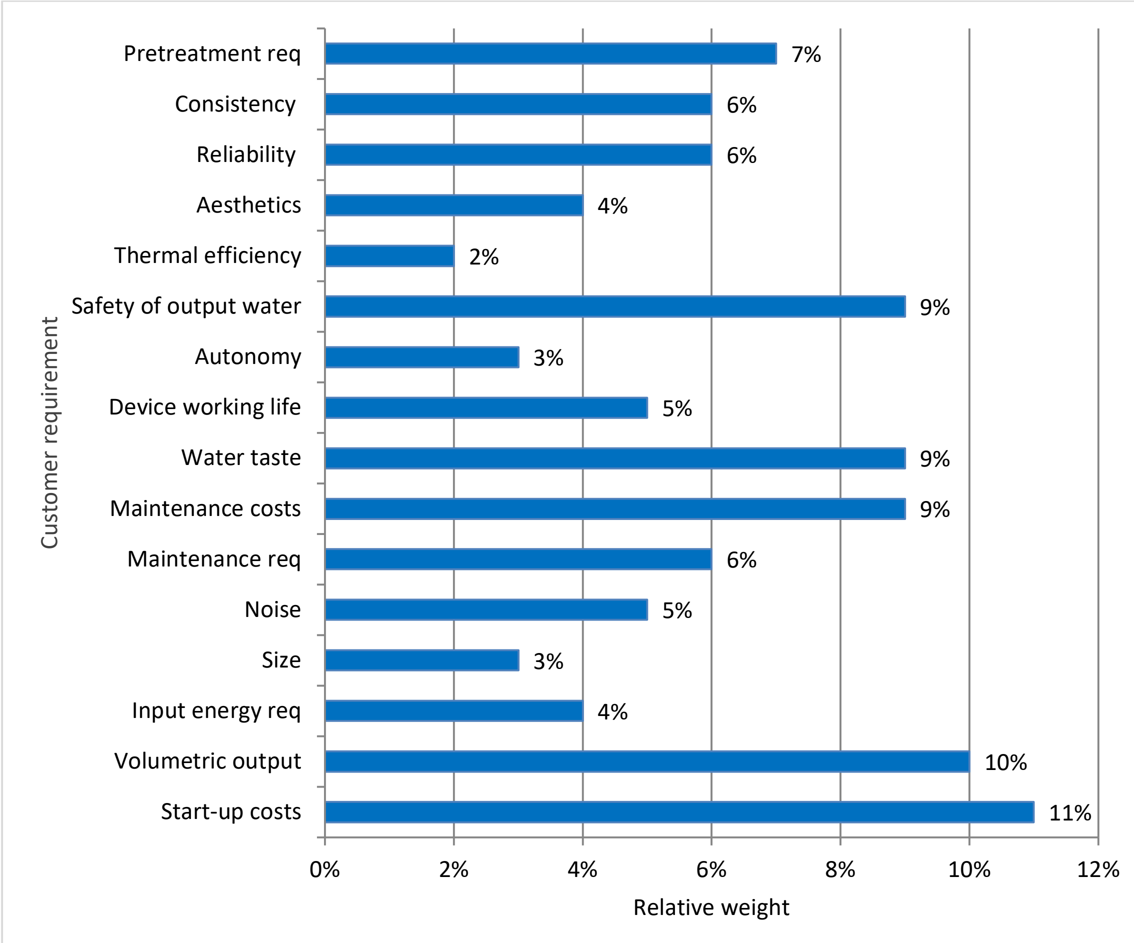

Figure 5-2: Relative weight of customer requirements from QFD

The functional requirements are the system parameters controlled by the designer; the relative weight of each parameter dictates the most important requirements. The relevant results from this study are illustrated in Table 5-22 and Figure 5-3.

Table 5-2: QFD functional requirements weighting

Functional Requirement	Technical Importance Rating	Relative Weight (%)
Materials	425.5	7
Manufacturing techniques	261.7	4
Insulation	463.8	8
Dimensions	225.5	4
TDS of input water	527.7	9
Coating of material	444.7	7
Weight	231.9	4
Basin water depth	491.5	8
Roof slope	370.2	6
Input and output water tanks	425.5	7
Valve on pipework	319.1	5

Orientation of still	289.4	5
TDS of output water	421.3	7
Reflectivity of glass cover	453.2	7
Length of input pipe	257.4	4
Shape of still	574.5	9

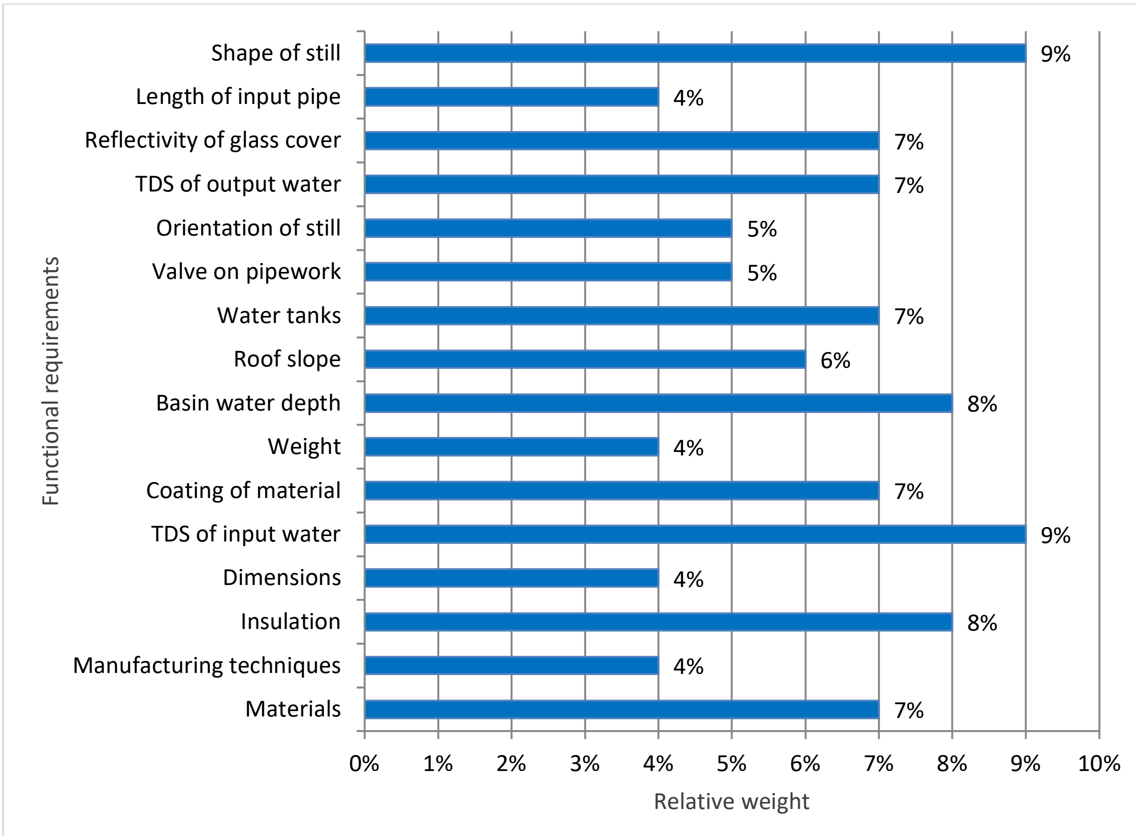

Figure 5-3: Relative weight of functional requirements from QFD

5.3 Analysis of the quality function deployment

The technical importance rating, which is calculated within the QFD, can be utilised as a keynote factor when designing a solar still. A technical importance rating of 450 was arbitrarily chosen as a benchmark to isolate important design considerations found through the QFD process. Using this rating the following features were noted to be most important in the design of the solar still:

1) Insulation
2) TDS of input water
3) Basin depth
4) Shape of still

5.4 Discussion

A generic QFD fulfilment process flowchart (Figure 5-1) was drawn up and utilised. An eight-part QFD was completed for the improved boiler still design. The results obtained from the QFD rank the importance of customer requirements (explicit and implicit) and functional requirements. The customer requirements are the characteristics of the design that are most important to the consumers. The five highest relative weights for customer requirements as per Table 5-1: start-up costs (11%), volumetric output (10%), safety of output water (9%), water taste (9%) and maintenance costs (9%). These are graphically depicted in Figure 5-2. Thus, it is evident that the consumers' fundamental concern is cost, either initial investment or service costs. The device had to be designed in a manner that would allow for easy and affordable production while also requiring minimal maintenance. Volumetric output is also heavily weighted, as the consumer is not willing to make an upfront investment in a device that is not capable of fulfilling their daily water consumption requirements. Water quality is another major concern, so output water needs to be safe to drink without fear of contamination. The four highest relative weights for functional requirements as per Table 5-2 were: shape of still (9%), TDS of input water (9%), basin water depth (8%) and insulation (8%). These are graphically depicted in Figure 5-3. Still shape is directly related to productivity, as noted in section 2 of Chapter 8. However, often the best performing still shapes are the most expensive to manufacture. It is therefore necessary to compromise on either cost or volumetric output when selecting still shape but referring back to customer requirements it is clear that start-up costs were weighted higher than volumetric output. For this reason, still shape was chosen for the experimental phase with cost in mind. TDS of input water, as noted in section 2 of Chapter 8, is inversely proportional to volumetric output. It is therefore necessary to minimise the TDS of input water to improve system performance characteristics. A maximum TDS of 35 000 ppm is suggested, which can encompass fresh, brackish and normal seawater. Basin water depth is imperative in determining volumetric output. Basin water depth is limited to 150 mm, ideally 50 mm in autumn and winter months. Lastly, insulation of the solar still is a functional requirement of great importance. Insulation improves operational performance by increasing thermal efficiency toward the later part of the day by trapping heat inside the still. However, this works both ways because it could hinder heat energy entering the still in the morning. Insulation was therefore disregarded in terms of the new boiler still design.

5.5 Summary of chapter

A QFD was carried out as part of the qualitative approach of the system design. The completed QFD is shown in Appendix B.2 and an analysis of the outcomes carried out with design recommendations made. The results of the QFD were examined.

5.6 References

[1] Solutions, UWS Business. QFD Templates. [Online] January 2014. [Cited: May 13, 2017.] http://www.uw-s.com/wp-content/uploads/2014/01/Full_HOQ_0.9.xlsx.

CHAPTER 6: MARKET ANALYSIS

6.1 Introduction

A market analysis was carried out, in which three double slope solar still designs were identified. The solar stills discussed below can be regarded as market competitors. Their working principles, key design features, performance characteristics, results obtained and limitations are noted. These provided valuable insights as a benchmark for design and performance characteristics for the research that was carried out.

6.2 Double slope solar still – Competitor A

[1] have designed, developed and tested a double slope solar still unit, as seen in Figure 6-1. The still performance was tested in Tulsande, located in the Maharashtra, India. Testing was carried out over an eight hour period using brackish water with a TDS of 364 ppm.

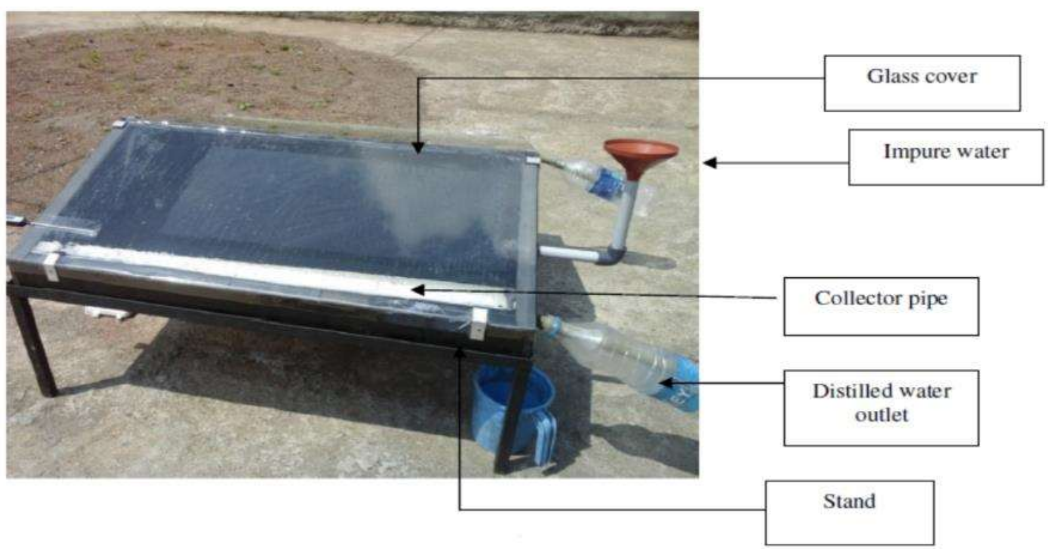

Figure 6-1: Competitor A

Table 6-1 provides a summary of the design specifications, testing conditions, performance characteristics and results obtained.

Table 6-1: Summary of competitor A

Parameter	Value/Description	Unit
Design Specifications		
Length	836	mm
Breadth	836	mm
Height	185	mm
Glass thickness	3.5	mm
Glass cover angle	15	degrees
Testing		
Basin water TDS	364	ppm
Basin water depth	20	mm
Maximum ambient operating temperature	40	°C
Daily average insolation	20.81×10^6	$J.m^{-2}$
Maximum solar radiation	786	W/m^2
Testing period	8	hours
Performance Characteristics and Results		
Volume of distilled water	1.6	L/day
Distilled water TDS	30	ppm
Distilled water pH	7.5	None
Condensate temperature	29	°C
Overall efficiency	22.33	%

The identifiable limitations in design and testing are as follows:

- Low water production in spite of favourable ambient temperatures
- Ineffective insolation of still
- Vapour and thermal losses through inlet and outlet water pipes
- Not testing for optimal basin water depth
- Relatively small collector size
- Different still orientations were not attempted

6.3 Double slope solar still – Competitor B

[2] have undertaken research into modified double sloped solar stills. A modified double slope still with a multi-wick addition was designed, manufactured and tested. The system was tested in Prayagraj, located in Uttar Pradesh, India. Experimentation was carried out in September and November 2015. The design included a multi-wick which is aimed at enabling capillarity thus enhancing the evaporation rate. Figure 6-2 is a photo taken of the completed solar still.

Figure 6-2: Competitor B

Table 6-2 provides a summary of the design specifications, testing conditions, performance characteristics and results obtained.

Table 6-2: Summary of competitor B

Parameter	Value/Description	Unit
Design Specifications		
Length	2000	mm
Breadth	1000	mm
Height	380	mm
Glass thickness (acrylic)	3	mm
Glass cover angle	15	degrees
Wick thickness	5	mm
Testing		
Basin water TDS	550	ppm
Basin water depth	50	mm
Maximum solar radiation (September)	1100	W/m2
Maximum solar radiation (November)	880	W/m2
Testing period	12	hours
Performance Characteristics and Results		
Volume of distilled water (September)	3.624	L/day
Volume of distilled water (November)	2.4	L/day

The identifiable limitations in design and testing are as follows:

- Different still orientations were not attempted

- Not testing for optimal basin water depth
- Vapour and thermal losses through inlet and outlet water pipes
- Ineffective insolation of still
- Increased maintenance requirements
- Fouling of wick material
- Possibility of organic growth in wick

6.4 Double slope solar still – Competitor C

A conventional double slope solar still was designed, fabricated and tested by [3], as depicted in Figure 6-3. Testing of the prototype took place near Nairobi, located in Kilifi County. Kenya. Testing took place over a 21 day period from 19 September 2018 to 9 October 2018.

Figure 6-3: Competitor C

Table 6-3 provides a summary of the design specifications, testing conditions, performance characteristics and results obtained.

Table 6-3: Summary of competitor C

Parameter	**Value/Description**	**Unit**
Design Specifications		
Length	1500	mm
Breadth	790	mm
Height	244	mm
Glass thickness	4	mm
Glass cover angle	15	degrees
Testing		
Basin water TDS	660	ppm
Basin water depth	20	mm
Mean ambient operating temperature	27.89	ºC
Daily average insolation	19.8 × 106	$J.m^{-2}$
Testing period	8 hours	hours
Performance Characteristics and Results		
Volume of distilled water (mean)	1.51	L/day
Distilled water TDS (mean)	31	ppm
Distilled water pH (mean)	6.49	None
Overall efficiency (mean)	16%	%

The identifiable limitations in design and testing are as follows:

- Low water production in spite of favourable ambient temperatures
- Ineffective insolation of still
- Not testing for optimal basin water depth
- Different still orientations were not attempted
- Thermal leakage noted in results
- Relatively low to moderate operational temperatures

6.5 Benchmark for SWOT analysis

By utilising the three competitors as benchmarks for the SWOT analysis, the strengths, weaknesses, opportunities and threats to the use of solar stills as an alternative method for sourcing potable water and for desalination were identified, as noted in Figure 6-4.

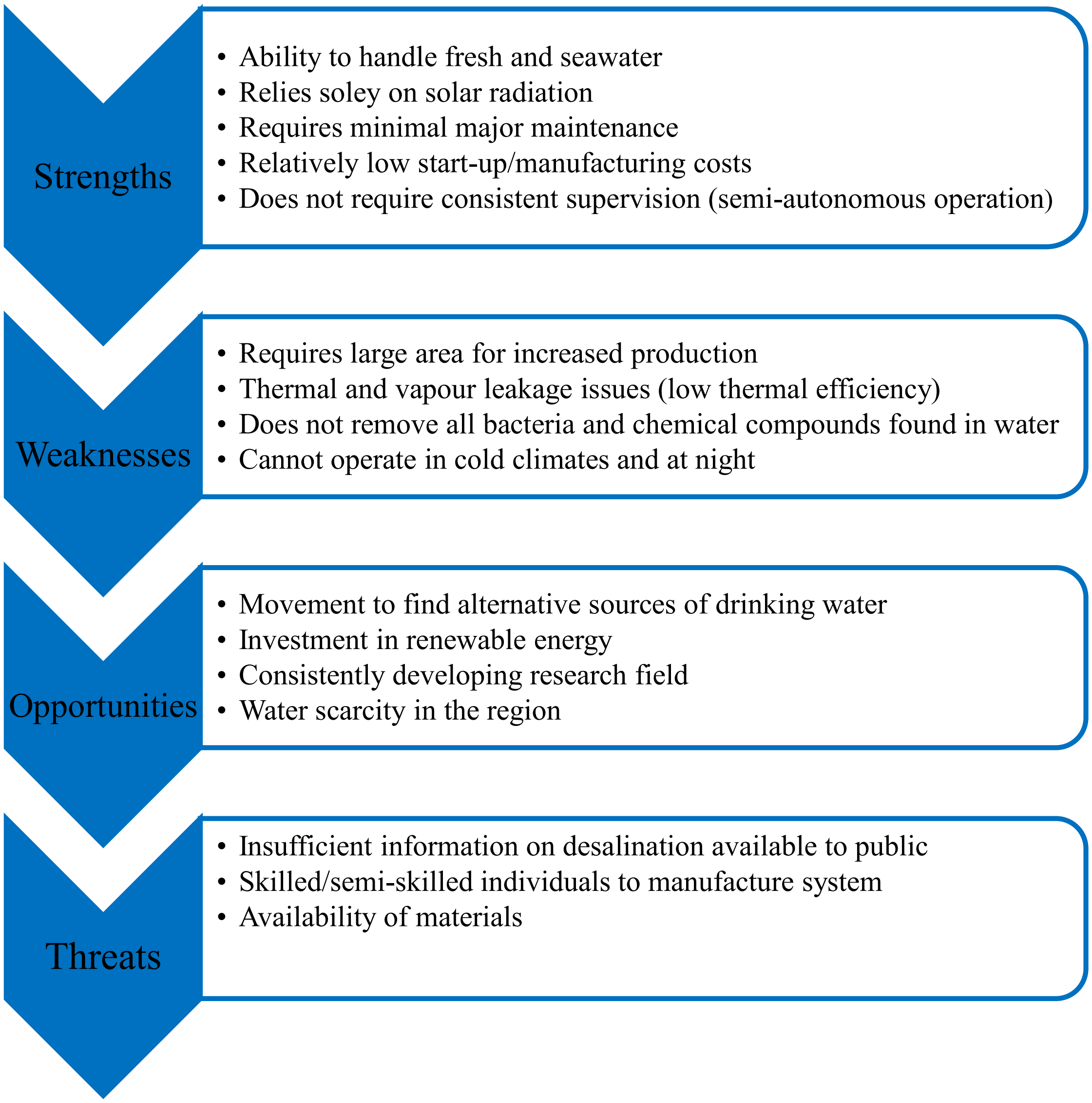

Figure 6-4: SWOT analysis of solar stills

6.6 Examination of SWOT analysis

Measures to build on strengths and utilise opportunities

Maintenance can be streamlined through efficient system design enabling quick and effective maintenance and cleaning of system. Through a FMEA (see Appendix B.3), a maintenance checklist can be developed stating issues that may arise with components, and how often to check for and fulfil maintenance requirements.

Consistent research and development in the field can motivate proprietary interests in such systems. New or recycled materials can be researched and tested to be used in system design and fabrication. In this manner, manufacturing and start-up costs can be minimised.

By proving concepts, testing prototypes and attempting new design approaches such systems can be optimised and to increase production yields and attract government investment.

Measures to overcome weaknesses and mitigate threats

Improve thermal efficiency through enhanced system insulation. Introduction of water before or after treatment to deal with the concerns of bacterial/chemical composition. Operational periods of the solar still can be increased through implementation of various energy storage methods.

System can be designed to include readily available materials while requiring simple manufacturing and assembly thus enabling fabrication by an increased number of individuals.

6.7 Discussion

The market analysis explored three double slope solar still designs and summarised their characteristics under the following headings: design specifications, testing conditions and performance results. The aim of this exercise was to ascertain the strengths and weaknesses in each design. The strengths were to be built on and incorporated into the improved boiler still for the test rig whereas the weaknesses would be mitigated or eliminated altogether if possible. Competitor A can be seen in Figure 6-1. Table 6-1 summarizes its characteristics; the overall efficiency of the square 15º sloped system was noted as 22.33 % with a maximum volumetric distillate output of 1.6 L/day. Competitor B – depicted in Figure 6-2 – produced the most promising results attaining a volumetric output rate of 3.624 L/day with a basin water TDS of 550 ppm noted in Table 6-2. Competitor C registered a volumetric output of 1.51 L/day in Table 6-3 but this can be attributed to the larger still area shown by Figure 6-3.

The market analysis identified three double slope solar still designs that were manufactured and tested. The limitations of each design were summarised which then formed the basis of the SWOT analysis completed in Figure 6-4. The SWOT analysis tool provided insight not only into desalination system design but also how desalination devices can be positioned in the market. Often time and resources are expended in product design and development but there is no realisable market segment for these products to fill and as such they fail to become profitable. The outcomes of the analysis can be utilised throughout the supply chain of desalination devices. The strengths of the double slope still design identified include: the ability to handle both fresh water and sea water, reliance only on solar radiation and comparatively low start-up cost. The large area required for increased production, thermal and vapour leakage issues and the inability to operate in cold climates and at night were the major weaknesses noted. Africa, the Middle East and Australia were noted as water scarce regions in Chapter 2. This provides a niche for desalination systems to fill. New largescale desalination projects have been noted in the Western

Cape province of South Africa and most parts of the Middle East with many others in Australia, North America and Africa. With an ever-growing consciousness of chemical and toxins that people ingest, alternative means of producing potable water has also arisen as a popular topic. Leveraging awareness of regional water scarcity and consumer health awareness, household desalination devices can readily increase market share, especially in developing countries in which piped water infrastructure does not yet exist. The main threat to household desalination devices is the lack of information regarding what desalination is and the available methods (as noted in the results of question 16 of the feasibility study). Furthermore, the availability of materials in certain regions may disallow mass and affordable production.

6.8 Summary of chapter

The market analysis compares three implemented designs; the results of the market analysis were used as points of benchmark and examination of a SWOT analysis. The SWOT analysis identified design and operational limitations so that an improved design could be proposed. The results of the market analysis and SWOT analysis were examined.

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CHAPTER 7: FAILURE MODES AND EFFECTS ANALYSIS

7.1 Introduction

A FMEA is a systematic design approach that:

1) Identifies potential failure modes
2) Evaluates and characterises the failure mode
3) Perceives methods to eliminate failure mode
4) Strengthens safety
5) Improves customer satisfaction
6) Helps eliminate or at least mitigate potential design/process issues

A FMEA template was sourced from the University of KwaZulu-Natal Design and Research Project 1 resources provided to students [1]. The FMEA that was carried out for the solar still can be seen in Appendix B.3. The following steps were used to complete the FMEA, as depicted in Figure 7-1.

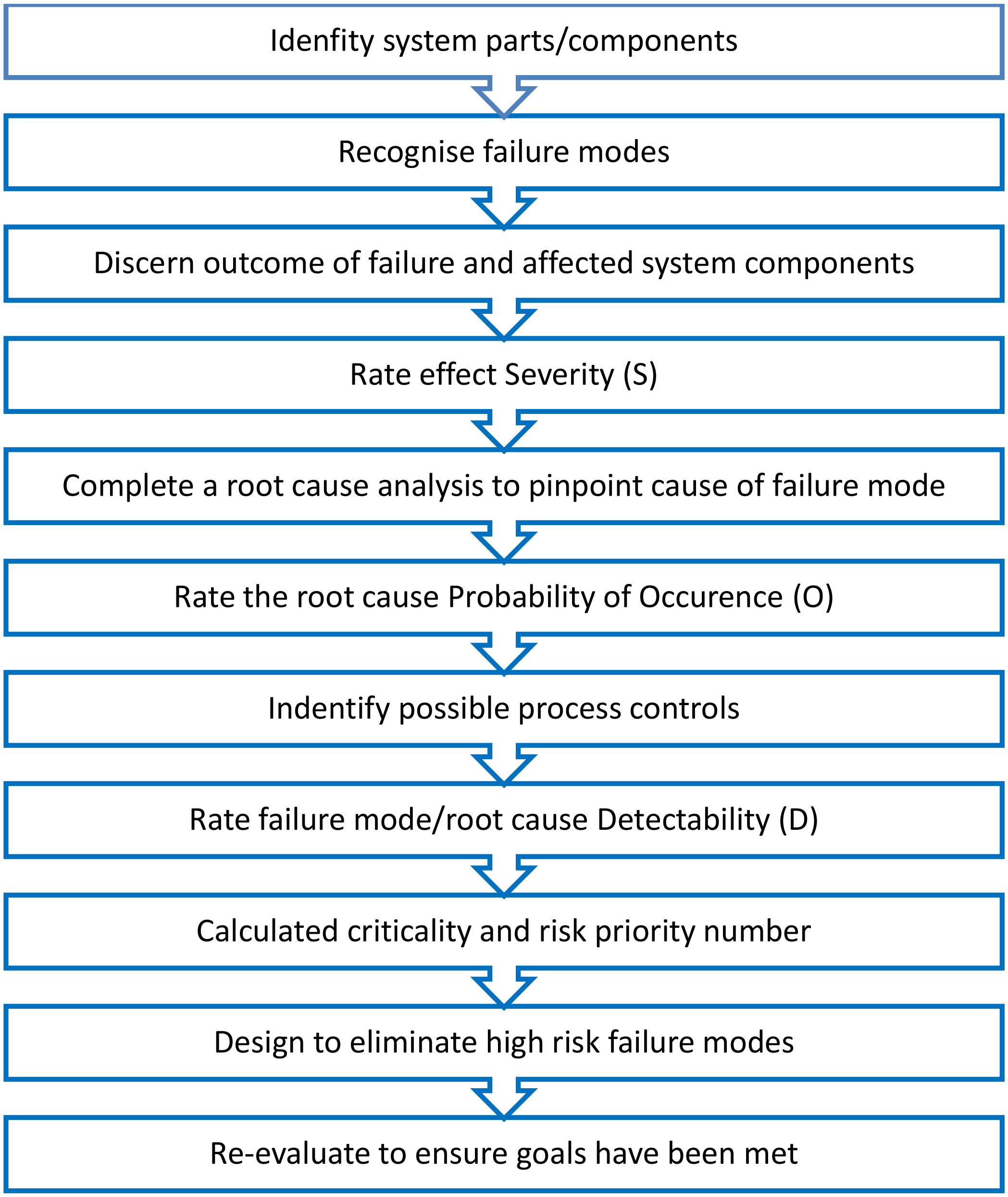

Figure 7-1: Failure Modes and Effect Analysis steps

7.2 Analysis of the Failure Modes and Effects Analysis

The FMEA was carried out for the solar still. Values for severity, occurrence and detection were given qualitatively. These were used to calculate Criticality (C) and Risk Priority Number (RPN).

7.2.1 Criticality

Criticality is the measure of how critical a given failure mode can be. Criticality ranges from 1 (best) to 100 (worst) and is calculated as follows:

$$C = S \times O \tag{7-1}$$

7.2.2 Risk priority number

RPN is the measure of how critical a failure mode is and the ability to detect and mitigate it. It ranges from 1 (best) to 1000 (worst) and is calculated as shown in Equation (7-2).

$$RPN = S \times O \times D \tag{7-2}$$

Through a qualitative analysis of the RPN and C of the FMEA the greatest number of issues arose when input water TDS was too great. This led to fouling of the glass cover, basin and distillate trough. Fouling of these specific components led to poor output water quality, decreased thermal efficiency and reduced volumetric output – which were also key customer requirements noted in the QFD.

As such, close attention to input water specifications needs to be paid. This can help decrease major performance inhibitors caused by input water TDS. Alternatively, a more rigorous maintenance strategy is required to deal with fouling in the event input water quality is out of the users' control. However, it should be noted that maintenance requirements and cost are two other important customer requirement factors. It is therefore necessary for the user to decide which route will better suit operability for the individual.

7.3 Discussion

The FMEA was carried out by qualitatively selecting ratings for severity, occurrence and detection. These are used to calculate the criticality and risk priority number. These two quantities were used to identify the items or functions that may fail. Thereafter, design changes and/or maintenance procedures were suggested accordingly to mitigate or eliminate their affects. The overall procedure followed can be found in Figure 7-1. The completed FMEA is located in Appendix B.3. Based on the results of the FMEA inlet water TDS and still orientation proved to be the two failure modes that had the most probable chance to cause system failure. Too high TDS registered an RPN of 210 and criticality of 30 while incorrect still orientation had an RPN and criticality of 140 and 35 respectively. A TDS range of 0 ppm to 35 000 ppm was suggested to address this failure mode thus ensure a new RPN and criticality of 175 and 25. This can be further decreased through a proper maintenance regime.

7.4 Summary of chapter

A FMEA was carried out and the results analysed. The FMEA was found to isolate design and operating parameters that may decrease the efficiency of the existing system. These results can be taken into consideration during the mechanical design phase.

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CHAPTER 8: DESIGN THEORY AND ANALYTICAL ANALYSIS OF A SOLAR STILL

The chapter reviews the theory behind still design and mathematical models used to analyse system performance. The system performance results obtained through the numerical solution of the mathematical model using MATLAB are for a double slope solar still operating in Durban, South Africa. The article has been accepted and will be published in the International Journal of Mechanical Engineering and Technology, IAEME Publications.

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DESIGN THEORY AND ANALYTICAL ANALYSIS OF A SOLAR STILL

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ABSTRACT

Rapid population growth and insufficient conservation of water resources in water scarce regions are but two reasons for the predicted water shortages that are likely to plague future generations. Over the last two decades there have been major strides forward in using desalination for the production of potable water on a large scale. Through continuous research and development new and improved methods have been found and implemented across the world. The viability of desalination as a reliable alternative potable water source has been proven on numerous occasions through various studies, projects and devices. This paper reviews the theory behind still design, mathematical models used to analyse system performance. The system performance results obtained through the numerical solution of the mathematical model using MATLAB are for a double slope solar still operating in Durban, South Africa.

Keywords: Solar, Water Desalination, System Modelling, Still design.

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1. INTRODUCTION

System modeling is one of the most important tools available to engineers. Modelling allows an individual to analyse, design, and predict the behavior of and therefore optimize and understand systems. A model may be a simple equation outputting a desired parameter to a complex dual phase CFD simulation. In current times, most available models are computer aided or solved. The common models available include:

1) Physical – a physical model is a graphical representation of a system. This may be a freehand sketch or a three-dimensional (3D) model.
2) Mathematical – the mathematical model includes the governing equations of a system. This model enables system design and performance characteristics verification.
3) Analogue – an analogue model makes use of an analogous system to model another.

4) Numerical – numerical models are used when conventional methods cannot be used to solve a mathematical model. These generally call for a computational approach.

2. ANALYTICAL MATHEMATICAL MODEL AND DESIGN THEORY

A specific analytical system model encompassing the design theory and considerations is presented in the sections below. The analytical model combines mathematical, analog and numerical techniques.

2.1. Design Theory for a Solar Still

Still design needs to consider various physical and operational parameters to allow for optimal system function. In some cases, these parameters are out of the control of the researcher e.g. the amount of solar irradiation an area receives. Other parameters, such as still area, can be chosen. Still performance is affected by three categories of parameters viz. climatic conditions, design specifications and operational parameters. These categories are further broken down, as seen in Figure 1 [1]. A brief description of each of these categories and parameters is presented below.

2.1.1. Climatic Conditions

1) Average solar irradiation – this is the amount of solar radiation received by the solar distillation system and is the most important factor affecting still performance. System productivity is highly dependent on the intensity and duration of the solar radiation, as noted by Kamal [2].
2) Wind velocity – the effects of wind on a solar still are almost negligible. There is an increase in still production with an increase in wind velocity [3]. Wind helps decrease the temperature of the condensing surface which then expands the temperature gradient between the basin and glass cover [4].
3) Ambient air temperature – studies by Malik et al. [5] showed an increase in still productivity of approximately 3 % with an ambient temperature increase of 5 °C. This was further proven by Al-Hinai et al. [6] who recorded an 8.2 % productivity increase with a 10 °C ambient temperature rise.
4) Dust and cloud cover – glass cover transmittance is vital in determining still productivity. Productivity increases with greater transmittance. Dust accumulation is directly responsible for a transmittance drop (Hegazy, 2001)[7]. Hottel & Woertz [8] carried out testing in Boston and noted a 1 % decrease in transmittance when a collect is covered in dust.

2.1.2. Design Specifications

1) Still material – selection of still material is extremely important as this affects still performance, maintenance requirements and device life. Careful selection of the glass cover, basin liner, condensate channel, still body and sealants material is necessary. A major challenge is also designing according to material availability and cost. Generally, glass is favored for the cover material due to its transmittance, but plastic can also be considered due to its low cost [9]. It is imperative for basin liner material to be watertight and be able to absorb sufficient solar radiation while being able to withstand high temperatures. Various forms of plastic and rubber can be utilized [10]. Condensate channels should be nonferrous and must not corrode. Aluminium is sometimes used but can corrode at high temperatures [11].

2) Basin depth - Phadatare & Verma [12] and Tripathi & Tiwari [13] conducted experiments to investigate the effect of basin depth and still productivity. They found that a decrease in brine depth leads to an increase in the volumetric output. This agrees with the logical thought that an increase in water volume in the basin means an increase in time for the brine to heat up to a temperature where phase change can occur.
3) Slope of cover – while yield is dependent on the tilt angle, the optimal tilt angle is dependent on a number of factors such as latitude, still orientation and time of year. Singh & Tiwari [14] suggested optimal tilt angle based on latitude. Kumar et al. [15] proposed a tilt angle of 15° based on a numerical analysis. Ghoneyem & Ileri [9] found that a yield increase of up to 63 % is possible due to a change of tilt angle.
4) Energy storage – energy storage materials help increase thermal efficiency, much like insulation, but also help to prolong operational times of solar stills. In these cases an energy storage material is placed inside the basin to absorb the heat energy supplied by solar radiation [16]. Black granite gravel was utilized by Rajaseenivasa et al. [17] and found that there was a 17 % to 20 % increase in still yield. Abdalla et al. [18] carried out an experimental analysis of three different types of energy storage materials and noted black rocks increased productivity by the greatest amount (20 %).
5) Insulation – insulation of solar stills helps improve thermal efficiency, although insulation thickness effects do saturate at a point [19]. It was noted that 60 mm thick insulation helped lead to an 80 % increase in still yields while thermal efficiency rose between 2 % and 4 % [20].
6) Still area – an increase in still area enables improved volumetric output due to a larger basin size. This, however, reduces the portability of the device and may lead to temperature gradients within the basin.
7) Height of roof – by reducing the height of the condensing surface (still roof) there will be an improvement in still performance. Ghoneyem [21] noted an increase of 11 % in productivity by reducing roof height by 5 cm.
8) Shape of still – the type and shape of solar still has huge implications on productivity. There is a tradeoff between potential output and cost, maintenance requirements and efficiency. Single and double slope stills are considerably more affordable to manufacture than wick and hybrid stills although they have reduced yield rates. It is therefore necessary to improve design specifications and change operational parameters to enhance yield rates for single basin stills.

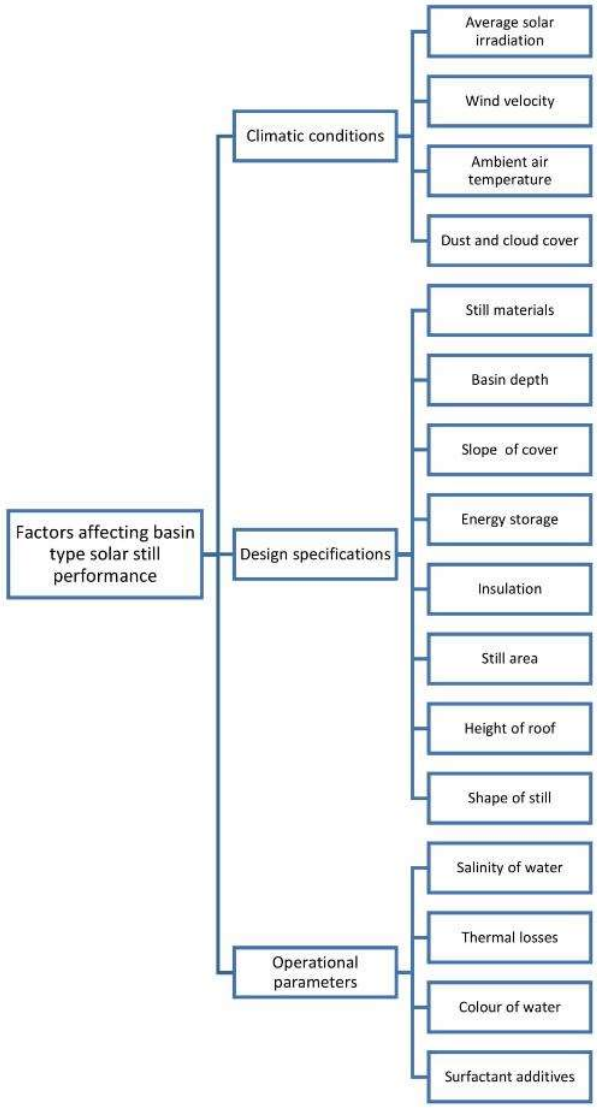

Figure 1. Factors affecting basin type solar still productivity

2.1.3. Operational Parameters

1) Salinity of water – Baibutaev et al. [22] changed the salt concentration of the basin water and investigated its effect on the volumetric output of distillate. It was noted that there was a decrease in daily production with an increase in water salinity. It also found an increase in corrosion rates with a greater salt content in basin water.
2) Thermal losses – these are losses to the surrounding environment or the ground. Insulation of the solar still and the use of sealant between material interfaces inhibit thermal losses, however total prevention of thermal losses is impossible. Therefore, it is imperative to find a good balance between use of insulation and sealants and the cost of manufacturing.
3) Colour of water – inclusion of dye into the basin water can help with absorption of solar radiation by the brine water. Rajvanshi [23] carried out an experiment to test the validity of dye inclusion and found productivity increased by as much as 29 % when using a black naphthylamine dye.
4) Surfactant additives – these are additives that change the properties of water by reducing surface tension and thus enhance heat transfer during boiling. Nafey et al. [24] showed a production increase of up to 7 % with a surfactant concentration of 300 ppm.

2.2. Analytical Model of the Solar Still System

The analytical model presented below utilizes analogue modelling through an analogous system representation for the heat transfer within the solar still. Mathematical models quantify system parameters and specifications. Using MATLAB, a numerical model will solve the mathematical model through iterative means.

2.2.1. Heat Transfer Energy Balance of System

The heat flow of a solar still can be seen in Figure 2.

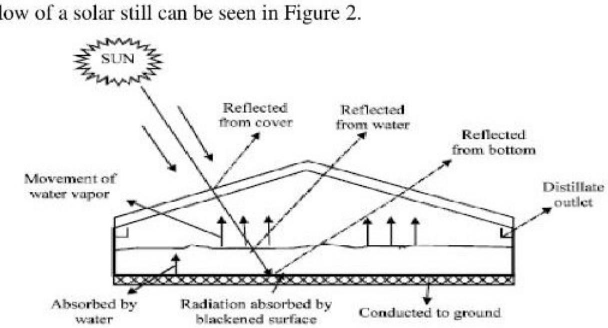

Figure 2. Heat flow of a double slope solar still [25]

Thermal modelling enables the simplification of a heat transfer system in terms of electric circuits. The thermal network of the system depicted in Figure 2 can be seen in Figure 3.

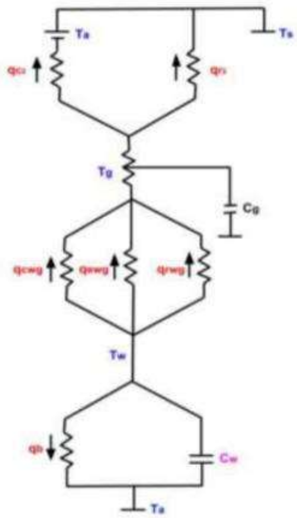

Figure 3. The thermal network for a roof type solar still [26]

The overall upward heat flow factor (U_t) for a solar still can be given by the following equation:

$$U_t = \left[\frac{1}{U_i} + \frac{1}{A_r U_o}\right] \tag{1}$$

The heat flow factor relationship is given on the assumptions that there is no temperature gradient in either the water or glass and that there exists no ventilation within the solar still.
To enable the solution of Eq. (2) the follow relationships should be specified:

$$U_i = h_{cwg} + h_{ewg} + h_{rwg} \tag{2}$$

$$U_o = \frac{h_{wg}(T_g - T_a)}{(T_g - T_s)} + h_{rgs} \tag{3}$$

$$A_r = \frac{A_g}{A_w} \tag{4}$$

A heat balance energy equation can be drawn up by means of Eqs. (1) to (4). This relationship can be seen in Eq. (5) below.
T_w is regarded as the source temperature.

- T_s is the sink temperature.

$$\frac{c_w}{A_w}\frac{d\tau_w}{d\tau} = \eta_o I - U_t(T_w - T_s) - U_b(T_w - T_a) \tag{5}$$

T_w can be found by integrating Eq. (5) with respect to time. This can be done by evaluating it over one hour intervals.

Assuming that heat is not absorbed by the insulation in the glass cover and that the glass cover has a negligible heat capacity, the heat flow from the water to the glass is given by:

$$q_{wg} = U_i(T_w - T_g) = U_t(T_w - T_s) \tag{6}$$

Heat energy from the water to glass that is used for evaporation is noted by:

$$q_{ewg} = h_{ewg}(T_w - T_g) \tag{7}$$

The evaporation heat flow utilization factor (F_e) is shown by:

$$F_e = \frac{h_{ewg}}{U_i} \tag{8}$$

The convective heat flow utilization factor (F_c) is:

$$F_c = \frac{h_{cwg}}{U_i} \tag{9}$$

While the radiation heat flow utilization factor (F_r) is:

$$F_r = \frac{h_{rwg}}{U_i} \tag{10}$$

By neglecting the following regarding the glass cover:

- Thermal resistance;
- Heat capacity;
- Solar radiation absorption;

and through a quasi-steady state analysis, the heat balance of the glass cover can be shown as:

$$q_{cga} + q_{rgs} = q_{ewg} + q_{rgs} + q_{cwg} \tag{11}$$

Eq. (12) can be noted in term of temperatures as seen below.

$$\begin{aligned} &A_r h_w(T_g - T_a) + A_r h_{rgs}(T_g - T_s) \\ &= (T_w - T_g)[h_{cwg} + h_{ewg} + h_{rwg}] \end{aligned} \tag{12}$$

2.2.2. Distillate output per hour

The energy that is utilized for evaporation can be found by:

$$q_e = \frac{h_{cwg} U_t}{U_i}(T_w - T_s) \tag{13}$$

While the mass of distilled water is:

$$m_w = \frac{q_e}{h_{fg}} \tag{14}$$

The change of enthalpy from saturated fluid to saturated vapour as a function of temperature is given by:

$$h_{fg} = 3044204.357 - 1679.11T_w \quad (15)$$

Once the convective heat transfer and mass transfer coefficients have been established, the heat loss due to evaporation from the water to the glass cover can be found using:

$$q_{el} = 16.28h_c(P_w - P_g) \quad (16)$$

The heat loss through the bottom of the still to the ground is shown in Eq. (17).

$$q_b = U_b(T_w - T_a) \quad (17)$$

The heat loss due to convection from the glass cover to the outside ambient air can be solved using:

$$q_{ca} = h_{ca}(T_g - T_a) \quad (18)$$

The forced convection heat transfer coefficient (h_{ca}) can be calculated as follows:

$$h_{ca} = 2.8 + 3.8V \quad (19)$$

The radiative heat loss, which is a function of sky and glass cover temperature, is given by:

$$q_{ra} = \varepsilon_g\sigma(T_g^4 - T_s^4) \quad (20)$$

2.2.3. Heat transfer coefficient

Heat transfer coefficients exist between the basin water and glass cover due to radiation, evaporation and convection. These are noted in Eqs. (21) to (23).

The convective heat transfer coefficient can be found by:

$$h_{cwg} = 0.884\left[(T_w - T_g) + T_w\left(\frac{P_w - P_g}{2016 - P_w}\right)\right]^{\frac{1}{3}} \quad (21)$$

The evaporative heat transfer coefficient can be found by:

$$h_{ewg} = \frac{9.15 \times 10^{-7} h_{cwg} \times h_{fg}(P_w - P_g)}{(T_w - T_g)} \quad (22)$$

The radiative heat transfer coefficient can be found by:

$$h_{rwg} = 0.9\sigma(T_w^2 - T_s^2)(T_w + T_g) \quad (23)$$

While the radiative heat transfer coefficient between the glass cover and sky is:

$$h_{rgs} = \varepsilon_g\sigma(T_g^2 + T_s^2)(T_g + T_s) \quad (24)$$

The sky temperature is a function of the ambient environmental temperature and is denoted by:

$$T_s = 0.0552 \times T_a^{1.5} \tag{25}$$

Partial pressure of water at any given temperature is given by the following:

$$P = \frac{165960.72 \times 10^{[X(a+bx+cx^3)]}}{T[(d \times x) + 1]} \tag{26}$$

Where:

$$x = 647.27 - T \tag{27}$$

And also:

$$a = 3.24378$$

$$b = 5.86826 \times 10^{-3}$$

$$c = 1.17023 \times 10^{-3}$$

$$d = 2.18784 \times 10^{-3}$$

2.2.4. Wind Velocity

The equation to find wind velocity as per Nelson & Starcher [27]is:

$$\frac{V_z}{V_1} = \frac{\ln\left(\frac{Z}{Z_0}\right)}{\ln\left(\frac{Z_1}{Z_0}\right)} \tag{28}$$

The wind heat transfer coefficient is given by:

$$h_w = 2.8 + 3V_z \tag{29}$$

2.2.5. Hourly radiation under cloudless skies

Through the use of the American Society of Heating, Refrigerating and Air-Conditioning Engineer Model the global radiation that a horizontal surface experiences can be given by:

$$I_g = I_b + I_d \tag{30}$$

The hourly beam radiation is:

$$I_b = I_{bn} \cos\theta_z \tag{31}$$

The hourly global radiation is:

$$I_g = I_{bn} \cos\theta_z + I_d \tag{32}$$

While the beam radiation that is in the direction of the ray is:

$$I_{bn} = A \times exp\left(-\frac{B}{\cos\theta_z}\right) \tag{33}$$

The hourly diffuse radiation is:

$$I_d = CI_{bn} \tag{34}$$

The values of constants A, B and C change each month, these then need to be selected using Table 1. These values were taken for the eastern seaboard of South Africa. These will be used for Durban.

Table 1. Empirical constants A, B and C for solar radiation [28]

Month	A	B	C
January	1618	0.0666	1.2404
February	1489	0.0672	1.2500
March	1606	0.511	1.4064
April	1500	0.0369	1.5375
May	1604	0.796	1.2173
June	1606	0.1143	1.0787
July	1470	0.0721	1.2576
August	1469	0.0847	1.1310
September	1434	0.0899	1.0777
October	1502	0.0697	1.1496
November	1452	0.0740	1.1318
December	1466	0.0782	1.3134

Beam Radiation

The tilt factor (r_b) for beam radiation is the ratio of the beam radiation flux that falls onto the tilted surface to the beam radiation that falls onto the horizontal surface. It can be shown by Eq. (35).

$$r_b = \frac{\cos\theta}{\cos\theta_z} = \frac{\sin\delta\sin(\emptyset - \beta) + \cos\delta\cos\omega\cos(\emptyset - \beta)}{\sin\emptyset\sin\delta + \cos\delta\cos\omega} \tag{35}$$

If the tilted surface is facing south, then $\cos\theta$ and $\cos\theta_z$ can be simplified to:

$$\cos\theta = \sin\delta\sin(\emptyset - \beta)\cos\omega \tag{36}$$

$$\cos\theta_z = \sin\emptyset\sin\delta + \cos\emptyset\cos\delta\cos\omega \tag{37}$$

Diffuse Radiation

The tilt factor (r_d) for diffuse radiation is the ratio of the diffuse radiation flux that falls onto the tilted surface to the diffuse radiation that falls onto the horizontal surface. It can be shown by Eq. (38) for a tilted surface with the slope of the still roof regarded as β.

$$r_d = \frac{1 + \cos\beta}{2} \tag{38}$$

Reflected Radiation

The tilt factor (r_r) for reflected radiation is given by:

$$r_r = \rho\left(\frac{1-\cos\beta}{2}\right) \tag{39}$$

The instantaneous flux that falls onto the tilted surface is:

$$I_T = I_b r_b + I_d r_d + r_r(I_b + I_d) \tag{40}$$

2.2.6. Prediction of Availability of Solar Radiation

An empirical method to calculate the clearness index and the hourly radiation received can be used as opposed to sourcing meteorological data daily.

Clearness Index

The ratio of radiation on a horizontal surface to extraterrestrial radiation is the Clearness Index (K_T). There are two available empirical methods that are able to calculate the monthly average of the daily radiation and the hourly radiation.

i. Daily Radiation Clearness Factor (K_T)

$$K_T = \frac{H}{H_o} \tag{41}$$

Where:

$$H_o = \frac{24\times 6300}{\pi} G_{on}\left[\cos\emptyset\cos\delta\sin\omega_3 + \sin\emptyset\sin\delta\left(\frac{\pi\times\omega_3}{180}\right)\right] \tag{42}$$

$$G_{on} = G_s\left[1 + 0.33\cos\left(\frac{360n}{365}\right)\right] \tag{43}$$

ii. Hourly Radiation Clearness Factor (k_T)

$$k_T = \frac{I}{I_o} \tag{44}$$

Where:

$$I_o = \frac{12\times 360}{\pi} G_{on}[\cos\emptyset\cos\delta\,(\sin\omega_2 - \sin\omega_1)] + \sin\emptyset\sin\delta\left[\frac{\pi(\omega_2-\omega_1)}{180}\right] \tag{45}$$

Hourly Radiation Received

The hourly solar radiation can be estimated using the daily values of radiation received. We can now calculate the solar radiation received at any given time and utilize it as an hourly average for solar radiation received.

The total daily radiation received (r_t) is:

$$r_t = \frac{I}{H} = \frac{\pi}{24}(a + b\cos\omega)\left[\frac{\cos\omega - \cos\omega_3}{\sin\omega_3 - \left(\frac{\pi\omega_3}{180}\right)\cos\omega_3}\right] \quad (46)$$

The coefficient a and b are found using the following:

$$a = 0.409 + 0.5016\sin(\omega_3 - 60) \quad (47)$$

$$b = 0.6609 - 0.4767\sin(\omega_3 - 60) \quad (48)$$

The daily diffuse radiation (r_d) is calculated using Eq. (49).

$$r_d = \frac{I_d}{H_d} = \frac{\pi}{24}\left(\frac{\cos\omega - \cos\omega_3}{\sin\omega_3 - \left(\frac{\pi\omega_3}{180}\right)\cos\omega_3}\right) \quad (49)$$

Liu & Jordan [29] proposed the equality seen in Eq. (50).

$$\frac{I_o}{H_o} = \frac{I_d}{H_d} \quad (50)$$

By substituting in Eq. (51) the following relationship can be attained:

$$\therefore I_o = H_o\frac{I_d}{H_d} = H_o r_d \quad (51)$$

The hourly radiation clearness factor (k_T) transforms into Eq. (52) using the results of Eq. (51).

$$k_T = \frac{I}{I_o} = \frac{r_t H}{r_d H_o} \quad (52)$$

The ratio of the total daily radiation received and the daily diffuse radiation received results in:

$$\frac{r_t}{r_d} = (a + b\cos\omega) \quad (53)$$

The hourly radiation clearness factor (k_T) as a function of the daily radiation clearness factor (K_T) can be derived from:

$$\therefore k_T = \frac{I}{I_o} = K_T(a + b\cos\omega) \quad (54)$$

I and I_o is now referred to as G_{total} and G_o. This will be used to calculate the solar radiation at any given time by means of:

$$\therefore \frac{G_{total}}{G_o} = K_T(a + b\cos\omega) \rightarrow G_{total} = G_o K_T(a + b\cos\omega) \quad (55)$$

The clearness factor for Durban, South Africa for the different months of the year 2007 can be seen in Table 2.

Table 2. Clearness factor in Durban for each month of the year 2007 [30]

Month	Clearness Factor (K_T)
January	0.54
February	0.56
March	0.50
April	0.52
May	0.61
June	0.57
July	0.59
August	0.55
September	0.51
October	0.41
November	0.42
December	0.49
Annual Average	0.52

2.2.7. Solar Still Efficiency

The solar still efficiency (η_i) is the ratio of the evaporation-condensation heat transfer to the input still radiation, and is given by:

$$\eta_i = \frac{q_e}{I} \quad (56)$$

Alternatively, solar still efficiency can be calculated using Equation (57). As shown below, the efficiency of the solar still is found by the ratio of distillate energy of vaporization to input still radiation.

$$\eta_i = \frac{m_w h_{fg}}{I} \quad (57)$$

3. RESULTS

A MATLAB code provides a solution to the mathematical system model. The results describe the following system performance indices for the middle of each month:

1) Evaporative water temperature
2) Glass cover temperature
3) Ambient temperature
4) Productivity
5) Solar intensity

The results are summarized in a table for each month (Tables 3 to 14) while the system temperatures, productivity and solar intensity as a function of time are also graphed (Figures 4 to 39).

3.1. January System Performance

Table 3. January performance results

Month	Time of day	Evaporative water temperature (°C)	Glass cover temperature (°C)	Ambient temperature (°C)	Productivity (ml/m².hr)	Solar intensity (kW/m²)
January	8:00	25.0000	21.8514	29.5000	67.2503	168.9916
	9:00	27.9476	24.5086	32.5000	77.3110	348.0432
	10:00	43.5815	40.1310	34.0000	167.8575	545.9216
	11:00	57.6110	54.1435	35.5000	316.5736	723.4932
	12:00	67.1073	63.6241	36.5000	475.7866	843.6884
	13:00	70.0329	66.5473	37.0000	537.5693	880.7181
	14:00	65.7529	62.2763	38.0000	448.6475	826.5463
	15:00	55.1960	51.7178	38.0000	286.0282	692.9154
	16:00	40.6160	37.1591	33.0000	146.2781	508.3883
	17:00	33.9453	29.9899	33.0000	86.8658	311.1885
	18:00	25.0358	21.5933	32.5000	66.3182	139.7235

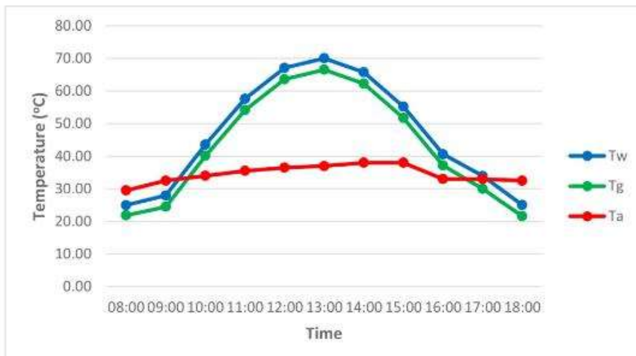

Figure 4. Still temperatures throughout the day – January

Figure 5. Productivity throughout the day – January

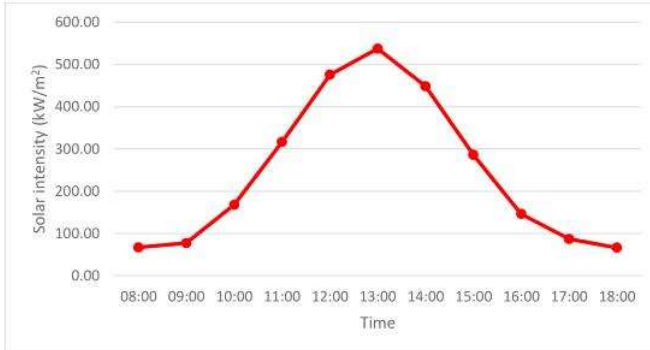

Figure 6. Solar intensity throughout the day – January

3.2. February System Performance

Table 4. February performance results

Month	Time of day	Evaporative water temperature (^{O}C)	Glass cover temperature (^{O}C)	Ambient temperature (^{O}C)	Productivity ($ml/m^2.hr$)	Solar intensity (kW/m^2)
February	8:00	25.0000	21.8217	22.5000	67.9671	154.1526
	9:00	26.5161	23.3492	25.0000	73.3852	333.6478
	10:00	42.4310	39.2532	28.0000	162.4885	535.0823
	11:00	56.9181	53.7237	29.5000	313.4193	718.4458
	12:00	66.9373	63.7289	30.5000	481.4045	845.2593
	13:00	70.3267	67.1153	31.5000	554.5359	888.1592
	14:00	66.3463	63.1448	32.5000	468.5996	837.7788
	15:00	55.8647	52.6799	33.0000	298.4459	705.1127
	16:00	41.1400	37.9741	32.5000	152.2505	518.7421
	17:00	32.1205	29.1899	32.0000	85.8644	317.6505
	18:00	25.2522	22.1013	31.5000	68.2214	141.5253

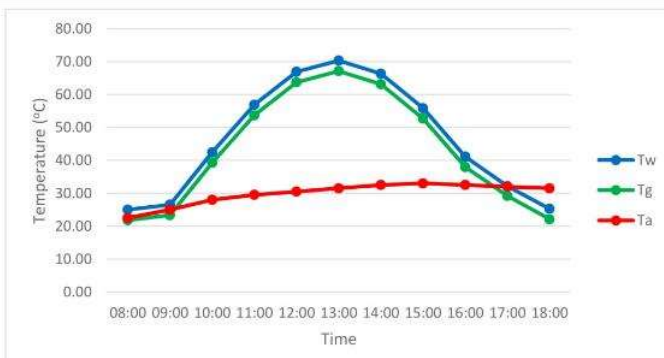

Figure 7. Still temperatures throughout the day – February

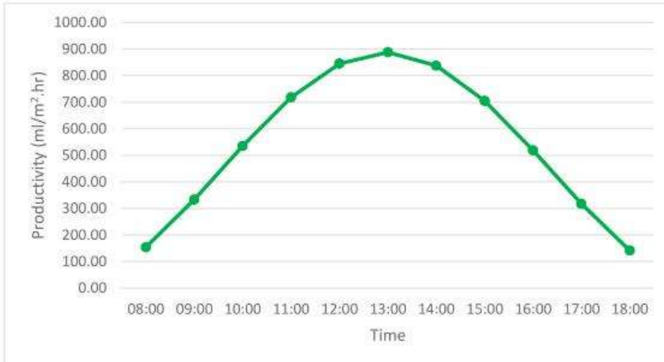

Figure 8. Productivity throughout the day – February

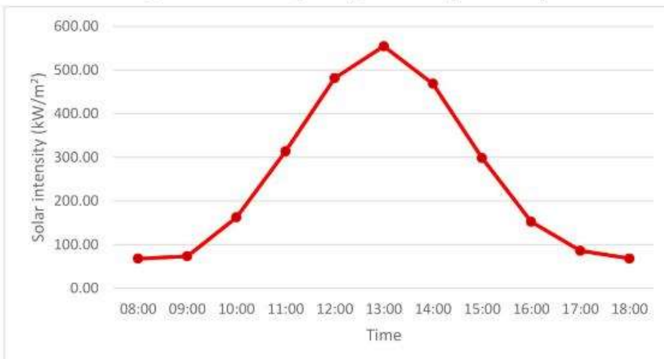

Figure 9. Solar intensity throughout the day – February

3.3. March System Performance

Table 5. March performance results

Month	Time of day	Evaporative water temperature (^{O}C)	Glass cover temperature (^{O}C)	Ambient temperature (^{O}C)	Productivity ($ml/m^2.hr$)	Solar intensity (kW/m^2)
March	8:00	25.0000	21.8409	29.5000	67.5002	153.2408
	9:00	26.8240	23.6674	30.5000	74.3172	337.5453
	10:00	42.9595	39.7994	31.5000	165.5227	541.7714
	11:00	57.3864	54.2090	35.0000	317.9674	724.3736
	12:00	67.0221	63.8307	36.0000	480.3222	846.3327
	13:00	69.7560	66.5608	37.0000	538.6478	880.9361
	14:00	64.9834	61.8018	37.5000	439.6694	820.5285
	15:00	53.7583	50.5968	38.5000	270.0480	678.4532
	16:00	38.5270	35.3849	38.5000	133.4296	485.6702
	17:00	28.5436	25.9765	38.0000	70.2501	282.9453
	18:00	22.5102	19.3828	37.5000	58.3210	110.6691

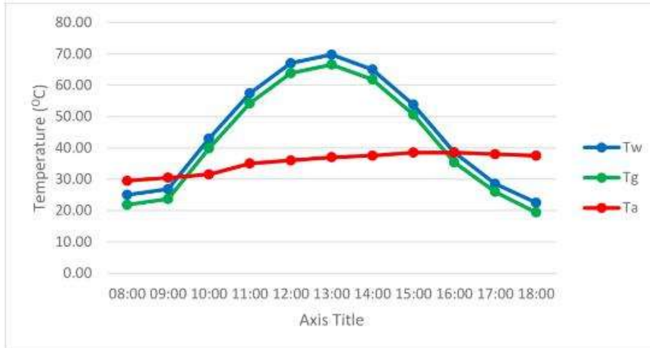

Figure 10. Still temperatures throughout the day – March

Figure 11. Productivity throughout the day – March

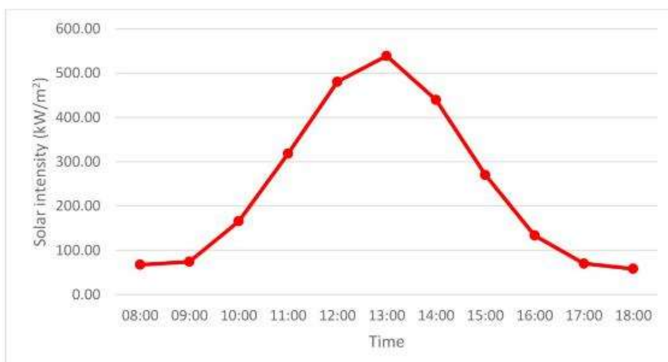

Figure 12. Solar intensity throughout the day – March

3.4. April System Performance

Table 6. April performance results

Month	Time of day	Evaporative water temperature (^oC)	Glass cover temperature (^oC)	Ambient temperature (^oC)	Productivity ($ml/m^2.hr$)	Solar intensity (kW/m^2)
April	8:00	25.0000	21.8577	32.5000	67.1017	156.2154
	9:00	27.1050	23.9649	33.5000	74.9894	341.1015
	10:00	42.8200	39.6744	34.5000	163.4511	540.0062
	11:00	56.3426	53.1827	37.5000	302.1035	711.1619
	12:00	64.7149	61.5395	39.0000	433.8174	817.1301
	13:00	66.0682	62.8920	39.0000	459.2026	834.2588
	14:00	60.0982	56.9336	39.5000	355.6083	758.6970
	15:00	48.1427	44.9938	39.5000	209.3082	607.3763
	16:00	32.8408	29.7073	38.5000	100.5085	413.6999
	17:00	25.1326	22.1929	37.5000	57.7063	219.0790
	18:00	17.4643	14.3412	36.5000	43.8678	62.5514

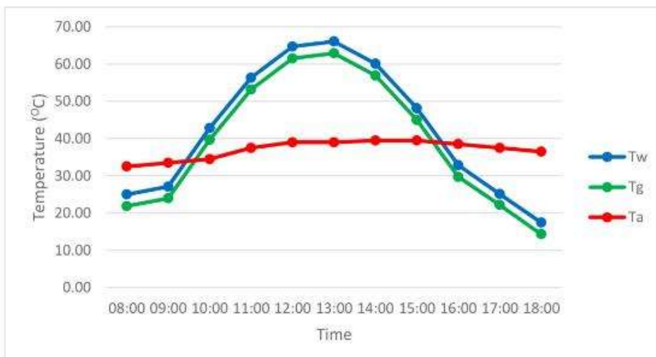

Figure 13. Still temperatures throughout the day - April

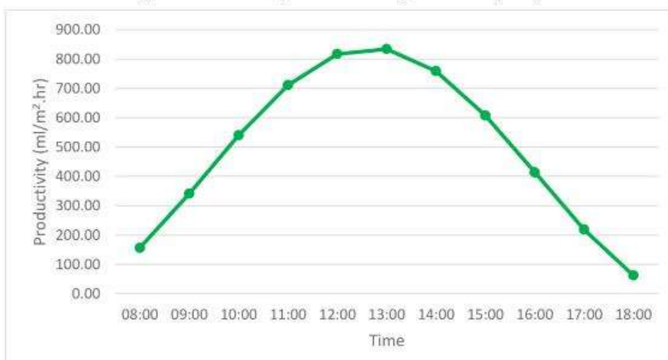

Figure 14. Productivity throughout the day – April

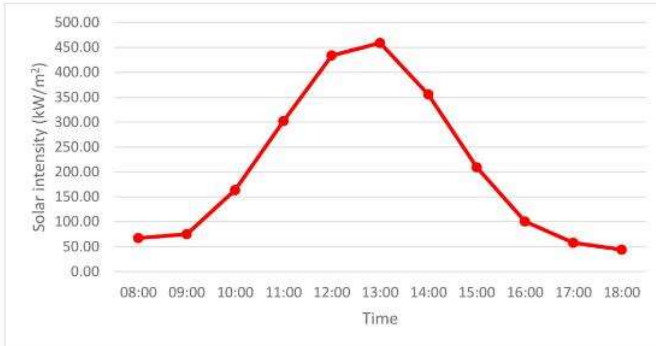

Figure 15. Solar intensity throughout the day – April

3.5. May System Performance

Table 7. May performance results

Month	Time of day	Evaporative water temperature (^oC)	Glass cover temperature (^oC)	Ambient temperature (^oC)	Productivity ($ml/m^2.hr$)	Solar intensity (kW/m^2)
May	8:00	23.0000	19.8213	24.0000	60.9965	140.2095
	9:00	25.0827	21.9150	25.5000	68.0065	315.5055
	10:00	39.7819	36.6053	28.5000	143.2667	501.5537
	11:00	52.1598	48.9728	30.0000	253.8864	658.2198
	12:00	59.4503	56.2556	31.5000	349.4953	750.4959
	13:00	59.9962	56.8084	32.5000	356.8973	757.4057
	14:00	53.6727	50.4994	34.5000	270.1312	677.3695
	15:00	41.9195	38.7588	35.5000	157.6696	528.6093
	16:00	27.3724	24.2215	34.5000	76.3399	344.4854
	17:00	18.5439	15.0808	33.0000	51.3022	165.0011
	18:00	13.1917	10.0466	31.5000	34.3997	26.7193

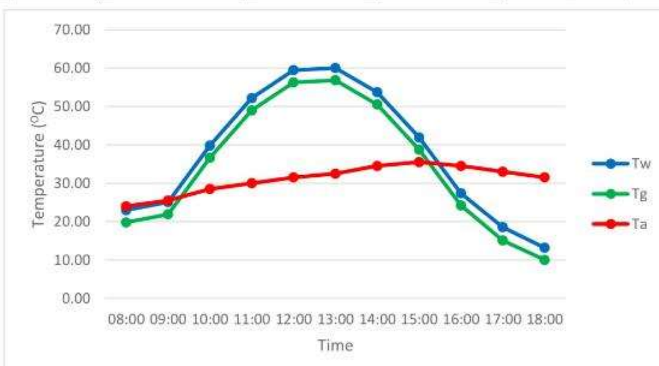

Figure 16. Still temperatures throughout the day - May

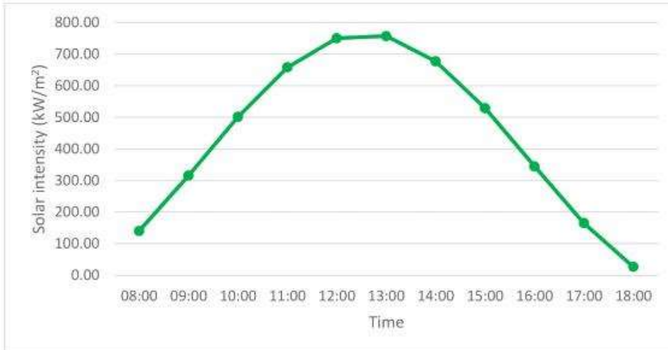

Figure 17. Productivity throughout the day – May

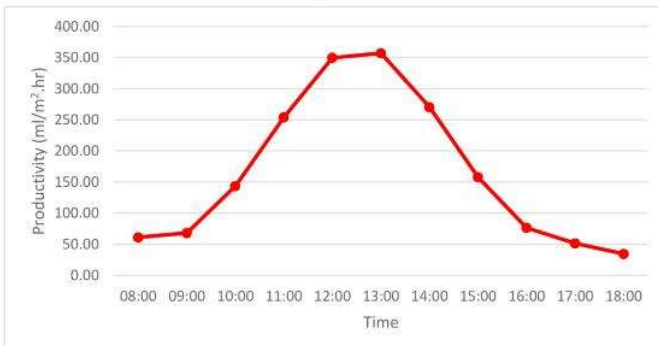

Figure 18. Solar intensity throughout the day – May

3.6. June System Performance

Table 8. June performance results

Month	Time of day	Evaporative water temperature (^oC)	Glass cover temperature (^oC)	Ambient temperature (^oC)	Productivity ($ml/m^2.hr$)	Solar intensity (kW/m^2)
June	8:00	20.0000	16.8173	19.5000	51.7340	85.3494
	9:00	19.1595	15.9840	23.0000	49.2163	240.5352
	10:00	32.8626	29.6789	24.5000	102.2808	413.9748
	11:00	45.0238	41.8386	25.5000	183.8016	567.8993
	12:00	52.8942	49.7061	28.5000	262.3593	667.5151
	13:00	54.6617	51.4730	30.5000	283.5981	689.8874
	14:00	49.9167	46.7289	31.0000	229.8060	629.8290
	15:00	39.7568	36.5823	29.5000	142.9885	501.2359
	16:00	26.5055	23.3470	29.5000	73.1222	333.5130
	17:00	18.4521	15.4121	29.5000	45.1318	164.0395
	18:00	13.1158	9.9664	29.5000	34.2939	28.6687

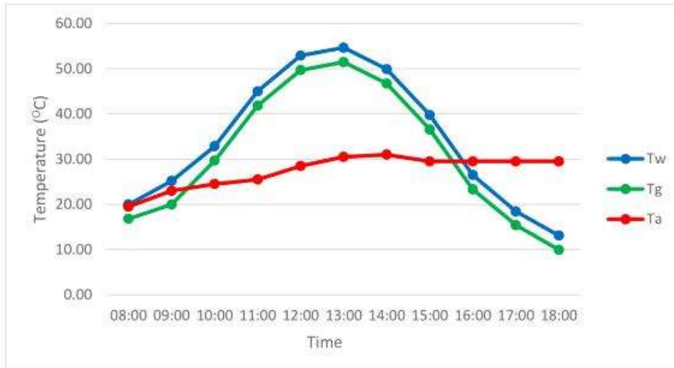

Figure 19. Still temperatures throughout the day – June

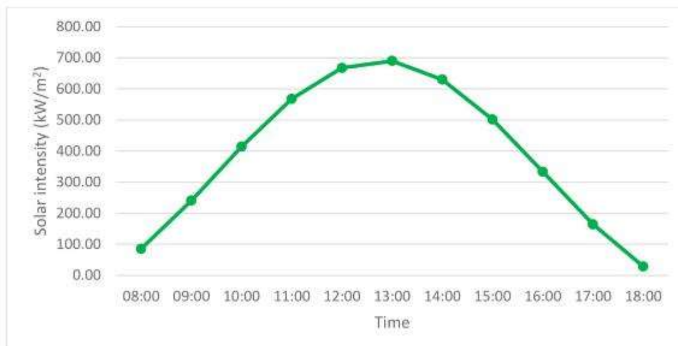

Figure 20. Productivity throughout the day – June

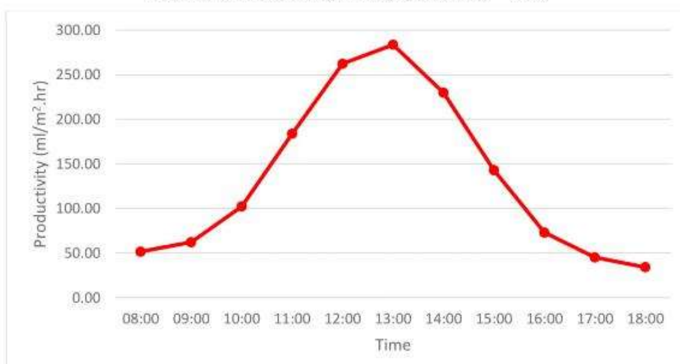

Figure 21. Solar intensity throughout the day – June

3.7. July System Performance

Table 9. July performance results

Month	Time of day	Evaporative water temperature (°C)	Glass cover temperature (°C)	Ambient temperature (°C)	Productivity (ml/m².hr)	Solar intensity (kW/m²)
July	8:00	20.0000	16.7863	14.5000	52.7943	62.0695
	9:00	16.9102	13.7057	16.0000	43.7248	212.0652
	10:00	30.8421	27.6455	17.5000	92.7549	388.4021
	11:00	43.8762	40.6716	22.0000	175.4455	553.3744
	12:00	53.0979	49.8893	23.5000	266.5893	670.0944
	13:00	56.3992	53.1897	25.5000	308.0473	711.8785
	14:00	53.0181	49.8137	26.5000	265.2736	669.0837
	15:00	43.7349	40.5410	26.5000	173.6624	551.5856
	16:00	30.6714	27.4878	26.0000	91.4453	386.2411
	17:00	22.1329	19.3047	25.0000	54.9923	210.0068
	18:00	16.7475	13.5696	23.5000	42.9084	60.5377

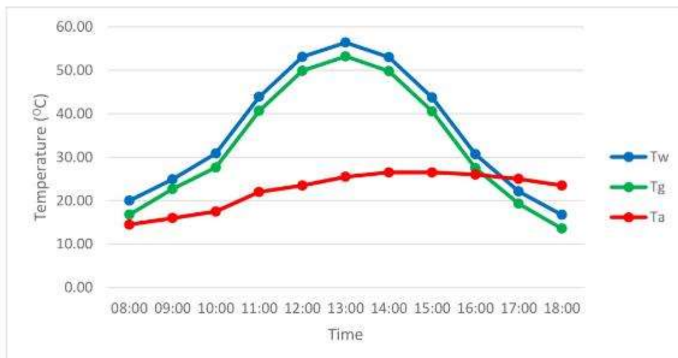

Figure 22. Still temperatures throughout the day – July

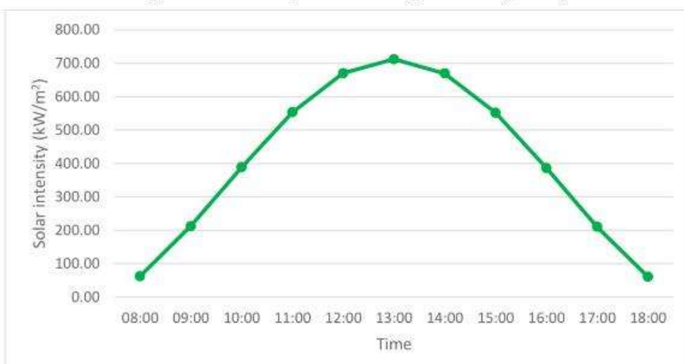

Figure 23. Productivity throughout the day – July

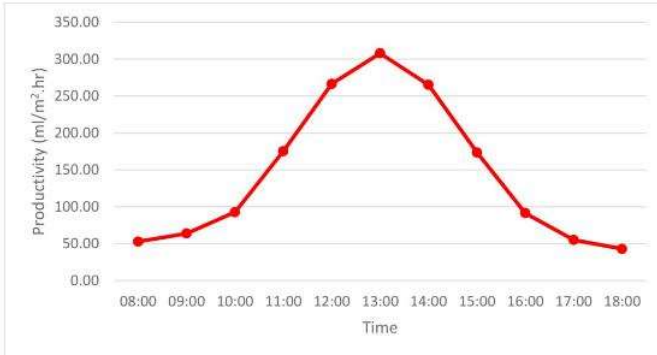

Figure 24. Solar Intensity throughout the day – July

3.8. August System Performance

Table 10. August performance results

Month	Time of day	Evaporative water temperature (^{o}C)	Glass cover temperature (^{o}C)	Ambient temperature (^{o}C)	Productivity ($ml/m^2.hr$)	Solar intensity (kW/m^2)
August	8:00	22.0000	18.8135	18.5000	57.9029	71.1111
	9:00	18.2554	15.0828	22.5000	46.7052	229.0918
	10:00	33.1062	29.9328	25.0000	103.0050	417.0582
	11:00	47.2298	44.0437	28.0000	203.4218	595.8207
	12:00	57.5275	54.3281	29.0000	322.3202	726.1589
	13:00	61.6818	58.4832	29.5000	384.8229	778.7400
	14:00	58.7472	55.5537	31.5000	338.9926	741.5968
	15:00	49.3921	46.2112	31.5000	223.9331	623.1901
	16:00	35.7280	32.5623	31.0000	117.0765	450.2430
	17:00	27.1287	23.6652	30.5000	71.8863	260.9220
	18:00	20.5589	16.6663	30.0000	63.5659	134.7869

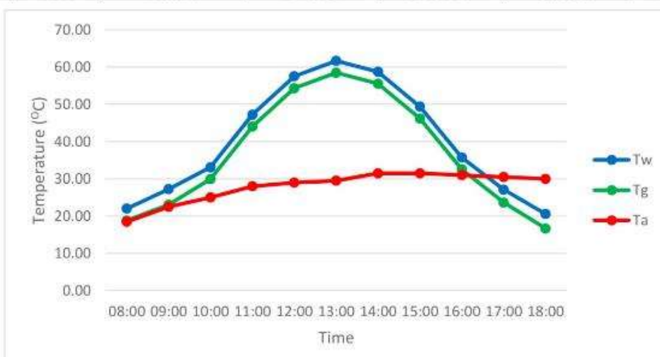

Figure 25. Still temperatures throughout the day – August

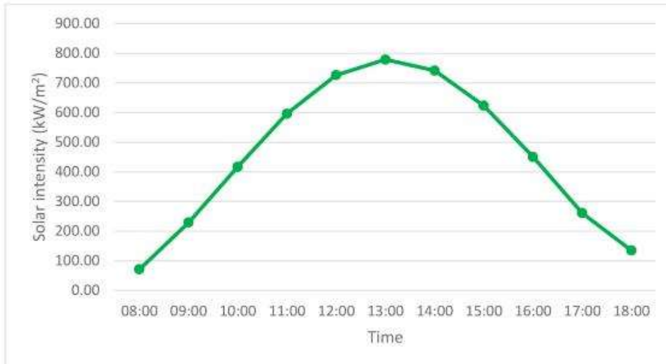

Figure 26. Productivity throughout the day – August

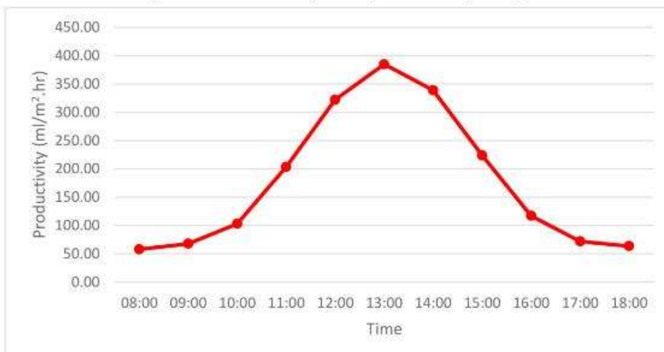

Figure 27. Solar intensity throughout the day – August

3.9. September System Performance

Table 11. September performance results

Month	Time of day	Evaporative water temperature (^oC)	Glass cover temperature (^oC)	Ambient temperature (^oC)	Productivity ($ml/m^2.hr$)	Solar intensity (kW/m^2)
September	8:00	24.0000	20.8397	24.0000	63.9865	107.0772
	9:00	22.2593	19.1110	29.0000	57.9444	279.7687
	10:00	38.0261	34.8742	31.5000	130.9562	479.3298
	11:00	52.6798	49.5160	34.5000	257.7251	664.8018
	12:00	63.0537	59.8719	36.5000	405.4497	796.1040
	13:00	66.8471	63.6599	36.5000	476.1612	844.1180
	14:00	63.2095	60.0313	37.0000	407.6236	798.0764
	15:00	52.9566	49.7924	37.5000	260.9315	668.3055
	16:00	38.3630	35.2149	36.5000	132.7456	483.5946
	17:00	29.2361	25.7784	35.5000	80.9050	283.8906
	18:00	22.5849	19.4448	33.5000	58.8213	110.2440

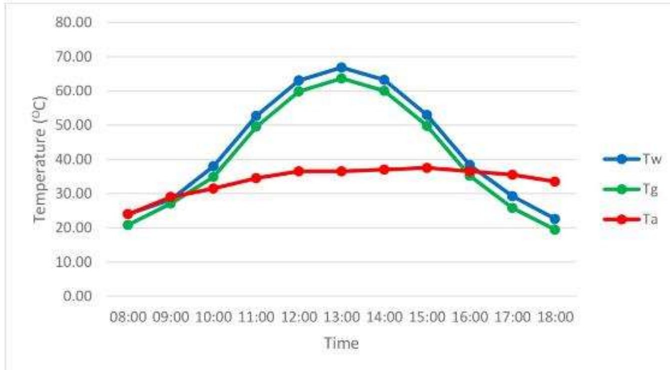

Figure 28. Still temperatures throughout the day – September

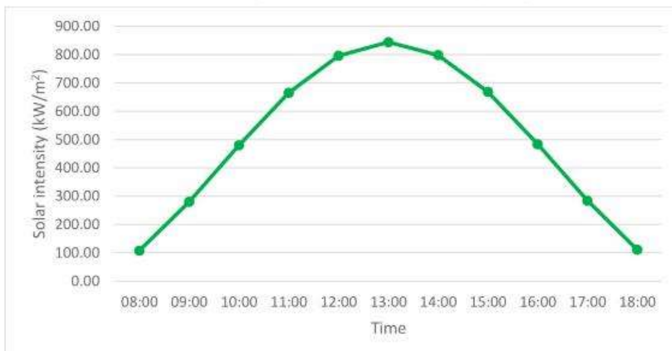

Figure 29. Productivity throughout the day – September

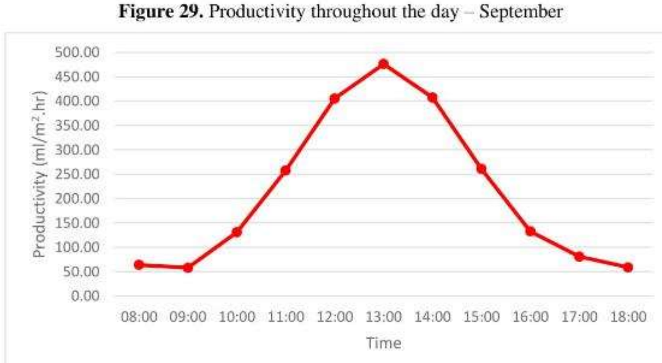

Figure 30. Solar intensity throughout the day – September

3.10. October System Performance

Table 12. October performance results

Month	Time of day	Evaporative water temperature (°C)	Glass cover temperature (°C)	Ambient temperature (°C)	Productivity (ml/m².hr)	Solar intensity (kW/m²)
October	8:00	25.0000	21.8535	29.0000	67.2007	156.9575
	9:00	27.1560	24.0159	32.5000	75.1925	341.7472
	10:00	43.2906	40.1404	34.5000	167.4923	545.9631
	11:00	57.6832	54.5171	36.5000	320.8156	728.1307
	12:00	67.2634	64.0791	38.0000	483.9915	849.3869
	13:00	69.9361	66.7461	38.0000	541.6985	883.2154
	14:00	65.1111	61.9330	38.0000	441.4846	822.1445
	15:00	53.8522	50.6945	38.5000	270.8039	679.6407
	16:00	38.6082	35.4701	38.5000	133.7428	486.6978
	17:00	31.5214	27.6629	38.0000	76.8675	284.0219
	18:00	22.5953	19.4720	37.5000	58.5088	111.8740

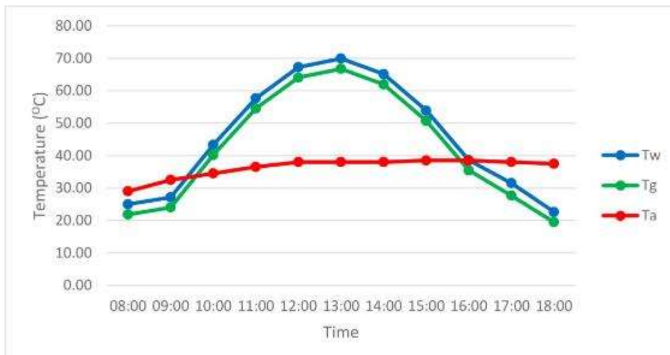

Figure 31. Still temperatures throughout the day – October

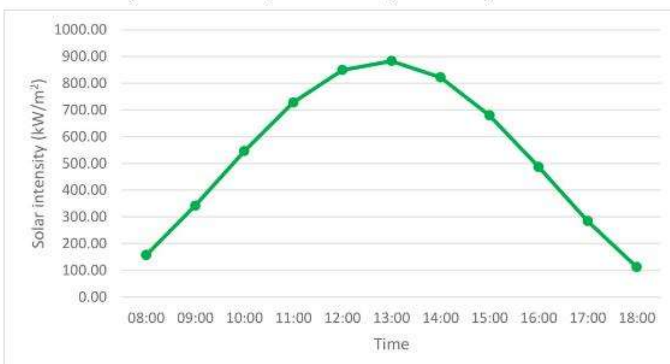

Figure 32. Productivity throughout the day – October

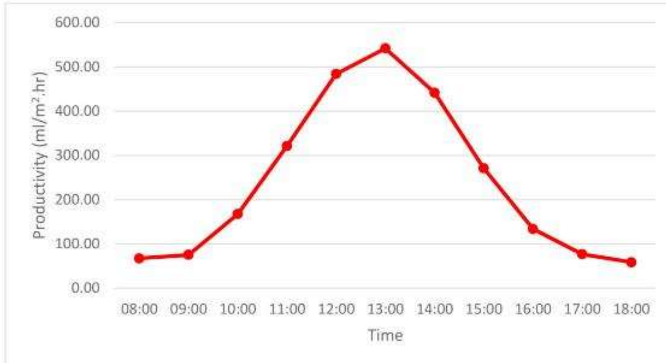

Figure 33. Solar intensity throughout the day – October

3.11. November System Performance

Table 13. November performance results

Month	Time of day	Evaporative water temperature (^{O}C)	Glass cover temperature (^{O}C)	Ambient temperature (^{O}C)	Productivity ($ml/m^2.hr$)	Solar intensity (kW/m^2)
November	8:00	28.0000	24.8486	30.5000	78.9112	183.1962
	9:00	29.3012	26.1569	33.0000	84.2267	368.8990
	10:00	45.1718	42.0191	35.0000	182.9731	569.7736
	11:00	59.0524	55.8839	37.5000	340.5314	745.4602
	12:00	68.0141	64.8319	39.0000	498.9380	858.8880
	13:00	70.1188	66.9377	40.0000	544.1240	885.5270
	14:00	64.9069	61.7389	41.5000	436.2286	819.5611
	15:00	53.5137	50.3644	42.0000	266.0184	675.3561
	16:00	38.3821	35.2504	41.5000	131.9758	483.8364
	17:00	34.4276	29.9918	40.5000	82.4530	284.7244
	18:00	22.6508	19.5317	39.5000	58.6014	116.6870

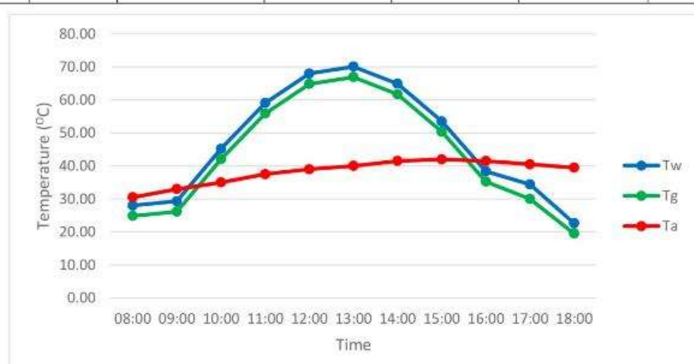

Figure 34. Still temperatures throughout the day – November

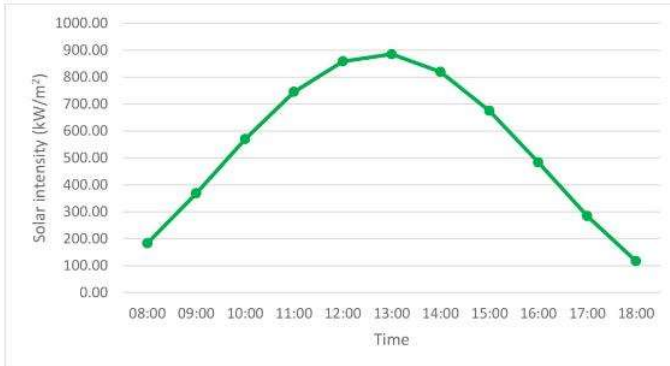

Figure 35. Productivity throughout the day – November

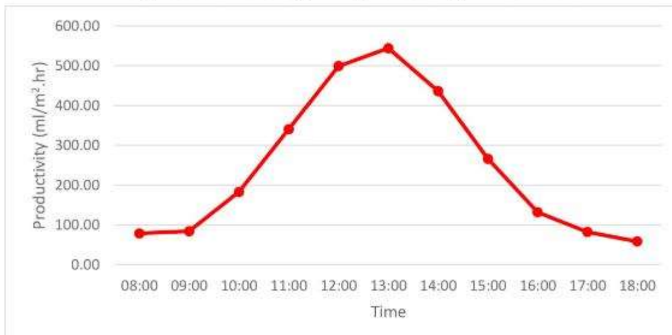

Figure 36. Solar intensity throughout the day – November

3.12. December System Performance

Table 14. December performance results

Month	Time of day	Evaporative water temperature (^{O}C)	Glass cover temperature (^{O}C)	Ambient temperature (^{O}C)	Productivity ($ml/m^2.hr$)	Solar intensity (kW/m^2)
December	8:00	28.0000	24.8611	33.5000	78.5628	177.7285
	9:00	28.7833	25.3561	36.0000	80.4309	358.6211
	10:00	44.4024	40.9672	37.5000	173.2608	556.3127
	11:00	58.2483	54.7974	40.0000	323.5353	731.5607
	12:00	67.4253	63.9566	41.5000	479.7294	847.7134
	13:00	69.9627	66.4923	41.5000	533.2352	879.8294
	14:00	65.3099	66.4923	42.5000	437.6756	820.9387
	15:00	54.4748	51.0344	43.0000	273.6470	683.7989
	16:00	39.7702	36.3492	42.5000	138.8648	497.6830
	17:00	33.8156	29.8804	42.0000	91.3942	301.0451
	18:00	25.7470	23.3863	40.5000	66.8658	143.2644

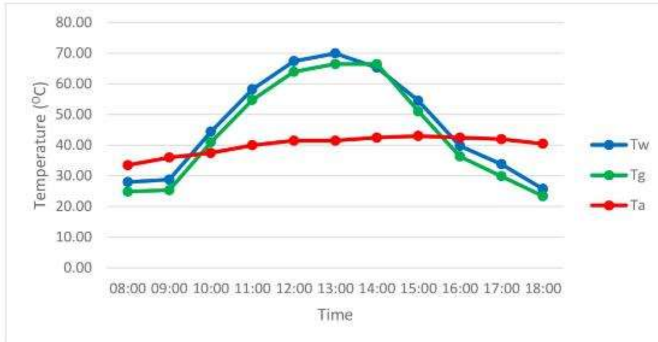

Figure 37. Still temperatures throughout the day – December

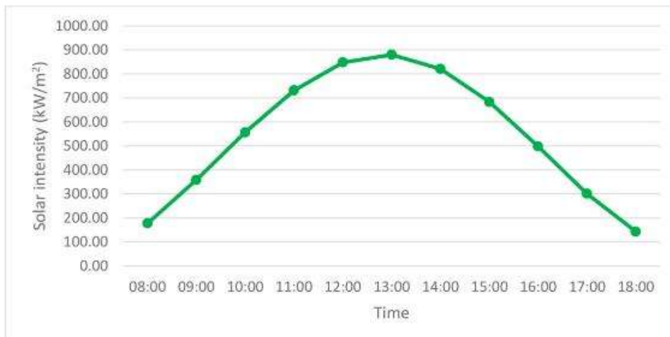

Figure 38. Productivity throughout the day – December

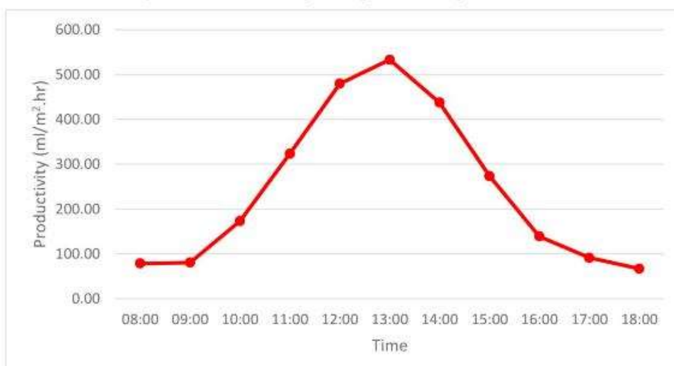

Figure 39. Solar intensity throughout the day – December

4. CONCLUSION

System modelling is a vital instrument in the tool box of an engineer. It allows the engineer to determine system performance characteristics, manipulate design parameters, account for design inconsistencies, prove concepts, compare against other forms of modelling etc. – the possibilities are vast. Solar distillation is a common method of desalination. Methods such as reverse osmosis are often favoured for their large scale productivity. Key factors such as climatic conditions, design specifications and operational parameters have to be accounted for and tailored to fit the desired application. A mathematical model for solar distillation in Durban, South Africa was solved using MATLAB to verify the glass, water and ambient temperature while the still productivity and solar intensity was also noted. System midday productivity was at its maximum in February and minimum in June. The graphical representation of the glass and basin water temperatures for all months showed a similar picture in terms of the bell-shaped rise and fall in temperature across the day.

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NOMENCLATURE

Symbol	Description	Unit
A	Area	m^2
C	Heat capacity	J/K
h_{fg}	Latent heat of evaporation	$W/m^2.K$
h	Heat transfer coefficient	$W/m^2.K$
I	Solar Radiation Intensity	W/m^2
P	Partial pressure	mm of Hg
q	Heat transfer rate	W
T	Temperature	K
U	Heat transfer coefficient between two mediums	$W.m^2.K$
ε	Absorptance	None
ϵ	Emittance	None
o	Optical efficiency	None
H	Monthly average of daily radiation	kJ/m^2. day
ω	Hour angle	Degree
s	Sunset hour angle	Degree
β	Slope angle	Degree
φ	Latitude	Degree
γ	Surface azimuth angle	Degree
δ	Declination angle	Degree
θ	Inclination angle	Degree
K_T	Clearness index	None
	Subscripts	
g	Glass cover	
w	Water in basin	
c	Convective	
r	Radiation	
e	Evaporation	
s	Sky	
t	Between water and glass cover	
o	Between glass cover and environment	
d	Diffuse	
z	Zenith	

8.1 Discussion

The analytical mathematical model was solved by two MATLAB programs i.e. g_t.m and Main_Program.m. The algorithms and code used can be found in Appendix C. The programs employed an iterative approach in the solution of the mathematical model. Solar still design theory is first described and categorised in climatic conditions, design specifications and operational parameters, as noted in Figure 1 of the Chapter 8 journal article "*Design Theory and Analytical Analysis of a Solar Still*" – which is accepted and to be published by the International Journal of Mechanical Engineering and Technology. The analytical model presented in section 2.2 of Chapter 8 was solved through the use of two MATLAB programs, as seen in Appendix C.1. The results obtained from the model include the following performance indices: evaporative water temperature, glass cover temperature, ambient temperature, productivity and solar intensity. These are achieved by modelling the generic solar still seen in Figure 2 by the thermal network found in Figure 3. The analytical model was specific to Durban, South Africa, on the 15th of each month between 8 am and 6 pm. The solar radiation empirical constants A, B and C, listed in Table 1, were taken for the eastern seaboard of South African in 2007 while the monthly Clearness Factors (K_T) in 2011 for Durban, from Table 2, were also utilised in the solution of the mathematical model. The system temperature i.e. evaporative, glass cover and ambient temperatures were plotted on the same set of axes for each month of the year in Figure 4 to Figure 39 while the results of each month can be found in Table 3 to Table 14. The first (January and February) and last two months (November and December) of the year recorded the highest temperatures for the analytical model. This can be expected as this coincides with the late spring and summer months in the southern hemisphere. Looking at the shape of the evaporative and glass cover temperature graphs, a bell shape relationship between time and temperature can be noted. Ambient temperature, however, expressed a more linear shape. An unanticipated still behavioural characteristic can be seen in the temperature vs. time plots; both evaporative water and glass cover temperature decrease after solar zenith at approximately 1 pm irrespective of ambient temperature remaining almost constant after this time. A proposed hypothesis related to this is: still productivity is more dependent on solar position i.e. direct solar radiation and minimal shadow, as opposed to ambient temperature. The still productivity plot across all 12 months displayed a similar smooth bell-shaped graph. Still productivity, much like the evaporative water and glass cover temperature, was at its maximum at 1 pm while the minimum productivity rate occurred either at 8 am or 6 pm. Solar intensity shared a similar graphical shape (bell shaped) but there was a much more drastic increase between 10 am to 12 pm and decrease between 2 pm and 4 pm. Much like the still temperatures and productivity, the maximum solar intensity occurred at 1 pm. The drastic increase and decrease of solar intensity were noted to be a factor attributable to the unanticipated still temperature characteristics. 70.33 °C and 54.66 °C were the maximum and minimum evaporative water temperatures at 1 pm in February and June respectively. The highest glass cover temperature at 1 pm occurred in November at 66.94 °C while June glass temperature was the lowest measuring 51.47 °C. A maximum solar intensity of 888.16 kW/m^2 at 1 pm was a recorded in February while the minimum value occurred in June with 689.89 kW/m^2. Solar zenith still productivity peaked at 554.54 ml/m^2.hr in February but only managed 283.60 ml/m^2.hr in June.

8.2 Summary of chapter

This chapter provided the theory behind the analytical model of the solar still. The performance indices, design considerations and operational parameters for the analytical model were described while the analytical mathematical model was derived. Results from the analytical model were summarised and provided in a table and/or graphical format. The results were considered and outcomes noted.

CHAPTER 9: DESIGN THEORY AND COMPUTATIONAL ANALYSIS OF A SOLAR STILL

This chapter provides the theory behind computational modelling of the solar still. The design theory behind a Computational Fluid Dynamics (CFD) simulation is provided and simplified for a heat transfer model. The simulation process for an ANSYS® CFD model is included and the results of the computational model are evaluated. The article has been published in the International Journal of Mechanical Engineering and Technology, IAEME Publications.

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DESIGN THEORY AND COMPUTATIONAL ANALYSIS OF A SOLAR STILL

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ABSTRACT

Over the last decade, computational modelling has become a more reliable and notable tool in the arsenal available to engineers. However, due to lack of training and information available, engineers prefer using more conventional analytical approaches to design, model and analyze desired systems. This research article describes the design theory, mathematical model employed by computational software and modelling process utilized in the three dimensional multiphase heat and mass transfer model of a double slope solar still. The double slope solar still performance results obtained from the computational analysis are summarized and graphed.

Keywords: Solar still, computational modelling, CFD, ANSYS

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1. INTRODUCTION

Computational Fluid Dynamics (CFD) software is a powerful tool available to engineers to design, model and analyze desired systems. The computational software makes use of simplified physical governing equations to solve mathematical models numerically. A good understanding of the theory behind computational models and the mathematical models employed are necessary for an individual to accurately utilize such software packages. It is crucial for computational software users to eliminate avoidable errors while also minimizing unavoidable errors. The basis of flow models stems from the Navier-Stokes Equations, which can be coupled to heat transfer models to simulate phase changes in a solar still. The choice of meshing elements is essential in ensuring the reliable modelling of a desire system. Design by computational model can provide a useful tool to which analytical and experimental results are compared.

2. DESIGN THEORY

Three are three fundamental physical principles that govern and are used to model flows in Computational Fluid Dynamics, namely [1]:

1. The conversation of mass
2. The conversation of momentum
3. The conversation of energy

The unity of principle one and two i.e. continuity and momentum equation yields the Navier-Stokes Equations.

The principles are generic for an infinitesimal volume in Cartesian coordinates and are given for:

- Viscous fluid
- Compressible flow
- Newtonian fluid
- Three-dimensional flow
- Unsteady state

The conversation of mass equation (Continuity Equation):

$$\frac{\partial \rho u}{\partial x}+\frac{\partial \rho v}{\partial y}+\frac{\partial \rho w}{\partial z}+\frac{\partial \rho}{\partial t}=0 \quad (1)$$

The conversation of momentum equation (Momentum Equation):

In the X-direction:

$$\rho\frac{Du}{Dt}=\rho g_x-\frac{\partial \rho}{\partial x}+\frac{\partial}{\partial x}\left[\mu\left(2\frac{\partial u}{\partial x}-\frac{2}{3}\mu\left(\frac{\partial u}{\partial x}+\frac{\partial v}{\partial y}+\frac{\partial w}{\partial z}\right)\right)\right]+\frac{\partial}{\partial y}\left[\mu\left(\frac{\partial u}{\partial y}+\frac{\partial v}{\partial x}\right)\right]+\frac{\partial}{\partial z}\left[\mu\left(\frac{\partial u}{\partial z}+\frac{\partial w}{\partial x}\right)\right] \quad (2)$$

In the Y-direction:

$$\rho\frac{Dv}{Dt}=\rho g_y-\frac{\partial \rho}{\partial y}+\frac{\partial}{\partial x}\left[\mu\left(2\frac{\partial u}{\partial y}+\frac{\partial v}{\partial x}\right)\right]+\frac{\partial}{\partial y}\left[\mu\left(2\frac{\partial v}{\partial y}-\frac{2}{3}\mu\left(\frac{\partial u}{\partial x}+\frac{\partial v}{\partial y}+\frac{\partial w}{\partial z}\right)\right)\right]+\frac{\partial}{\partial z}\left[\mu\left(\frac{\partial v}{\partial z}+\frac{\partial w}{\partial y}\right)\right] \quad (3)$$

In the Z-direction:

$$\rho\frac{Dw}{Dt}=\rho g_z-\frac{\partial \rho}{\partial z}+\frac{\partial}{\partial x}\left[\mu\left(2\frac{\partial u}{\partial z}+\frac{\partial v}{\partial x}\right)\right]+\frac{\partial}{\partial y}\left[\mu\left(\frac{\partial v}{\partial z}+\frac{\partial w}{\partial y}\right)\right]+\frac{\partial}{\partial z}\left[\mu\left(2\frac{\partial w}{\partial x}-\frac{2}{3}\mu\left(\frac{\partial u}{\partial x}+\frac{\partial v}{\partial y}+\frac{\partial w}{\partial z}\right)\right)\right] \quad (4)$$

The conversation of energy (Energy Equation):

The energy equation is utilized when a flow experiences a change in internal energy.

$$\frac{\partial(\rho i)}{\partial t}+\frac{\partial(\rho i u)}{\partial t}+\frac{\partial(\rho i v)}{\partial t}+\frac{\partial(\rho i w)}{\partial t}=-p\left(\frac{\partial u}{\partial x}+\frac{\partial v}{\partial y}+\frac{\partial w}{\partial z}\right)+\frac{\partial}{\partial x}\left(\kappa\frac{\partial T}{\partial x}\right)\frac{\partial}{\partial y}\left(\kappa\frac{\partial T}{\partial x}\right)\frac{\partial}{\partial z}\left(\kappa\frac{\partial T}{\partial x}\right)+\Phi+S_i \quad (5)$$

Equations of state

Equations of state for an ideal gas (or gas modelled as an ideal gas) are given below by Eq. (6) and Eq. (7). These are introduced to help solve for the unknowns of the above equations i.e. (i, T, p, u, v, w, ρ).

$$p=\rho RT \quad (6)$$

$$i=c_vT \quad (7)$$

2.1. Computational Model for Passive Single/Double Slope Solar Still using a Simplified Heat Transfer Model

A passive still works on the principle of natural convection. Within the still there is both a concentration and temperature gradient acting simultaneously. To access the heat transfer within the still and simplify the Navier-Stokes Equations certain assumptions can be made regarding the nature of flow within the system, namely [2]:

- Two-dimensional (2D) flow
- Steady state (not time dependent0
- Laminar flow
- Inviscid fluid
- Humid air modelled as an ideal gas
- Walls are adiabatic
- The water surface and glass cover temperature is constant

Using the above assumptions, a simplified heat transfer model can be found. This model will be coupled with the Navier-Stokes Equations by a given computational software to model the heat and mass transfer within a solar still system [3–5].

$$\frac{\partial U}{\partial X} + \frac{\partial V}{\partial Y} = 0 \quad (8)$$

$$U\frac{\partial U}{\partial X} + V\frac{\partial U}{\partial Y} = -\frac{\partial P}{\partial X} + Pr\left(\frac{\partial^2 U}{\partial X^2} + \frac{\partial^2 U}{\partial Y^2}\right) \quad (9)$$

$$U\frac{\partial V}{\partial X} + V\frac{\partial V}{\partial Y} = -\frac{\partial P}{\partial Y} + Pr\left(\frac{\partial^2 V}{\partial X^2} + \frac{\partial^2 V}{\partial Y^2}\right) + Ra\ \times Pr(0 + Br \times C) \quad (10)$$

$$U\frac{\partial \theta}{\partial X} + V\frac{\partial \theta}{\partial Y} = \frac{\partial^2 \theta}{\partial X^2} + \frac{\partial^2 \theta}{\partial Y^2} \quad (11)$$

$$U\frac{\partial C}{\partial X} + V\frac{\partial C}{\partial Y} = \frac{1}{Le}\left(\frac{\partial^2 U}{\partial X^2} + \frac{\partial^2 U}{\partial Y^2}\right) \quad (12)$$

The dimensionless variables can be noted as:

$$X = \frac{x}{L}\ ;\ Y = \frac{y}{L};\ U = \frac{uL}{v};\ V = \frac{vL}{v};\ P = \frac{pL^2}{\rho v^2} \quad (13)$$

Dimensionless temperature:

$$\theta = \frac{T - T_g}{T_w - T_g} \quad (14)$$

Dimensionless concentration:

$$C = \frac{c - c_g}{c_w - c_g} \quad (15)$$

The Prandtl number can be found using:

$$Pr = \frac{v}{\alpha} \quad (16)$$

Rayleigh number is given by:

$$Ra = \frac{g\beta_t(T_w - T_g)L^3}{\alpha v} \quad (17)$$

Lewis number is:

$$Le = \frac{\alpha}{D} = \frac{Sc}{Pr} \quad (18)$$

The ratio of buoyancy:

$$Br = \frac{\beta_c(c_w - c_g)}{\beta_t(T_w - T_g)} \quad (19)$$

Where:

$$\beta_t = -\frac{1}{\rho_o}\left(\frac{\partial \rho_o}{\partial T}\right)_P \tag{20}$$

And

$$\beta_c = -\frac{1}{\rho_o}\left(\frac{\partial \rho_o}{\partial C}\right)_P \tag{21}$$

If the following about the Prandtl and Lewis number is true:

$$(0.700 < Pr < 0.707)\ and\ (0.865 < Le < 0.931)$$

Then the boundary conditions for a single or double slope solar still are as follows:

For the glass cover:

$$U = V = 0\ ;\ \theta = C = 0 \tag{22}$$

For the still bottom:

$$U = V = 0\ ;\ \theta = C = 1 \tag{23}$$

For the side walls:

$$U = V = 0\ ;\ \frac{\partial \theta}{\partial x} = 0\ ;\ \frac{\partial C}{\partial x} = 0 \tag{24}$$

Using the simplification of the generic heat transfer model seen above, Computational Fluid Dynamics Software can then model the natural convection heat transfer within the double slope solar still. Computational software such as ANSYS® and Siemens NX® are capable of coupling fluid flow, heat transfer and state change models to simulate various systems. Key quantities such as the rate of product formation can be computed and compared against theoretical values attained through the analytical mathematical model procedure.

3. MODEL SETUP

3.1. Generic Modelling Process

ANSYS® was chosen as the computational software to model the solar still as it is readily available and has sufficient resources for students at the University of KwaZulu-Natal.

The process of computational modelling begins with an initial engineering problem statement and ends with the analysis/validation of results obtained from the simulation. The following series of steps can be followed from start to end:

Step 1: Examination of the problem statement

Step 2: Preparation of the geometry

- Utilization of Computer Aided Design (CAD) software, or drawing function within computational software, to model the flow path/geometry

Step 3: Pre-processing

- Import the geometrical CAD model into the computational software
- Select and generate a mesh
- Specification of discretization parameters
- Select the type of physical model
- Provide material properties
- Specification of initial and boundary conditions
- Selection of solver and related solution parameters

Step 4: Solve Model

- Allow the computational software to solve the model set up to a desired number of iterations, amount of time, convergence etc.

Step 5: Post-processing

- The retrieval and qualitative review of the results obtained
- Quantitative measurements, data extraction, graph and image generation

Step 6: Authentication of results

- Verifying the validity of the result acquired through the computational model

3.2. Specific Modelling Process

ANSYS® 2018 academic version was utilized to carry out the three-dimensional multiphase heat and mass transfer model to simulate a double slope solar still. The method utilized to set up the simulation is described while the simulation outcome screenshots are also provided (Table 1).

Table 1 ANSYS® Fluent model description

Step	Action description
1	Analysis system • Fluid flow (Fluent)
2	Geometry • Import geometry (.IGES file drawn on CAD file)
3	Mesh • Generate mesh ➢ Default ❖ Element order – Change to quadratic ❖ Element size – 10 mm ➢ Sizing ❖ Use adaptive sizing – Yes ❖ Span angle centre – Fine ❖ Minimum edge length – 10 mm ➢ Quality ❖ Smoothing – Medium ➢ Geometry ❖ Rename still components ▪ Glass 1 ▪ Glass 2 ▪ Sidewall 1 ▪ Sidewall 2 ▪ Frontwall ▪ Backwall ▪ Absorber-plate
4	Setup • General ➢ Time ❖ Change to Transient ➢ Gravity ❖ Enable ❖ Y (m/s^2) = -9.81 • Model ➢ Multiphase

- Volume of fluid
  - Enable
- Number of Eulerian phase
  - Change to 3
- Scheme
  - Change to implicit

- Energy
  - Energy equation
    - Enable
- Viscous
  - Change to K-epsilon
  - K-epsilon Model
    - Change to RNG
- Radiation
  - Discrete Transfer Radiation Model (DTRM)
    - Enable
  - Solar load
    - Solar ray tracing
      - Enable
  - Illumination parameter
    - Direct solar irradiation (W/m^2)
      - Change to solar calculator
    - Diffuse solar irradiation (W/m^2)
      - Change to solar calculator
  - Solar calculator
    - Global position (Durban)
      - Latitude = -29.8587^{O}
      - Longitude = 31.0218^{O}
      - GMT = +2
    - Mesh orientation

	North	East
X	-1	0
Y	0	0
Z	0	-1

- Materials
  - Fluid
    - Fluent database
      - Select water-vapour
      - Select water-liquid
    - Water-vapour
      - Density
        - Change to incompressible ideal gas
    - Water-liquid
      - Density
        - Change to piecewise-linear
        - Increase points to 12

Points	Temperature (K)	Density (kg/m^3)
1	293	998
2	303	995
3	313	992
4	323	988
5	333	983
6	343	978

7	353	972
8	363	965
9	373	958
10	383	951
11	393	943
12	403	935

- Solid
  - Fluent database
    - Select stainless steel
    - Select glass
  - Glass
    - Chemical formula
      - Chang to "gl"
    - Density
      - Change to 2500
    - Cp
      - Change to 750
    - Thermal conductivity
      - Change to 1.15
- Phases
  - Phase 1 – Primary phase
    - Select phase material – air
    - Rename as "air"
  - Phase 2 – Secondary
    - Select phase material – water-liquid
    - Rename as "water"
  - Phase 3 – Secondary
    - Select phase material – water-vapour
    - Rename as "vapour"
  - Define
    - Units
      - Surface tension (dyn/cm)
  - Interaction
    - Mass
      - Number of mass transfer mechanisms
        - Increase to 2
      - From water to vapour
        - evaporation-condensation
      - From vapour to water
        - evaporation-condensation
    - Surface tension
      - Surface tension force modelling
        - Enable
      - Adhesion options
        - Select wall adhesion
      - Surface tension coefficients

From	To	Option	Value
water	air	constant	73
vapour	air	constant	73
vapour	water	constant	73

- Boundary Conditions
  - Absorber-plate
    - Radiation

- BC type
  - Opaque
- Participates in solar ray tracing
  - Enable

- Backwall
  - Thermal
    - Material
      - Select stainless steel
    - Thermal conditions
      - Change to convection
    - Heat transfer
      - Change to 3
  - Radiation
    - Participates in solar ray tracing
      - Enable
- Frontwall
  - Thermal
    - Material
      - Select stainless steel
    - Thermal conditions
      - Change to convection
    - Heat transfer
      - Change to 3
  - Radiation
    - Participates in solar ray tracing
      - Enable
- Sidewall 1
  - Thermal
    - Material
      - Select stainless steel
    - Thermal conditions
      - Change to convection
    - Heat transfer
      - Change to 3
  - Radiation
    - Participates in solar ray tracing
      - Enable
- Sidewall 2
  - Thermal
    - Material
      - Select stainless steel
    - Thermal conditions
      - Change to convection
    - Heat transfer
      - Change to 3
  - Radiation
    - Participates in solar ray tracing
      - Enable
- Glass 1
  - Thermal
    - Material
      - Select glass
    - BC Type
      - Semi-transparent
    - Absorptivity

	o Change to 0.1 ▪ Transmissivity o Change to 0.8 ❖ Radiation ▪ Participates in solar ray tracing o Enable ➢ Glass 2 ❖ Thermal ▪ Material o Select glass ▪ BC Type o Semi-transparent ▪ Absorptivity o Change to 0.1 ▪ Transmissivity o Change to 0.8 ❖ Radiation ▪ Participates in solar ray tracing o Enable
5	Initialize • Standard initialization ➢ Enable • Patch ➢ Change to water ➢ Volume fraction ❖ Change to 1 ➢ Register ❖ Change to Patch-hexahredron-ro
6	Run calculation • Time step size (s) ➢ Change to 30 • Number of time steps ➢ Change to 120 • Max iteration/time step ➢ Change to 10 • Calculate
7	Results • Contour ➢ Contours ❖ Select temperature ❖ Select total temperature

3.2.1. Simulation Outcomes

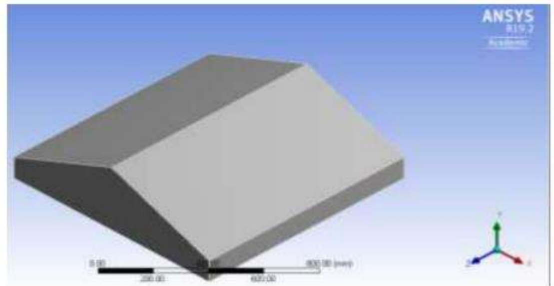

Figure 1 Still geometry

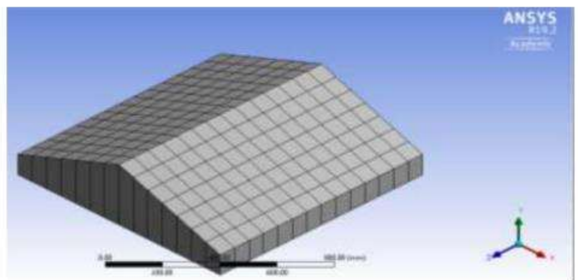

Figure 2 Initial still mesh

Table 2 Initial still mesh statistics

Mesh Components	Number
Nodes	450
Elements	196

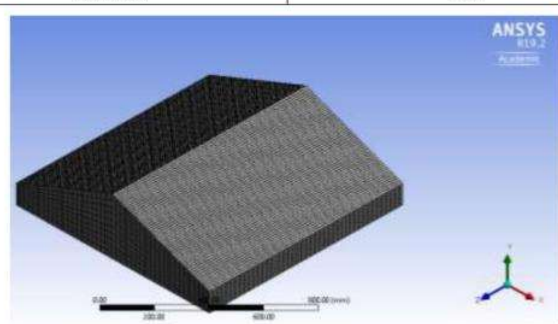

Figure 3 Refined still mesh

Table 3 Refined still mesh statistics

Mesh Components	Number
Nodes	453749
Elements	104000

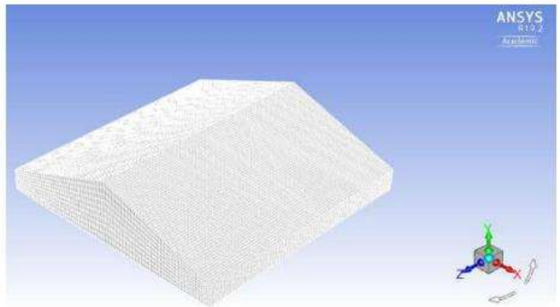

Figure 4 Still wireframe mesh

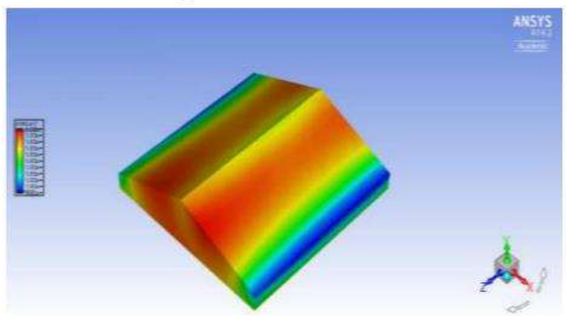

Figure 5 Still temperature profile (December)

4. RESULTS

The computation model was set up to simulate the performance characteristics of the boiler still on the 15th day of each month from 8 am to 6 pm. The results obtained are specific to the city of Durban, South Africa for solar irradiance conditions in 2018 as per ANSYS® Fluent DTRM. The results extracted from the ANSYS® simulation include:

1. Evaporative water temperature
2. Glass cover temperature
3. Productivity

4.1. January System Performance – Computational model

Table 4 January computational performance results

Month	Time of day	Evaporative water temperature (°C)	Glass cover temperature (°C)	Productivity (ml/m².hr)
January	08:00	24.0000	24.0000	61.9063
	09:00	28.2552	30.4873	75.1490
	10:00	37.8891	42.3150	160.4856
	11:00	51.9186	55.6978	303.9853
	12:00	61.4149	68.3698	460.1492
	13:00	64.3405	70.2546	520.7126
	14:00	60.0605	64.2158	461.7413
	15:00	54.3259	55.6941	369.1020
	16:00	46.8736	45.2130	289.1430
	17:00	37.2368	35.2600	158.0489
	18:00	28.0358	23.8715	96.8104

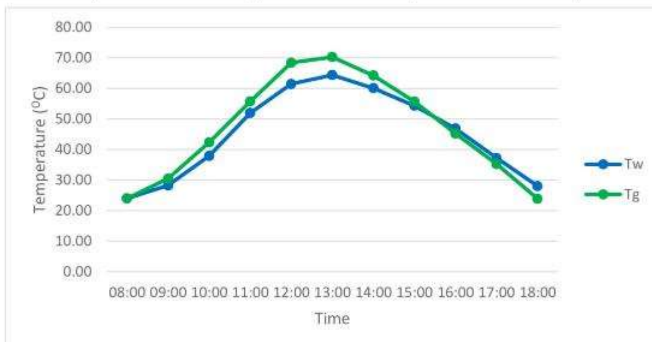

Figure 6 Computational still temperatures throughout the day – January

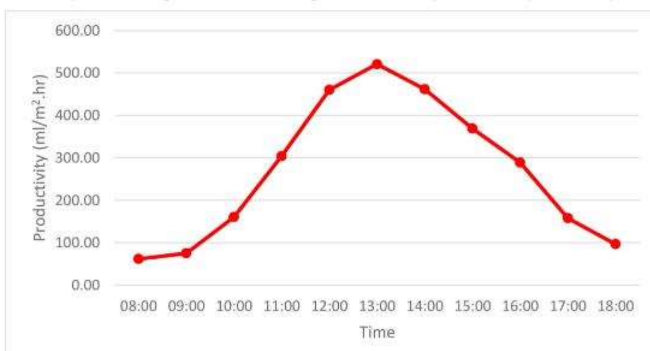

Figure 7 Computational productivity throughout the day – January

4.2. February System Performance – Computational model

Table 5 February computational performance results

Month	Time of day	Evaporative water temperature (^oC)	Glass cover temperature (^oC)	Productivity ($ml/m^2.hr$)
February	08:00	24.0000	24.0000	61.9063
	09:00	27.2679	29.5000	78.5080
	10:00	36.9018	41.3277	163.8446
	11:00	50.9313	54.7105	307.3443
	12:00	60.4276	67.3825	453.2071
	13:00	64.9985	70.9126	513.7705
	14:00	60.7185	64.8738	466.1093
	15:00	54.9839	56.3521	373.4700
	16:00	46.2156	47.5550	293.5110
	17:00	36.5788	35.6020	155.4583
	18:00	27.3778	25.2135	79.0244

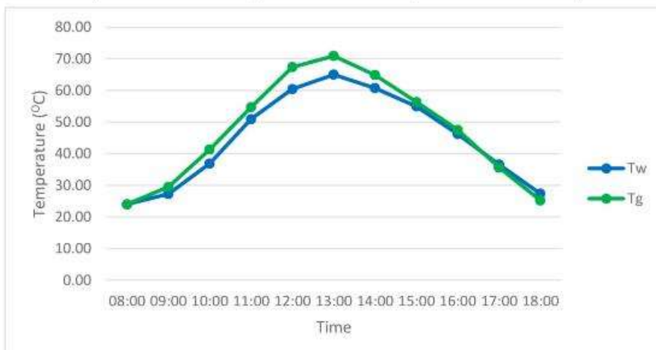

Figure 8 Computational still temperatures throughout the day – February

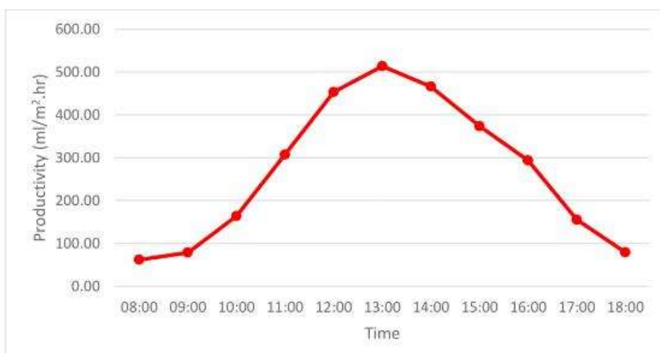

Figure 9 Computational productivity throughout the day – February

4.3. March System Performance – Computational model

Table 6 March computational performance results

Month	Time of day	Evaporative water temperature (°C)	Glass cover temperature (°C)	Productivity (ml/m².hr)
March	08:00	23.0000	23.0000	65.4044
	09:00	27.1421	29.3742	82.0061
	10:00	36.7760	41.2019	167.3427
	11:00	50.9313	54.7105	308.4602
	12:00	61.9345	68.8894	454.3230
	13:00	66.5054	72.4195	504.8864
	14:00	62.2254	66.3807	466.1093
	15:00	54.6569	56.0251	370.4899
	16:00	42.8886	47.2280	268.5309
	17:00	34.2518	37.2750	148.5793
	18:00	26.0508	26.8865	72.1454

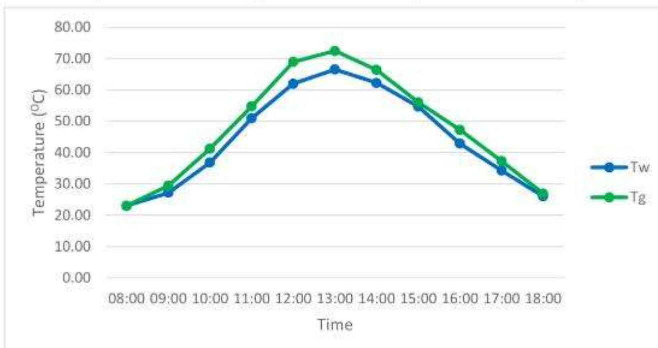

Figure 10 Computational still temperatures throughout the day – March

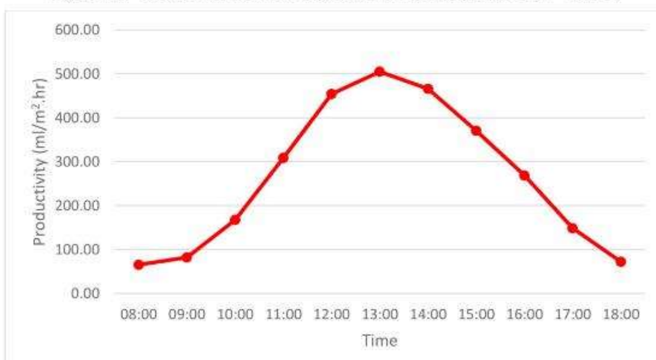

Figure 11 Computational productivity throughout the day – March

4.4. April System Performance – Computational Model

Table 7 April computational performance results

Month	Time of day	Evaporative water temperature (°C)	Glass cover temperature (°C)	Productivity (ml/m².hr)
April	08:00	23.0000	23.0000	63.1460
	09:00	24.4549	27.6870	76.1583
	10:00	32.0888	39.5147	164.5822
	11:00	47.2441	53.0233	304.7124
	12:00	61.4758	68.4307	454.3230
	13:00	66.0467	71.9608	482.6957
	14:00	61.7667	65.9220	423.8700
	15:00	52.6568	56.0250	339.6671
	16:00	40.8885	45.2279	212.8201
	17:00	31.3060	34.3292	80.9529
	18:00	23.1050	23.9407	59.7905

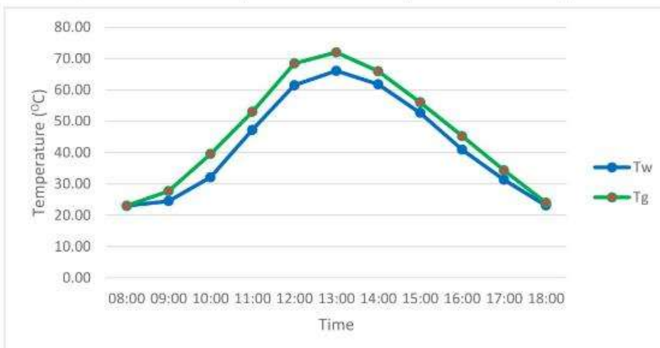

Figure 12 Computational still temperatures throughout the day –April

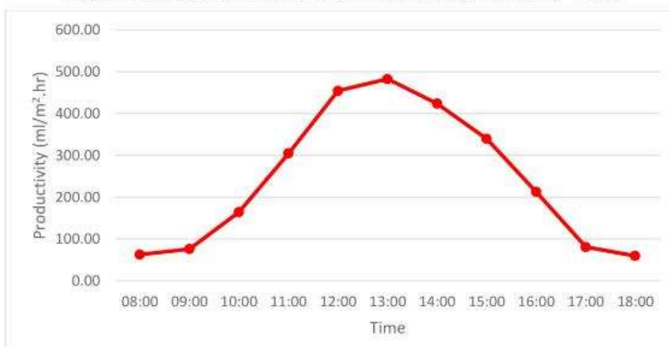

Figure 13 Computational productivity throughout the day – April

4.5. May System Performance – Computational model

Table 8 May computational performance results

Month	Time of day	Evaporative water temperature (°C)	Glass cover temperature (°C)	Productivity (ml/m².hr)
May	08:00	23.0000	23.0000	60.9867
	09:00	24.1334	23.3613	70.9990
	10:00	31.7673	35.1890	159.4229
	11:00	46.9226	48.6976	283.7312
	12:00	58.9938	64.1050	433.3418
	13:00	63.5647	67.6351	461.7145
	14:00	59.2847	61.5963	402.8888
	15:00	51.6539	51.6993	290.7461
	16:00	39.8856	40.9022	163.8991
	17:00	22.3248	28.0035	59.9079
	18:00	18.1238	19.6150	38.7455

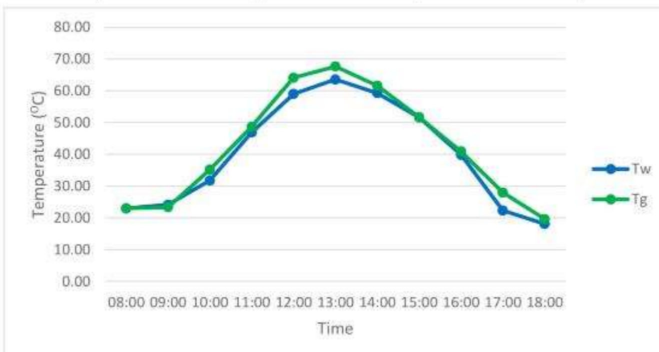

Figure 14 Computational still temperatures throughout the day – May

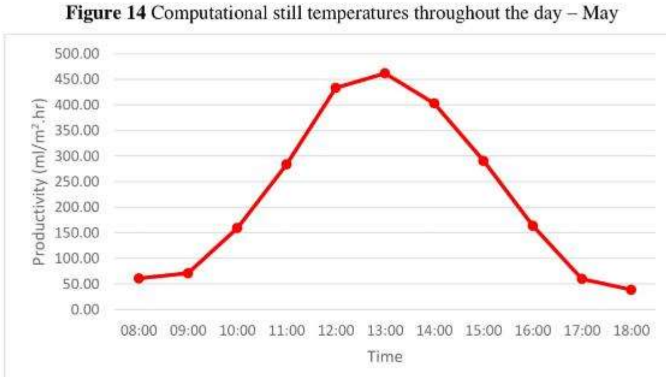

Figure 15 Computational productivity throughout the day – May

4.6. June System Performance – Computational model

Table 9 June computational performance results

Month	Time of day	Evaporative water temperature (^{O}C)	Glass cover temperature (^{O}C)	Productivity ($ml/m^2.hr$)
June	08:00	21.0000	21.0000	51.6353
	09:00	23.2611	23.3613	61.6476
	10:00	30.8950	28.6159	118.4986
	11:00	46.0503	47.0870	242.8069
	12:00	53.8682	52.6271	304.6957
	13:00	58.4391	59.0234	333.0684
	14:00	54.1591	52.8140	274.2427
	15:00	48.7246	49.3311	232.1314
	16:00	36.9563	34.0587	105.2844
	17:00	19.5508	18.6045	52.9711
	18:00	15.3498	15.1222	31.0452

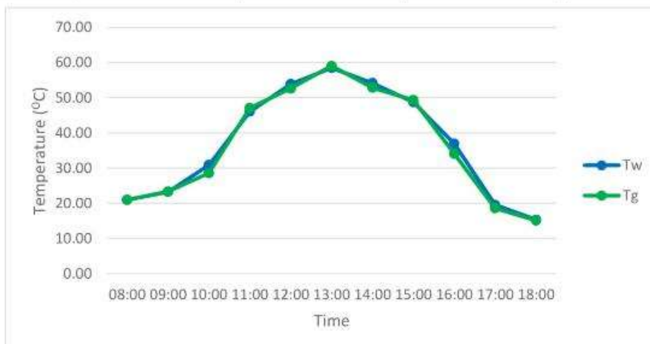

Figure 16 Computational still temperatures throughout the day – June

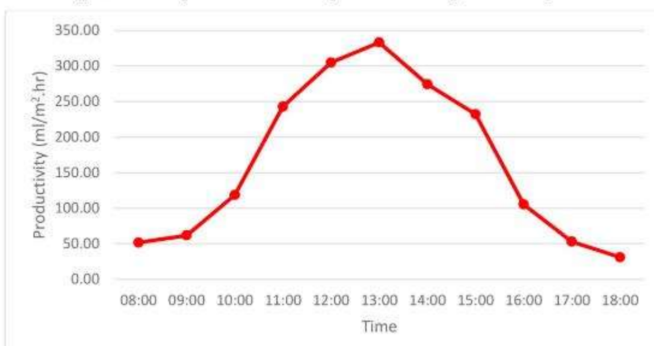

Figure 17 Computational productivity throughout the day – June

4.7. July System Performance – Computational model

Table 10 July computational performance results

Month	Time of day	Evaporative water temperature (°C)	Glass cover temperature (°C)	Productivity ($ml/m^2.hr$)
July	08:00	20.0000	20.0000	49.2605
	09:00	22.6921	22.3941	59.2728
	10:00	30.3218	27.9982	96.2629
	11:00	45.9627	47.0870	201.9289
	12:00	53.1159	51.9215	286.0534
	13:00	56.9871	52.1473	314.4261
	14:00	53.9658	51.0028	270.0533
	15:00	44.4435	41.8720	197.9420
	16:00	32.8470	29.2935	99.8428
	17:00	18.2471	16.3966	47.6234
	18:00	14.9313	14.5474	29.4712

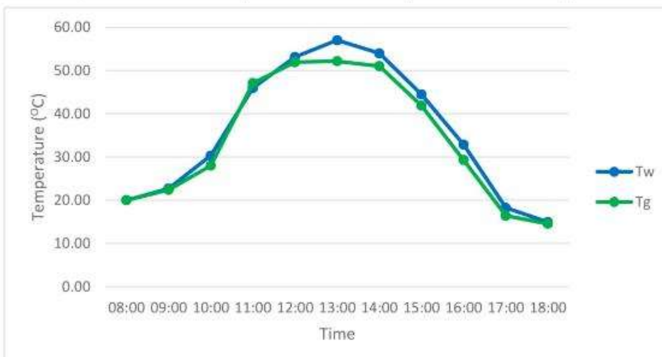

Figure 18 Computational still temperatures throughout the day – July

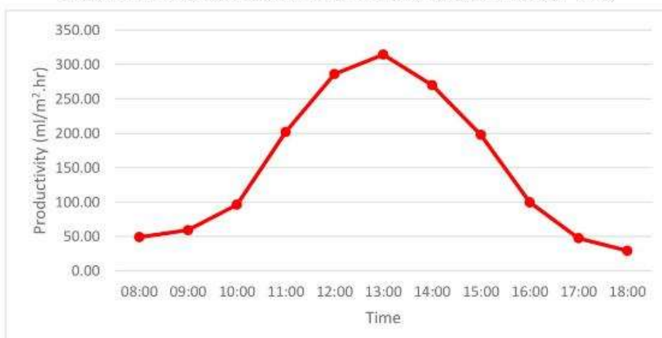

Figure 19 Computational productivity throughout the day – July

4.8. August System Performance – Computational model

Table 11 August computational performance results

Month	Time of day	Evaporative water temperature (°C)	Glass cover temperature (°C)	Productivity (ml/m².hr)
August	08:00	21.0000	21.0000	51.9877
	09:00	26.3399	27.0419	62.7435
	10:00	36.0816	38.7580	116.7412
	11:00	48.0747	49.1990	201.9289
	12:00	56.0887	56.8943	314.4637
	13:00	59.9599	60.1201	342.8364
	14:00	56.9386	57.9756	308.0511
	15:00	48.6613	49.0898	197.9420
	16:00	37.0648	36.5113	104.7839
	17:00	23.1436	21.2931	58.6947
	18:00	19.8278	18.4439	51.9725

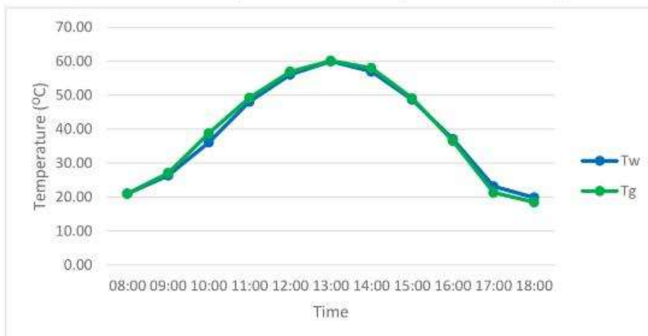

Figure 20 Computational still temperatures throughout the day – August

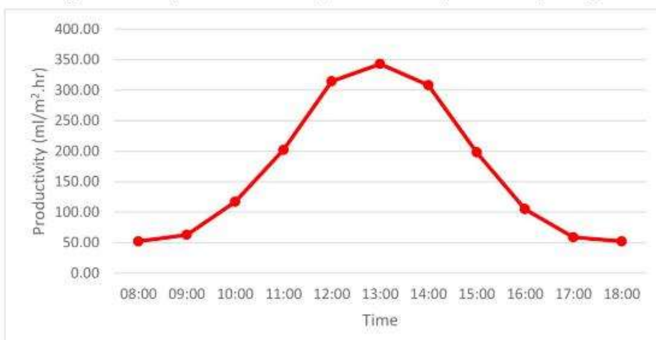

Figure 21 Computational productivity throughout the day – August

4.9. September System Performance – Computational model

Table 12 September computational performance results

Month	Time of day	Evaporative water temperature (^oC)	Glass cover temperature (^oC)	Productivity ($ml/m^2.hr$)
September	08:00	23.0000	23.0000	62.8715
	09:00	30.0522	29.3502	79.6843
	10:00	42.7683	39.0919	138.5707
	11:00	59.1465	57.0222	258.9471
	12:00	67.8418	65.0362	410.3678
	13:00	72.0676	68.9074	486.2173
	14:00	66.9231	65.8861	412.9713
	15:00	58.6467	54.2182	289.3600
	16:00	41.0682	42.6217	243.3100
	17:00	26.2251	28.0756	96.3217
	18:00	23.3759	24.7598	78.3914

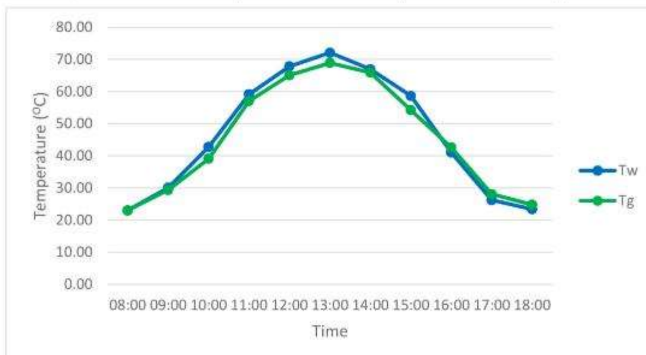

Figure 22 Computational still temperatures throughout the day – September

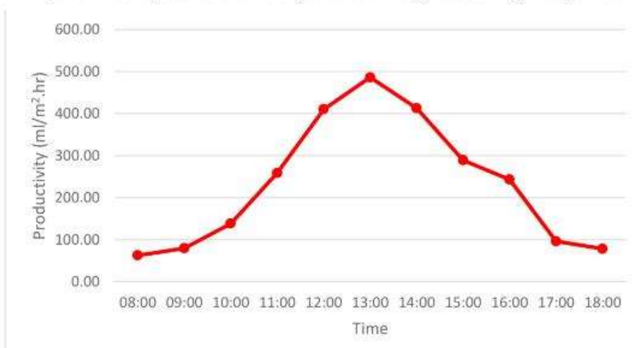

Figure 23 Computational productivity throughout the day – September

4.10. October System Performance– Computational model

Table 13 October computational performance results

Month	Time of day	Evaporative water temperature (^{O}C)	Glass cover temperature (^{O}C)	Productivity ($ml/m^2.hr$)
October	08:00	25.0000	25.0000	65.6941
	09:00	31.0394	29.5856	80.0039
	10:00	43.7555	39.3273	137.1283
	11:00	60.1337	57.0222	278.9514
	12:00	68.1106	66.0225	487.8713
	13:00	72.3364	69.8937	530.1783
	14:00	67.1919	66.8724	463.7810
	15:00	59.4300	53.7397	285.0159
	16:00	41.8515	40.1432	196.3210
	17:00	26.3540	24.0733	82.3148
	18:00	23.5048	21.7575	72.3783

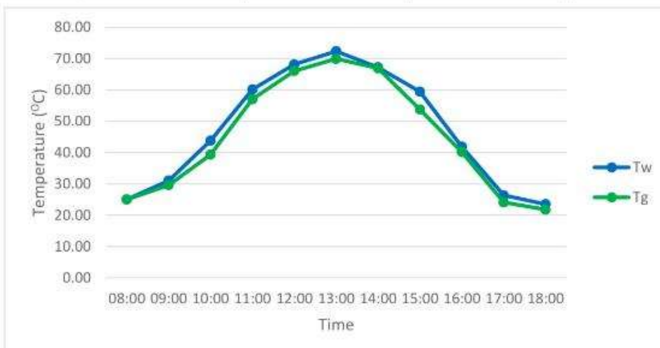

Figure 24 Computational still temperatures throughout the day – October

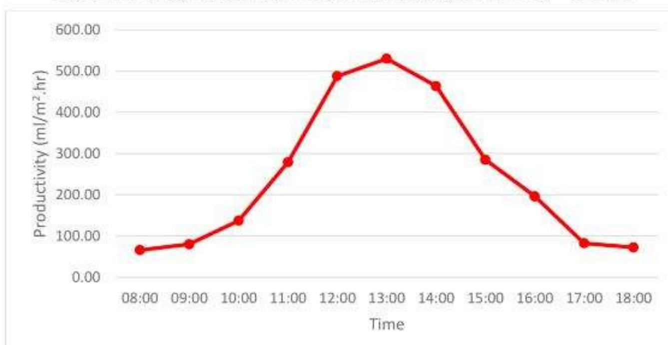

Figure 25 Computational productivity throughout the day – October

4.11. November System Performance – Computational model

Table 14 November computational performance results

Month	Time of day	Evaporative water temperature (^oC)	Glass cover temperature (^oC)	Productivity ($ml/m^2.hr$)
November	08:00	27.0000	27.0000	72.1873
	09:00	32.3504	30.0545	81.2841
	10:00	45.0665	39.7962	168.6478
	11:00	62.3009	57.4911	323.7233
	12:00	68.9668	66.4914	482.2370
	13:00	73.1926	70.3626	538.6170
	14:00	68.0481	67.3413	460.7429
	15:00	60.2862	57.2086	280.7839
	16:00	42.4388	39.6121	184.9733
	17:00	26.9413	24.5422	85.6717
	18:00	24.0921	22.2264	69.4554

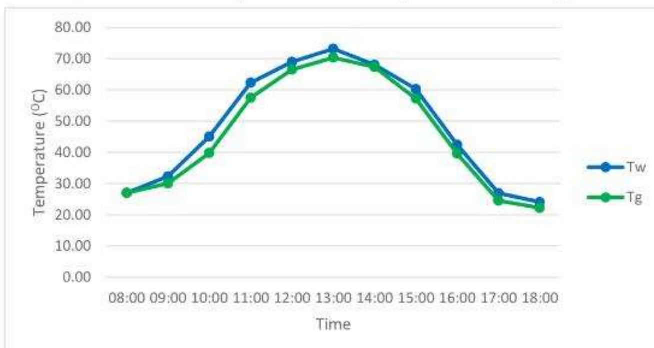

Figure 26 Computational still temperatures throughout the day – November

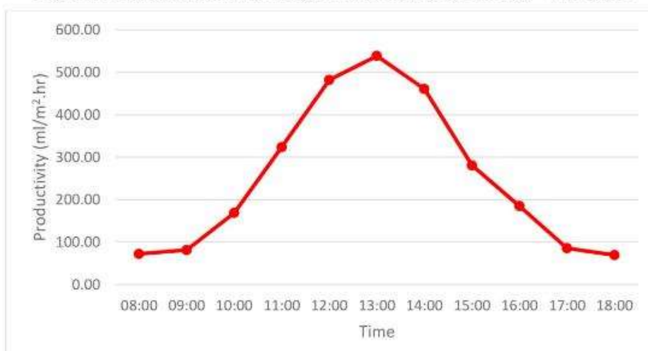

Figure 27 Computational productivity throughout the day – November

4.12. December System Performance – Computational model

Table 15 December computational performance results

Month	Time of day	Evaporative water temperature (^{O}C)	Glass cover temperature (^{O}C)	Productivity ($ml/m^2.hr$)
December	08:00	29.0000	29.0000	78.1882
	09:00	33.9475	31.6516	82.9441
	10:00	46.6636	41.3933	182.3225
	11:00	63.8980	61.0882	343.8143
	12:00	70.2065	67.7311	491.3367
	13:00	74.4323	71.6023	557.6142
	14:00	69.2878	67.5810	507.2543
	15:00	61.2732	58.1956	448.2571
	16:00	43.4258	40.5991	298.7400
	17:00	30.6385	25.2394	131.3719
	18:00	24.7893	21.9236	82.4130

Figure 28 Computational still temperatures throughout the day – December

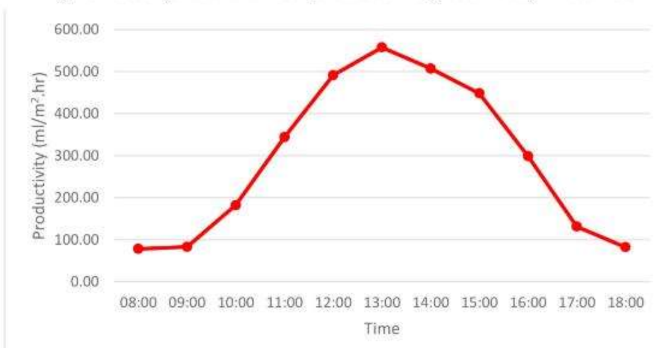

Figure 29 Computational productivity throughout the day – December

5. CONCLUSION

A three-dimensional multiphase heat and mass transfer model was carried out to simulate and understand the performance characteristics of a double slope solar still in Durban, South Africa. The evaporative water temperature, glass cover temperature and productivity of the system was recorded, summarised and graphed for the 15th day of each calendar month.

ACRONYMS

CFD – Computational Fluid Dynamics

CAD – Computer Aided Design

DTRM – Discrete Transfer Radiation Model

NOMENCLATURE

Symbols

Br = Ratio of buoyancy	P = Pressure (Pa)
C = Dimensionless concentration	Pr = Prandtl number
c_v = Molar specific heat at constant volume (J. mol. K)	R = Gas constant (J / mol. K)
g = Gravitational acceleration (m/s^{-2})	Ra = Rayleigh number
i = Internal energy (J)	Re = Reynolds number
L = Length (m)	S_i = Heat sink
Le = Lewis number	T = Temperature (K)

Greek Letters

α = Thermal diffusivity (m^2/s)	μ = Dynamic viscosity (N.s/ m^2)
β = Thermal expansion coefficient (K^{-1})	ρ = Density (kg/m^3)
θ = Dimensionless temperature	υ = Kinematic viscosity (m^2/s)
κ = Thermal conductivity (W/m. k)	Φ = Heat source

Subscript

g = Glass	w = Water

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9.1 Background

This section provides a technical background of the computational model setup in the journal article presented in Chapter 9 titled "*Design Theory and Computational Analysis of a Solar Still*". The information provided below allows for a greater understand on simulation design choices and are further discussed in Section 9.2.

9.1.1 Flow characteristics

A Computational Fluid Dynamics (CFD) simulation model is directly impacted by the following four flow characteristics [1]:

1. Compressibility
2. Laminar or turbulent flow
3. Time dependence
4. Viscous effects

9.1.1.1 Compressibility

Fluid can be regarded as either compressible or incompressible. A compressible flow is one that undergoes a considerable change in density as the fluid passes through a flow domain. The effects of fluid compressibility cannot be neglected for high speed flows. It is suggested that a fluid be regarded as compressible for Mach Numbers > 0.3. In this case, density becomes as a dependent variable in the system governing equations. Fluids that are naturally incompressible or with Mach Numbers < 0.3 can be regarded as incompressible.

9.1.1.2 Laminar or turbulent flow

A flow can be regarded as laminar, transitional or turbulent. The classification of flow can be done using the Reynolds Number (R_e) of a flow. The Reynolds Number in which a flow can be regarded as turbulent is noted in Table 9-1 [2, 3].

Table 9-1: Reynolds number flow characteristics

Flow Type	Natural Flow	Reynolds Number
Bounded Flow	Internal Flow	≥ 2300
Unbounded Flow	Around Obstacle	≥ 20000
	Along Flat Surface	≥ 500000

A turbulent flow leads to an increased heat transfer coefficient and a noticeably varied velocity profile.

9.1.1.3 Time dependence

When a flow is independent of time it is regarded as a steady state. Time dependence of a flow is regarded as an unsteady state. A steady state flow results in a consistent flow field whereas an unsteady state flow results in a changing flow field.

9.1.1.4 Viscous effects

A flow may be regarded as viscous or inviscid depending on the degree to which the viscosity of the fluid affects the nature of flow. All fluids have a viscosity however when this viscosity is low enough it can be neglected, and the fluid can be regarded as inviscid.

9.1.2 Type of error in computational analysis

Computational analysis is an approximate numerical solution and, as such, errors in the analysis may occur. Some types of errors can be avoided but others cannot. Good practice dictates that avoidable errors should be eliminated while those that cannot be avoided should be minimised. The errors that most commonly occur in computational analysis are noted in Table 9-2.

Table 9-2: Errors that occur in computational modelling

Errors that are avoidable	Errors that are not avoidable
• Physical modelling error • Iteration error • Discretisation error • Input error	• Round off error • Programming error

9.1.2.1 Time variable

Time in a computational model can be regarded as a dependent or an independent variable. As such there are three different types of time variable analyses available to be utilised in a model. These are explained below using a load placed on a beam as an example:

- Static analysis – load on the beam is not time dependent (does not vary with time).
- Quasistatic analysis – load on the beam is time dependent (varies with time) but inertial effects can still be ignored.
- Dynamic analysis – load on the beam is time dependent (varies with time) but inertial effects cannot be ignored.

9.1.2.2 Meshing elements for 3D geometries

The order of an element (i.e. first- or second-order), refers to the nature of the interpolation function used to calculate response indices between the corner nodes of an element. A first-order element interpolates such values linearly. A second-order element uses a quadratic interpolation function and hence features an extra edge-node midway between the corner nodes. Second-order elements are generally more accurate than first-order elements but are more computationally expensive (owing to the extra nodes).

There are four types of 3D meshing elements that are commonly available in ANSYS®. These four types of 3D meshing elements are summarised in Table 9-3. The types of meshing elements can be seen in Figure 9-1 [4].

Table 9-3: Types of first and second order three-dimensional meshing elements

Type	Description	Number of nodes	Number of nodes	Used for
HEX	Hexahedral shaped element	8 corner nodes (HEX8)	8 corner and 12 edge nodes (HEX20)	Acceptable for general use
TET	Tetrahedral shaped element	4 corner nodes (TET4)	4 corner and 6 edge nodes (TET10)	Used in automatic mesh generation
WED	Wedge or Prism shaped element	6 corner nodes (WED6)	6 corner and 9 edge nodes (WED15)	Used in transition area between solids
PYR	Pyramid shaped element	5 corner nodes (PYR5)	5 corner and 8 edge nodes (PYR13)	Transition area between square and triangular faced solids

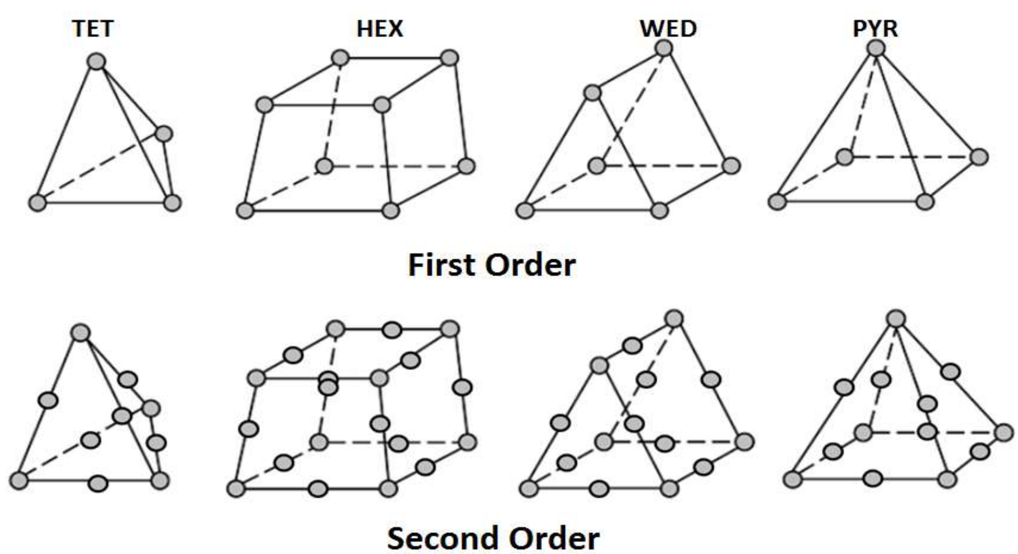

Figure 9-1: First and second order three dimensional meshes

9.2 Discussion

Background theory on flow characteristics was provided on compressibility, laminar and turbulent flow, time dependence and viscous effects. This provided the setting to understanding selections made during the solar still simulation carried out on ANSYS®. Table 9-1 summarized the Reynolds number flow characteristic. Subsequently, the error involved in computational analysis was described. Table 9-2 differentiated avoidable and unavoidable errors. Physical modelling error arises from not accurately simulating the system; this can be due to poor selection of boundary conditions, physical relationships, phases, materials and models. Discretisation error is also another major error that is avoidable and is described further in Section 9.1.2. Discretisation relates to mesh selection; the different types of first- and second-order 3D meshing elements and what they are used for are listed in Table 9-3, depicted in Figure 9-1. The solar still simulation was carried out on ANSYS® Fluent. The default mesh order was changed to quadratic and element size reduced to 10 mm as noted in Table 1 of the article titled Design Theory and Computational Analysis of a Solar Still in Chapter 9 – which is accepted and will be published in the International Journal of Mechanical Engineering and Technology. This was carried out to reduce numerical error in the solving stages, furthermore computational expense is minimised. In total the mesh consisted of 453 749 nodes and 104 000 elements as shown in Table 3. A K-epsilon turbulence model was selected as it predicts conditions such as wall boundaries. Spalart-allmaras and K-omega are better suited to aerospace and near wall conditions respectively. The radiation model selected was the Discrete Transfer Radiation Model. This was carried out by elimination as the P-1 model suffers from a lack of accuracy based on geometry, Rosseland is specific for optical density materials, the DO model cannot be used for grey radiation, while the S2S radiation method does not allow for hanging nodes. Solar ray tracing was enabled to allow for an estimation of the distribution of solar energy on the various still components e.g. basin (absorber-plate). Basin water density was selected as a piecewise function as opposed to a constant which allowed for a more realistic simulation. The time step was selected to 30 seconds and the number of time steps changes to 120. This meant that a single iteration would model 30 seconds of still operation totalling 60 minutes.

A computational model was carried out on ANSYS®. The 2018 ANSYS® Fluent DTRM academic version was used to set up the simulation on this three-dimensional heat and mass transfer model. The boiler still performance was recorded for the 15th day of every month between 8 am and 6 pm. The performance indices provided from the simulation included evaporative water temperature, glass cover temperature and productivity; these were plotted on the line graphs in Figure 6 to Figure 29. Results obtained through the computational model were summarised and placed in Table 3 to Table 15 for each calendar month. The evaporative water temperature and glass cover temperature was plotted against time for each month on the same set of axes. This plot, for four out of twelve months, showed glass cover temperature higher than evaporative water temperature for most of the day. Evaporative water was only marginally greater than glass cover temperature for the remaining eight months, a suggested reason for this is that ANSYS® provided to boundary condition options for wall transparency i.e. opaque and semi-transparent. Semi-transparent was selected for the glass cover which resulted in reduced transmittance through the cover to the basin water. The software assumed a unilateral initial temperature for both the glass cover and basin water. End of day temperature for both the basin water and glass cover was either equal to or less than start of day temperature; this was greatly exaggerated in the winter months – when sunsets occurs earlier. Much like the analytical model, maximum productivity occurred at solar zenith – 1 pm. The productivity trend across the day followed a bell-shaped plot with the greatest increase in productivity occurring between 10 am and 12 pm. The temperature contour shown in Figure 5 outputs the expected temperature gradient across the still. The still roof faded from a dark red – at the top of the still – to a deep blue toward the still sides. The collecting troughs are located at the still sides in an elevated position, as the temperature reduces at this point. The maximum surface temperature is noted toward the roof ridge because hot air and vapour rises and forms an insulating blanket thus raising the glass cover surface temperature in this region. 74.43 °C and 56.99 °C were the maximum and minimum evaporative water temperatures at 1 pm in December and July respectively. The highest glass cover temperature at 1 pm occurred in March at 72.42 °C while June glass temperature was the lowest measuring 52.15 °C. Solar zenith still productivity peaked at 557.61 ml/m^2.hr in December while only managed 314.43 ml/m^2.hr in July.

9.3 Summary of chapter

CHAPTER 9 provided the theory behind computational modelling of the solar still. The design theory behind a CFD simulation was provided and simplified for a heat transfer model. The simulation process for an ANSYS® CFD model was noted. Lastly, the results of the computational model were evaluated.

9.4 References

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CHAPTER 10: DESIGN THEORY AND EXPERIMENTAL ANALYSIS OF A SOLAR STILL

10.1 Experimental procedure

An experimental model was designed to verify the performance characteristics of the still boiler of the solar powered desalination test rig.

Introduction

The solar powered desalination test rig available at the University of KwaZulu-Natal Mechanical Engineering workshop was tested to obtain a benchmark against which the new still design could be compared. The testing procedure is described below. The experimental model carried out sought to ascertain the following:

1) Evaporative water temperature
2) Glass cover temperature
3) Ambient temperature
4) Productivity

Aim

Verify the solar powered desalination test rig still performance characteristics.

Objectives

Measure the evaporative water temperature, glass cover temperature, ambient temperature and productivity of the solar powered desalination test rig.

Apparatus

1) Infrared temperature gun
2) Submersible thermometer
3) Measuring cylinder
4) Thermometer
5) Solar still
6) Saline/brine water
7) Watch/Clock

Assumptions

1) The boiler still is clean and dry prior to experiment.

2) The inner glass temperature is equal to the outer glass temperature.
3) Basin water temperature is constant regardless of depth.
4) Measuring cylinder is clean and dry between each measurement.
5) All condensed water that accumulated into collector trough is drained into measuring cylinder.
6) The entire results reading process takes less than one minute for each hourly measurement.

Procedure

1) Fill 25 litres of seawater into the still boiler of the test rig (TDS = 35 000 mg/l).
2) Place submersible thermometer into basin water.
3) Test rig should be positioned such that the boiler still side walls face east and west respectively while the backwall faces north.
4) The watch should be used to keep track of time. Measurements should be taken each hour starting at 8 am and ending at 6 pm.
5) The thermometer should be utilised to measure the ambient temperature hourly.
6) Glass cover temperature should be measured using the infrared temperature gun hourly.
7) Condensed water that accumulates in the collector trough must be drained hourly and the volume recorded using the measuring cylinder.
8) This must be repeated twice on a further two consecutive days.

10.2 Results

The results obtained were from the testing of the single slope solar still part of the solar powered desalination plant test rig available at the University of KwaZulu-Natal. The test was carried out in August 2019 at the Mechanical Engineering Building Workshop at the University of KwaZulu-Natal, Howard College. The results collected describe the following performance indices:

1) Evaporative water temperature
2) Glass cover temperature
3) Ambient temperature
4) Productivity

The results are summarised in table form for the month of August while the system temperatures and productivity as a function of time are also graphed.

10.2.1 Day 1 – 14th August 2019

Table 10-1: Day 1 experimental performance result

Date	Time of day	Evaporative water temperature (^{O}C)	Glass cover temperature (^{O}C)	Ambient temperature (^{O}C)	Productivity ($ml/m^2.hr$)
14th August	8:00	20.35	17.28	16.50	22.70
	9:00	21.16	19.09	20.50	25.02
	10:00	27.08	23.53	23.00	39.88
	11:00	41.21	37.64	26.00	75.44
	12:00	51.14	47.56	27.00	114.63
	13:00	55.29	51.71	28.00	132.46
	14:00	52.36	48.78	29.50	114.07
	15:00	43.86	40.30	29.50	74.67
	16:00	30.20	26.65	29.00	39.32
	17:00	22.98	19.14	28.50	23.65
	18:00	18.54	14.26	27.00	18.45

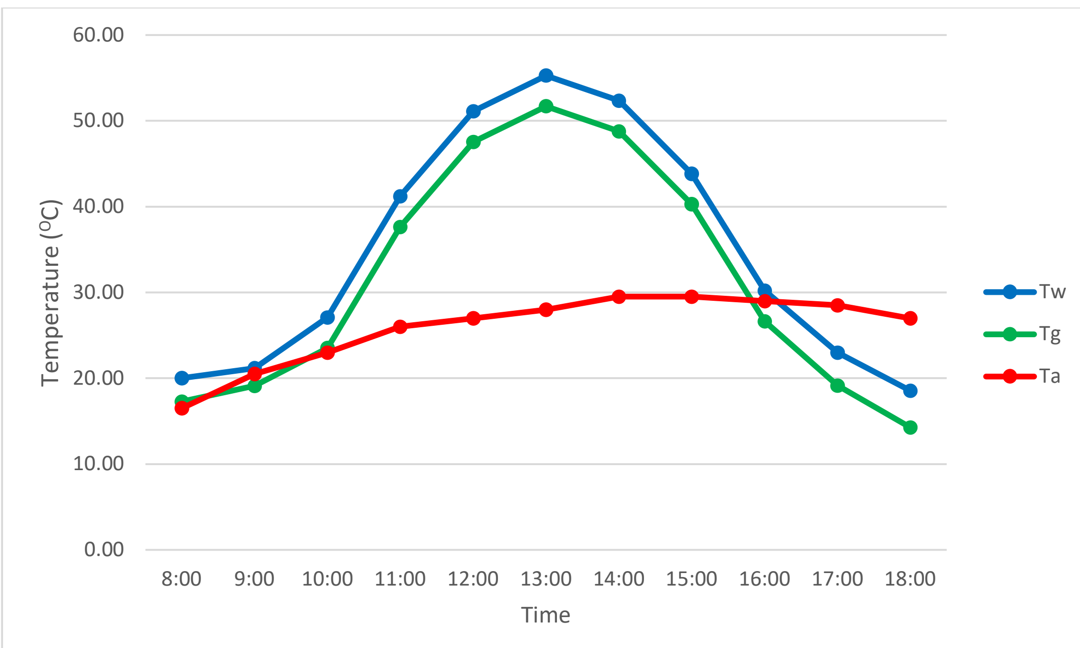

Figure 10-1: Experimental still temperatures – Day 1

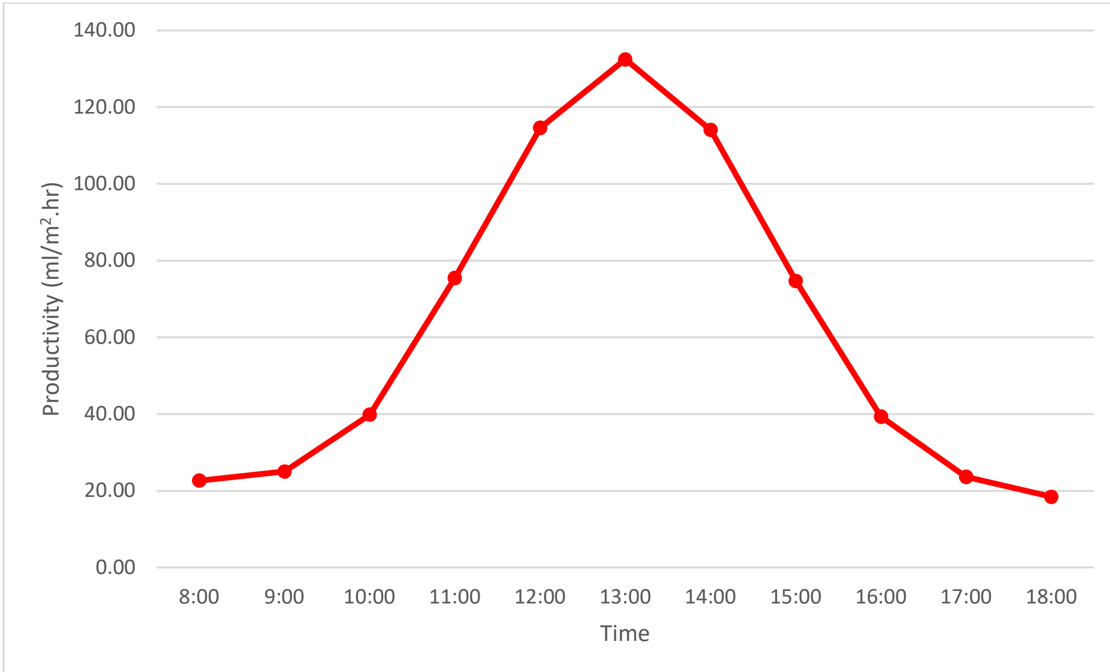

Figure 10-2: Experimental productivity – Day 1

10.2.2 Day 2 – 15th August 2019

Table 10-2: Day 2 experimental performance results

Date	Time of day	Evaporative water temperature (^{O}C)	Glass cover temperature (^{O}C)	Ambient temperature (^{O}C)	Productivity ($ml/m^2.hr$)
15th August	8:00	21.02	17.91	15.50	27.04
	9:00	21.69	20.83	17.00	35.32
	10:00	25.97	23.89	18.50	48.10
	11:00	39.01	36.92	23.00	95.00
	12:00	47.86	45.77	24.50	150.52
	13:00	51.16	49.07	26.50	179.71
	14:00	47.78	45.69	27.50	158.31
	15:00	39.35	37.28	27.00	104.58
	16:00	26.29	24.23	26.00	54.67
	17:00	19.13	17.42	25.00	33.57
	18:00	15.88	13.82	22.50	29.69

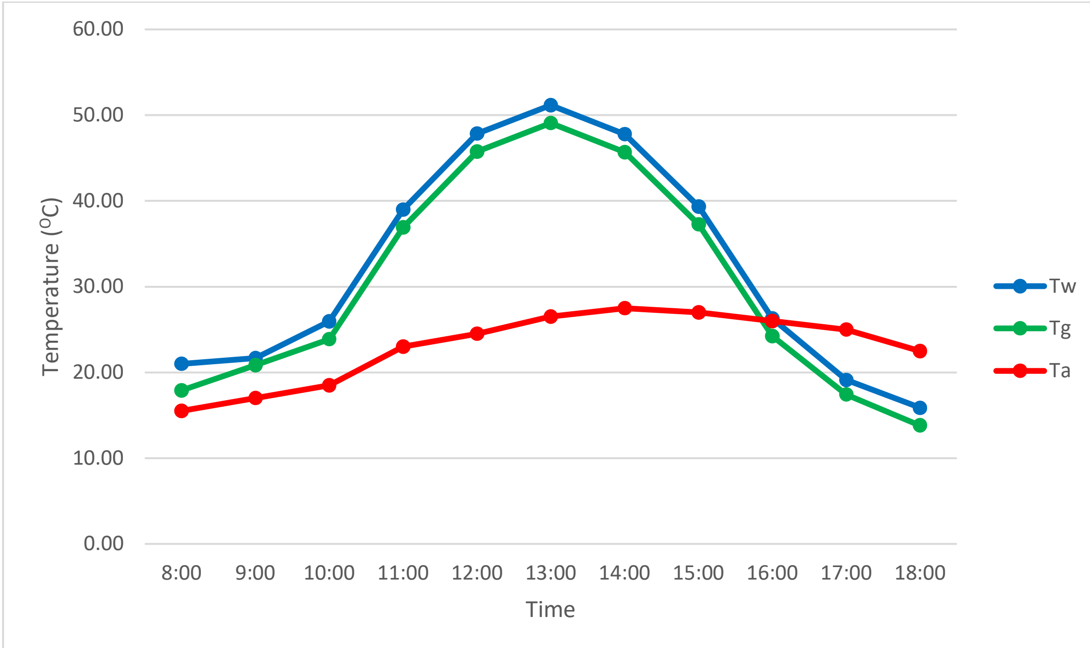

Figure 10-3: Experimental still temperatures – Day 2

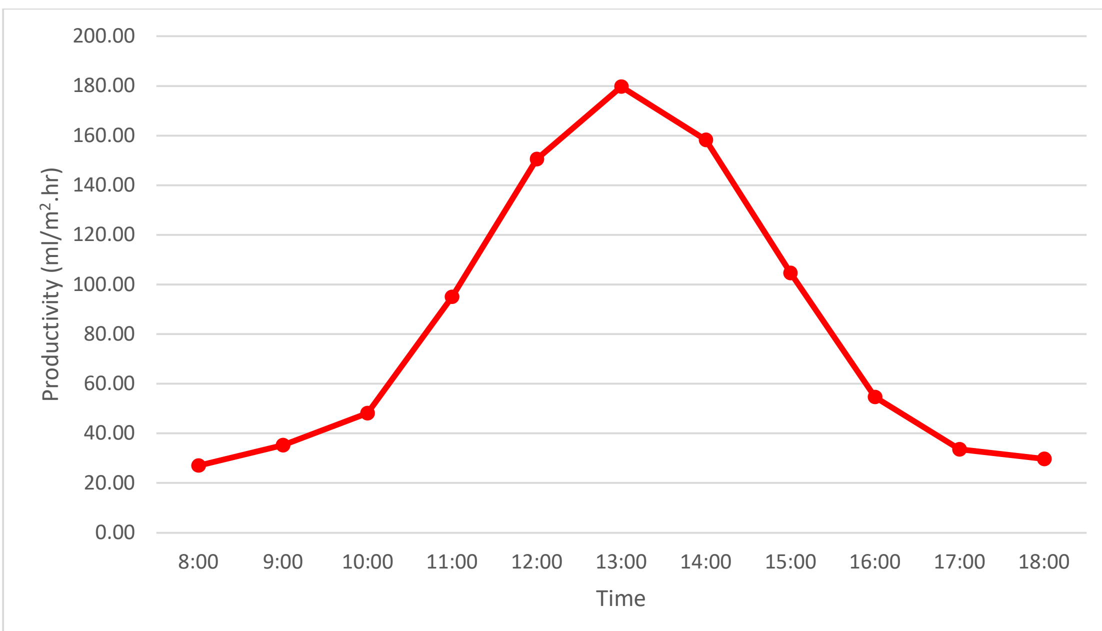

Figure 10-4: Experimental productivity – Day 2

10.2.3 Day 3 – 16th August 2019

Table 10-3: Day 3 experimental performance results

Date	Time of day	Evaporative water temperature (^{O}C)	Glass cover temperature (^{O}C)	Ambient temperature (^{O}C)	Productivity ($ml/m^2.hr$)
16th August	8:00	24.86	19.61	19.00	26.23
	9:00	26.88	24.18	24.00	30.76
	10:00	31.47	28.77	26.50	53.69
	11:00	46.13	43.41	29.50	105.67
	12:00	56.13	53.40	31.50	166.23
	13:00	59.93	57.19	31.50	195.23
	14:00	56.29	53.56	32.00	167.13
	15:00	46.90	44.18	31.50	106.98
	16:00	32.30	29.60	30.00	54.43
	17:00	24.56	21.55	28.50	33.17
	18:00	20.03	17.34	27.00	24.12

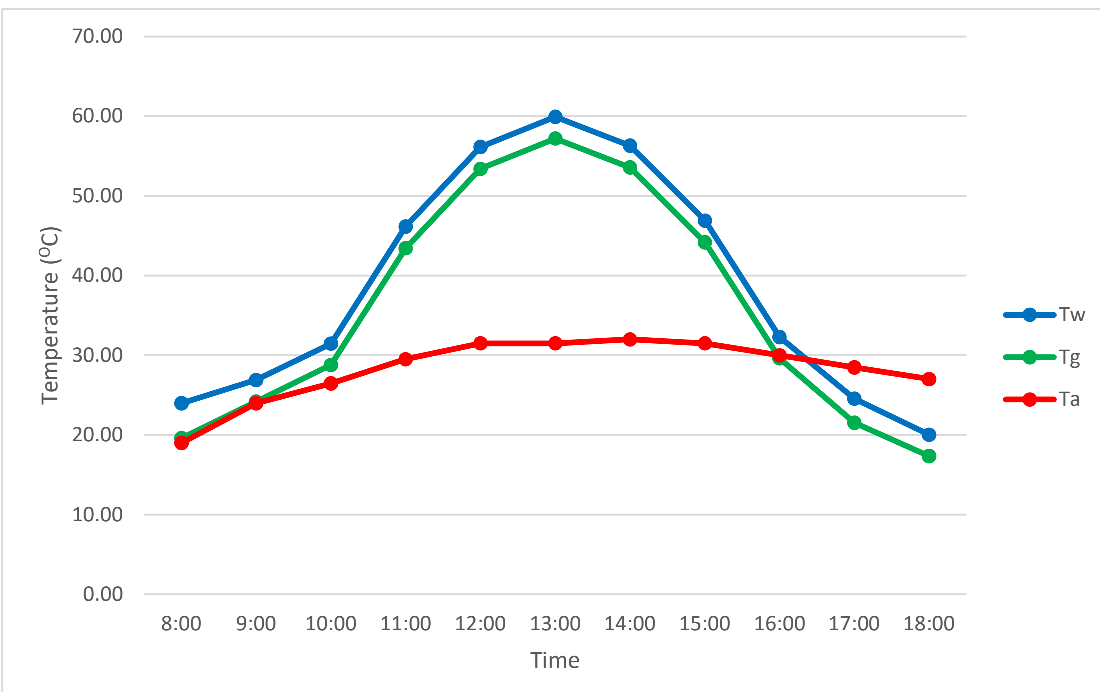

Figure 10-5: Experimental still temperatures – Day 3

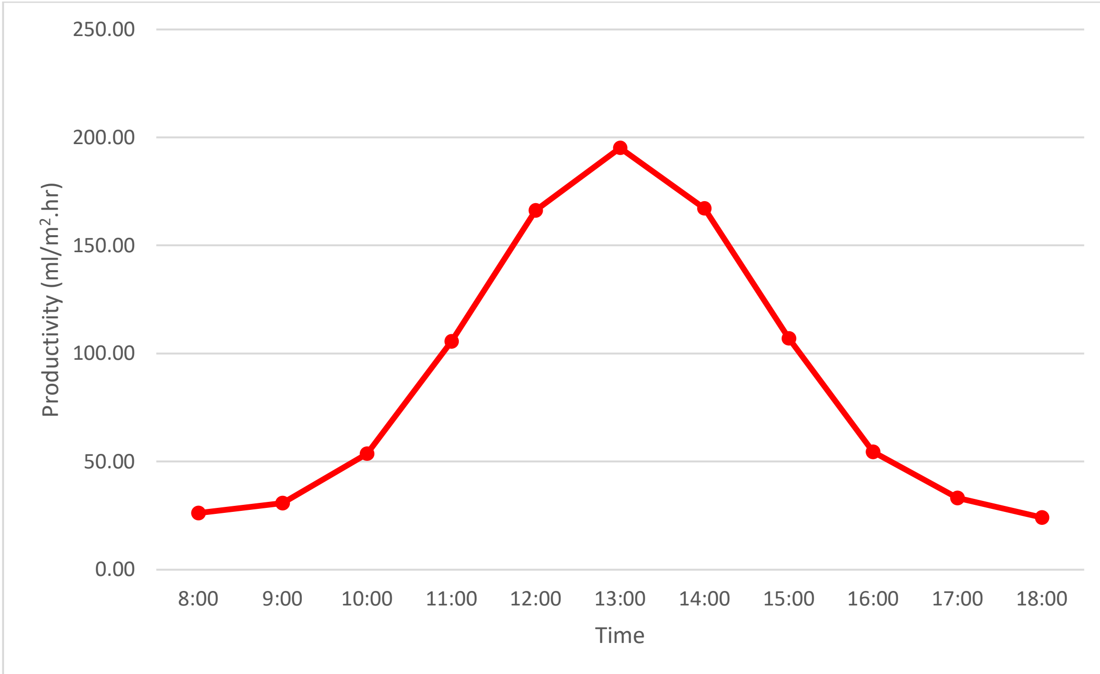

Figure 10-6: Experimental productivity – Day 3

10.3 Discussion

The current solar powered water desalination test rig was brought to service in an experimental procedure from 14th to 16th August. The aim of the experiment was to validate the current performance characteristics of the existing boiler still and compare the evaporative water temperature, glass cover temperature and productivity against the analytical and computational results to ascertain whether the new boiler design enhanced still performance. A three-day experimental mode was carried out. The existing boiler still of the solar powered desalination plant test rig was tested to ascertain current system performance indices, namely: evaporative water temperature, glass cover temperature, ambient temperature and productivity. The results were collected between 14th and 16th August 2019 at the Mechanical Engineering Workshop at the University of KwaZulu-Natal in the time period 8 am to 6 pm and given in Table 10-1 to Table 10-3. The experimental procedure and equipment utilised was described in section 10.1. System temperatures were plotted on the same set of axes against time for each day and are shown in Figure 10-1 to Figure 10-6. The temperature plots for the experimental model noted the same overall bell shape as the analytical and computational model, with peak performance occurring at 1 pm each day. The greatest measured evaporative water temperature (59.93 °C), glass cover temperature (57.19 °C) and productivity (195.23 ml/m^2.hr) occurred on the third day of experimentation, 16th August, when the maximum ambient temperature peaked at 32 °C (Table 10-3). The 15th of August recorded the lowest evaporative water temperature (51.16 °C) and glass temperature (49.07 °C) respectively (Figure 10-3). However, day 1 still recorded the lowest productivity of 132.46 ml/m^2.hr, seen in Figure 10-2. This thus implies that temperature is not the only driving factor effecting productivity, and that direct solar irradiation also has a considerable influence.

10.4 Summary of chapter

The experimental approach was used to verify the performance characteristics of the current solar powered desalination plant test rig. The experimental procedure was noted and the results summarised, tabled and graphed. These results were discussed.

CHAPTER 11: COMPARISON OF QUANTITATIVE RESULTS

11.1 Hourly Comparison

The results obtained through the analytical, computational and experimental model are summarised for the month of August. Day 2 of the experimental results was selected to be compared as the analytical and computational models both work with the 15th of each calendar month as a reference (Tables 11-1, 11-2, 11-3). The analytical and computational results were reduced to two decimal places for uniformity. The results are also represented graphically (Figures 11-1, 11-2, 11-3). The performance results provided are:

1) Evaporative water temperature
2) Glass cover temperature
3) Productivity

11.1.1 Hourly evaporative water temperature

Table 11-1: Hourly evaporative water temperature results for the three different models

Month	Time of Day	Evaporative water temperature (^{O}C)		
		Analytical	Computational	Experimental
August	8:00	22.00	21.00	21.35
	9:00	27.26	26.34	21.69
	10:00	33.11	36.08	25.97
	11:00	47.23	48.07	39.01
	12:00	57.53	56.09	47.86
	13:00	61.68	59.96	51.16
	14:00	58.75	56.94	47.78
	15:00	49.39	48.66	39.35
	16:00	35.73	37.06	26.29
	17:00	27.13	23.14	19.13
	18:00	20.56	19.83	15.88

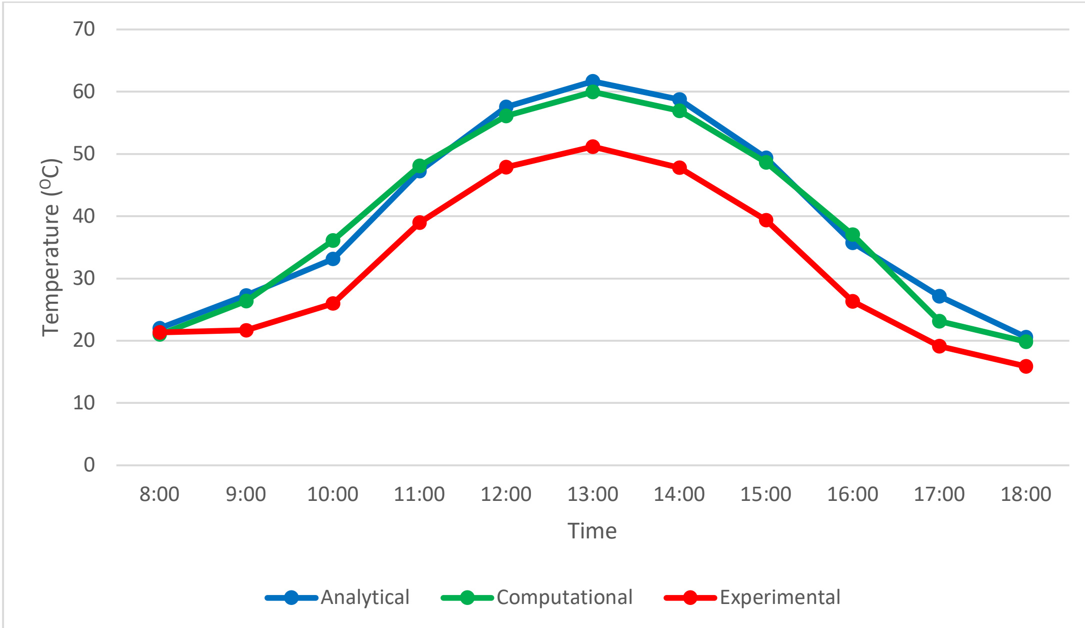

Figure 11-1: Hourly evaporative water temperature for the three different models

11.1.2 Hourly glass cover temperature

Table 11-2: Hourly glass cover temperature results for the three different models

Month	Time of Day	Glass cover temperature (^{O}C)		
		Analytical	Computational	Experimental
August	8:00	18.81	21.00	17.91
	9:00	23.08	27.04	20.83
	10:00	29.93	38.76	23.89
	11:00	44.04	49.20	36.92
	12:00	54.33	56.89	45.77
	13:00	58.48	60.12	49.07
	14:00	55.55	57.98	45.69
	15:00	46.21	49.09	37.28
	16:00	32.56	36.51	24.23
	17:00	23.67	21.29	17.42
	18:00	16.67	18.44	13.82

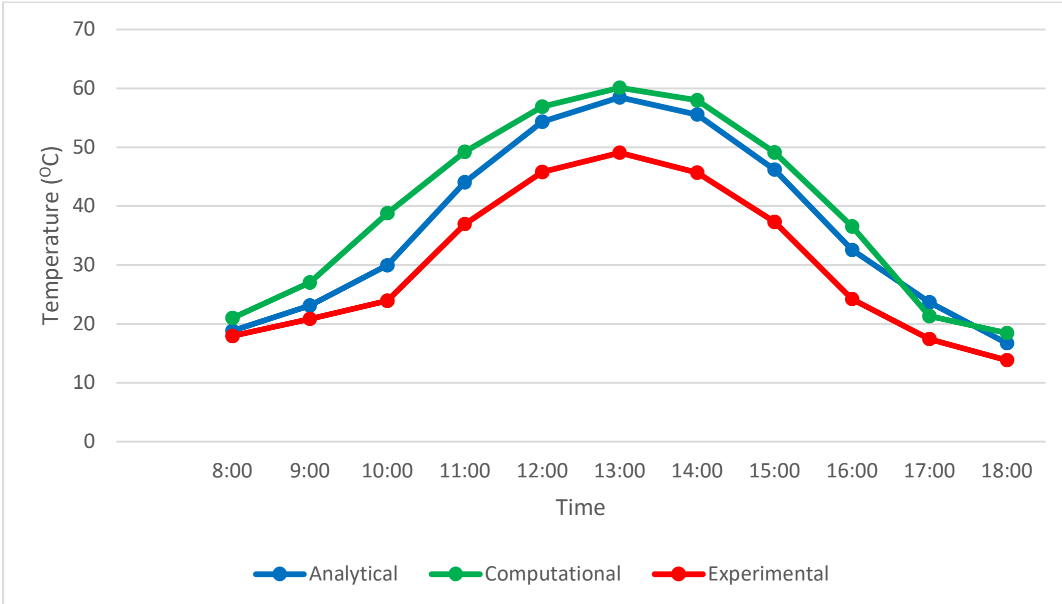

Figure 11-2: Hourly glass cover temperature for the three different models

11.1.3 Hourly productivity

Table 11-3: Hourly productivity results for the three different models

Month	Time of Day	Productivity ($ml/m^2.hr$)		
		Analytical	Computational	Experimental
August	8:00	57.90	51.99	27.04
	9:00	67.71	62.74	35.32
	10:00	103.01	116.74	48.10
	11:00	203.42	201.93	95.00
	12:00	322.32	314.46	150.52
	13:00	384.82	342.84	179.71
	14:00	338.99	308.05	158.31
	15:00	223.93	197.94	104.58
	16:00	117.08	104.78	54.67
	17:00	71.89	58.69	33.57
	18:00	63.57	51.97	29.69

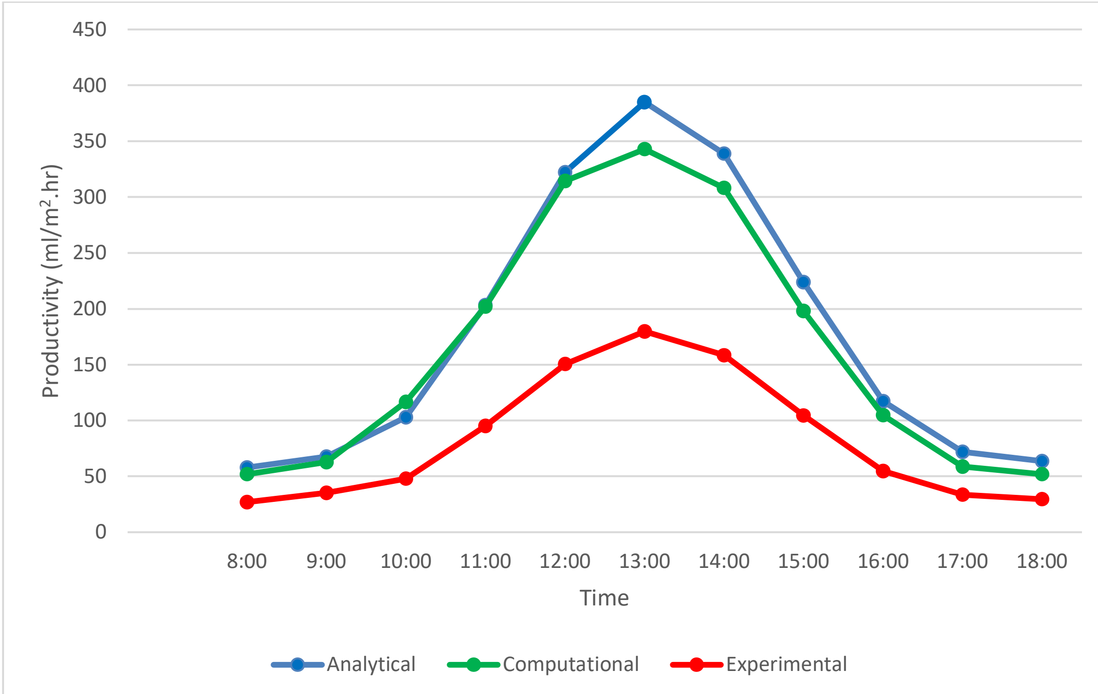

Figure 11-3: Hourly productivity for the three different models

11.2 Monthly Comparison

The results obtained through the analytical, computational and experimental model are summarised for each month (Tables 11-4, 11-5, 11-6). These results were obtained through statistical analysis of the results obtained via the three modelling techniques employed. The analytical and computational results were reduced to two decimal places for uniformity. The results are also represented graphically (Figures 11-4, 11-5, 11-6). The performance results provided are:

1) Average volumetric output
2) Average evaporative water temperature
3) Average glass cover temperature

11.2.1 Monthly average volumetric output

Table 11-4: Monthly average volumetric output results for the three different models

Month	Average volumetric output (ml)		
	Analytical	Computational	Experimental
January	2433.17	2688.39	N/A
February	2478.71	2678.32	N/A
March	2378.18	2643.89	N/A
April	2061.51	2420.65	N/A
May	1656.72	2688.39	N/A
June	1337.58	1643.66	N/A
July	1443.31	1501.94	N/A
August	1776.94	1647.41	618.46
September	2142.05	2324.56	N/A
October	2398.00	2436.03	N/A
November	2459.07	2498.48	N/A
December	2433.82	2912.96	N/A

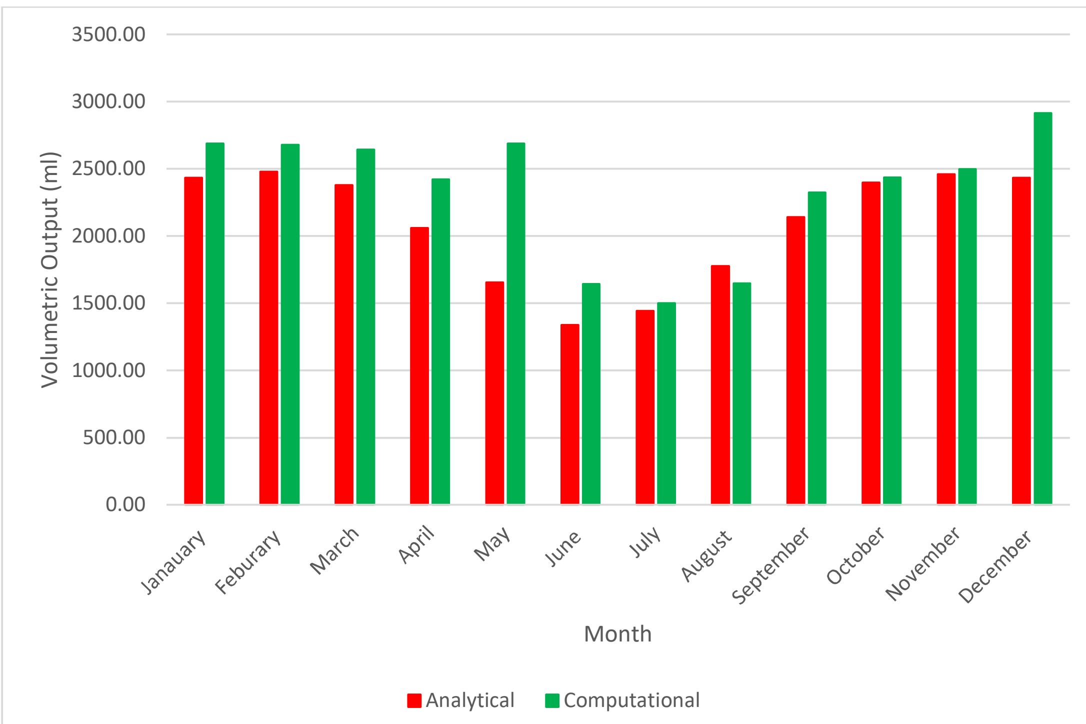

Figure 11-4: Average volumetric output results for the analytical and computational model

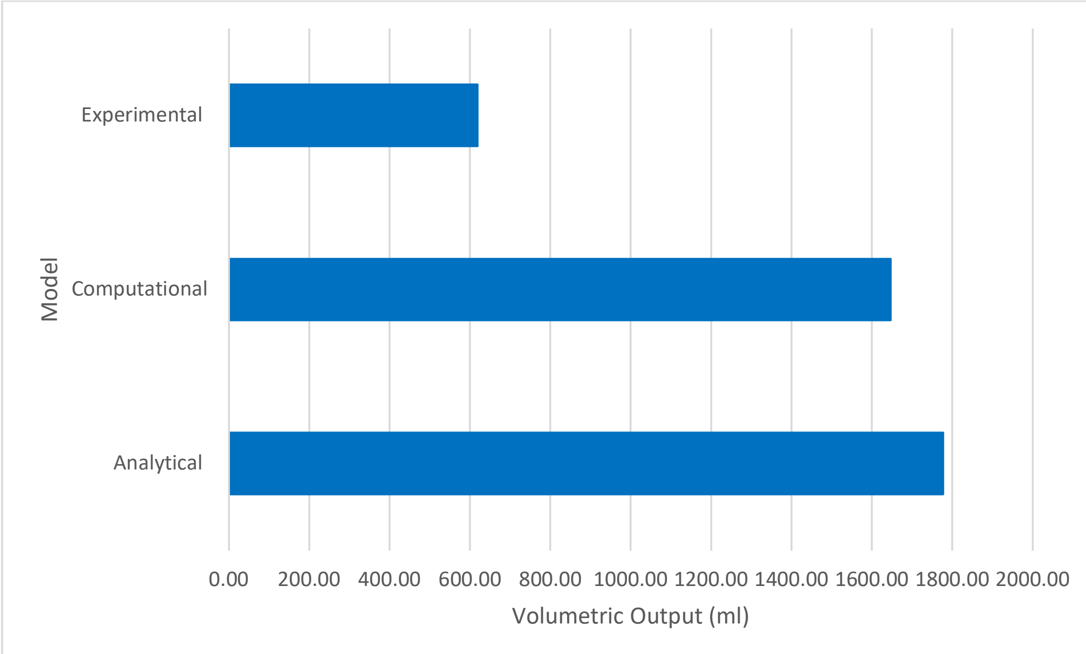

Figure 11-5: August average volumetric output results for the three different models

11.2.2 Monthly average evaporative water temperature

Table 11-5: Monthly average evaporative water temperature results for the three different models

Month	Average evaporative water temperature (^{O}C)		
	Analytical	Computational	Experimental
January	46.53	44.94	N/A
February	46.26	44.58	N/A
March	45.21	44.21	N/A
April	42.34	42.18	N/A
May	37.65	39.97	N/A
June	34.40	37.11	N/A
July	35.95	35.77	N/A
August	40.03	39.38	32.28
September	43.57	46.47	N/A
October	45.64	47.16	N/A
November	46.69	48.24	N/A
December	46.90	49.78	N/A

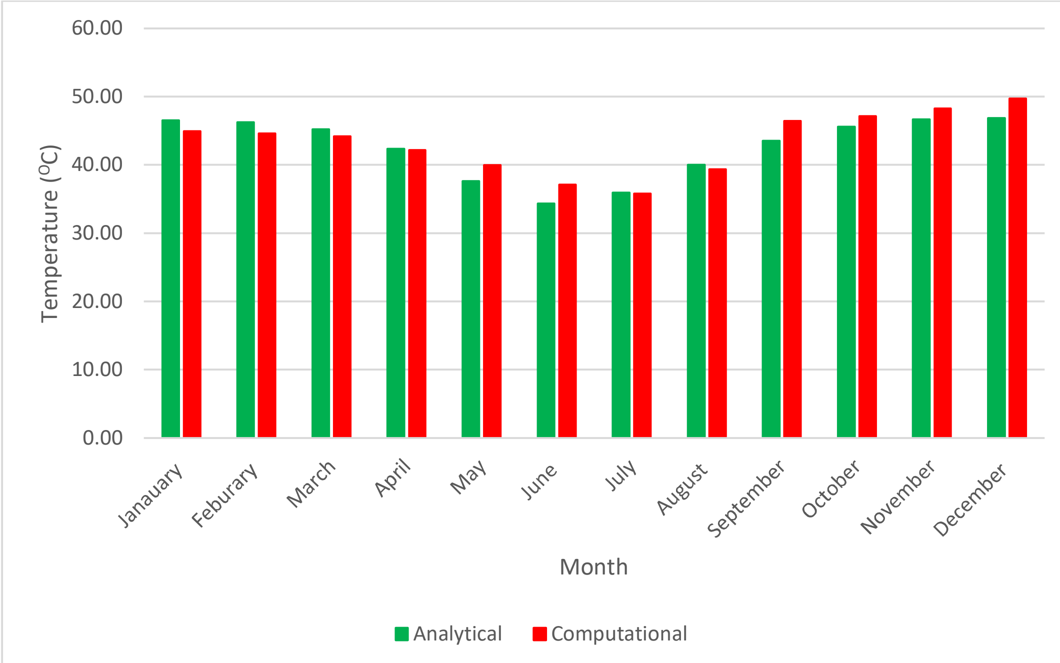

Figure 11-6: Average evaporative water temperature results for the analytical and computational model

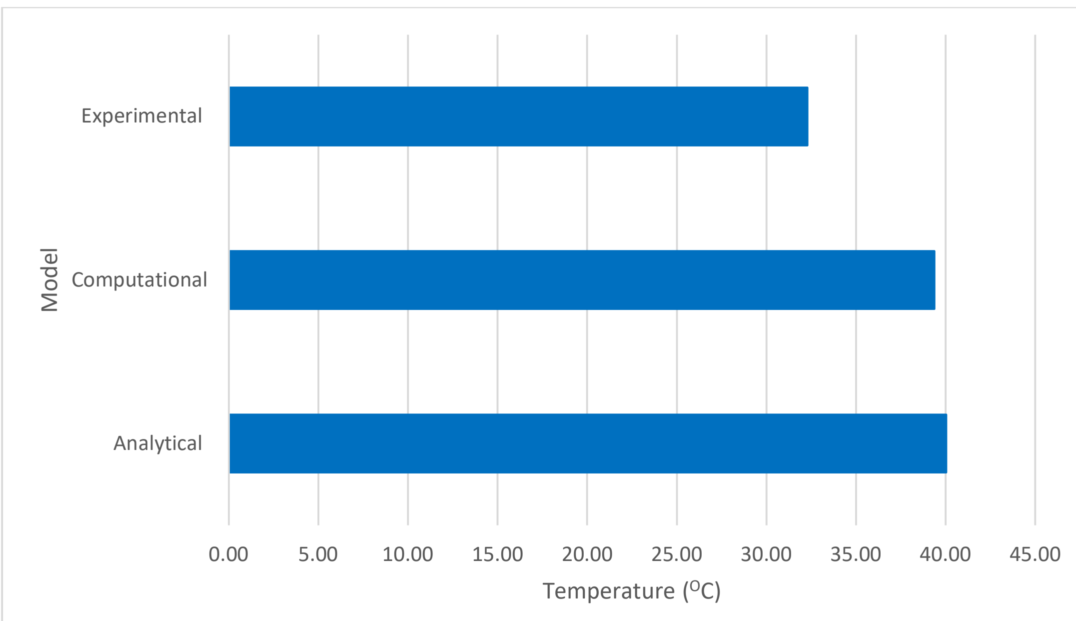

Figure 11-7: August average evaporative water temperature results for the three different models

11.2.3 Monthly average glass cover temperature

Table 11-6: Monthly average glass cover temperature results for the three different models

Month	Average glass cover temperature (OC)		
	Analytical	Computational	Experimental
January	43.05	46.85	N/A
February	43.10	47.04	N/A
March	42.10	47.58	N/A
April	39.21	46.28	N/A
May	34.45	42.16	N/A
June	31.05	36.51	N/A
July	32.87	34.06	N/A
August	36.67	39.67	30.26
September	40.56	45.27	N/A
October	42.42	44.86	N/A
November	43.41	45.65	N/A
December	43.96	46.91	N/A

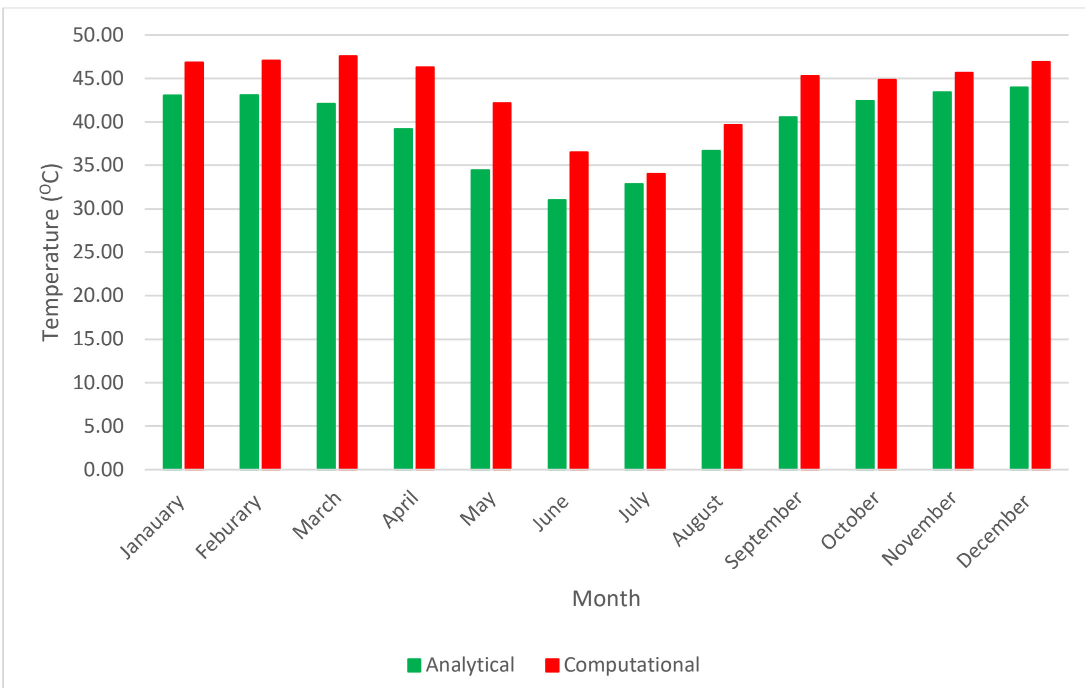

Figure 11-8: Average glass cover temperature results for the analytical and computational model

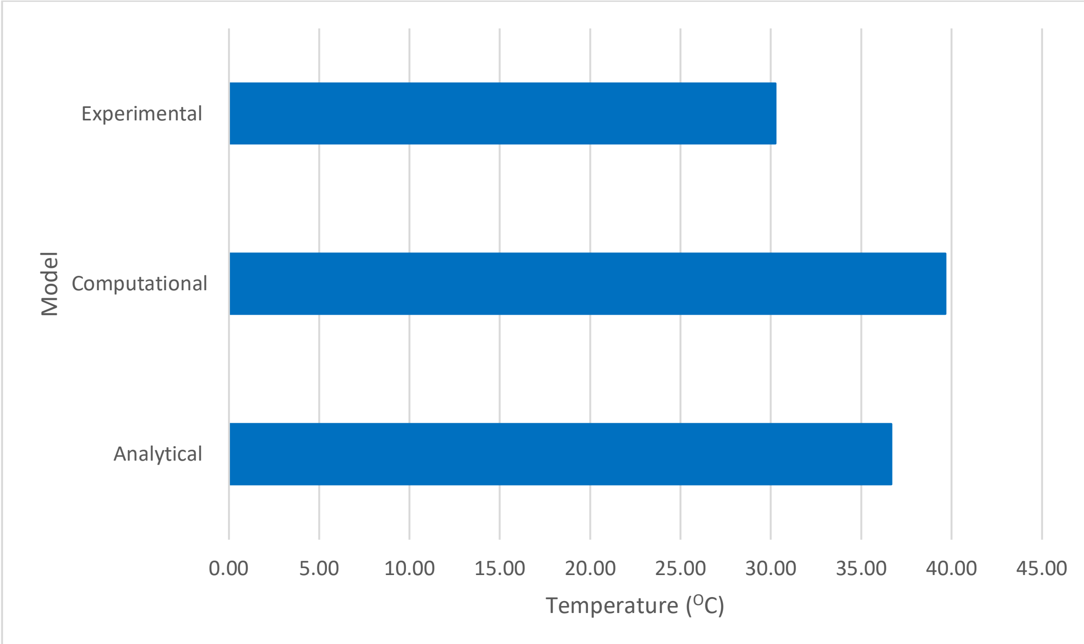

Figure 11-9: August average glass cover temperature results for the three different models

11.3 Discussion

A comparison of results was carried out between three models. The first compared the hourly evaporative water temperature, glass cover temperature and productivity of the three models for the 15th of August. The analytical, computational and experimental results were plotted on the same set of axes for each performance characteristic. The first graph labelled Figure 11-1, hourly evaporative water temperature vs. time, showed a similar overall plot shape across the three models. The analytical approached noted a 20.56 % increase in still evaporative water temperature at solar zenith between the proposed improved double slope boiler still and the existing single slope boiler still while the computational approach saw a 17.20 % rise. The glass cover temperature of the proposed boiler still design at 1 pm improved by 22.5 % according to the computational approach and 19.18 % through the analytical approach compared to the current boiler still glass cover temperature as calculated from the results listed in Table 11-2 and depicted in Figure 11-2. The most notable improvement was displayed across the boiler still productivity. Experimental boiler still productivity of the existing boiler still system at 1 pm was 179.71 ml/m^2.hr while the analytical and computational approaches recorded hourly productivity rates of 384.82 ml/m^2.hr and 342.84 ml/m^2.hr respectively, as can be seen in Figure 11-3. This meant that there was a 114.13 % and 90.77 % increase in productivity between the existing boiler still and proposed improved boiler still according to the analytical and computational models according to the results grouped in Table 11-3. The second comparison constituted the monthly; average volumetric output, average evaporative water temperature and average glass cover temperature. August was the only month to include results from all three models as the experimental model was carried out exclusively in this month. Average volumetric output was calculated by multiplying the productivity with the area of the still (1 m^2) and number of hours of operation (10 hours). The computational model resulted in a greater volumetric output than the analytical model for all months excluding August, as shown in Figure 11-4. May's volumetric output was quite high compared to the analytical model, which could be attributed to a combination of high temperatures and a greater Clearness Factor in May 2018. As expected, the volumetric output in Durban improved, as recorded in Table 11-4, during the November to March periods due to increase temperature and reduced cloudiness. August volumetric output for the improved boiler still design was recorded at 1776.96 ml and 1647.41 ml for the analytical and computational models respectively, meaning the new design led to a 187.32 % or 166.37 % increase in distillate output when compared to the experimental productivity of the current system. The marked improvement in productivity can be viewed in bar graph Figure 11-5. There was a strong agreement between the analytical and computational model regarding the monthly average evaporative water temperature, with the largest temperature difference only 2.90 °C, subtracting results populated in Table 11-5. In the month of August Figure 11-7 shows the difference between the analytical and computational model evaporative temperatures was 0.65 °C while this increased to 7.75 °C for the experimental model. Average evaporative water temperatures were greatest in the month of December – as seen in Figure 11-6 – which therefore helped achieve the highest volumetric output for the same month. Conversely, the computational model output a greater average glass cover temperature (39.67 °C) compared to the analytical model (36.67 °C), noted by Figure 11-8 and Table 11-6. The experimental average glass cover temperature reached 30.26 °C, logged in Figure 11-9. This experimental average glass cover temperature is only 76.28 % of the maximum average glass cover temperature across the three models when calculating it against the average glass cover temperatures registered in Table 11-6.

11.4 Summary of chapter

The results obtained through the analytical, computational and experimental model were statistically analysed. These results are directly compared either hourly or monthly and were summarised in tables and graphs. Finally, the comparison was discussed.

CHAPTER 12: CONCLUSION, RECOMMENDATIONS AND FUTURE RESEARCH

The need for research into renewable and alternative methods to produce potable water stems from severe water scarcity issues that exist and have worsened in certain parts of the world. The aim of the project was to increase the performance characteristics of the solar powered desalination plant test rig that exists at the Discipline of Mechanical Engineering workshop, University of KwaZulu-Natal. The current boiler still design was noted by the initial design group as a point of possible improvement. As such, the boiler still was isolated to be improved upon. There were five objectives, outlined in the introduction, that were drawn up to help meet the aim of the master's project.

The first objective was to improve system performance by readdressing boiler still design. The proposed design conceptualised a new double slope solar still that would reduce the shadow effect that normally plagues single slope designs. An analytical and computational mode was carried out to ascertain the theoretical improved performance characteristics of the new double slope solar boiler still design and then compared to the experimental model performance results of the current single slope solar boiler still. The analytical approach noted a 114.13 % increase in still productivity while the computational approach recorded a 90.77 % increase when compared to the current single slope design.

Enhanced operational efficiency was achieved through selection of still materials that aided in thermal insulation. Operational and design parameters such as water basin depth, roof slope angle and input water TDS were selected based on literature. Water basin depth was limited to 150 mm, roof slope angle was selected at 15º and the input water TDS range maximum capped at 35 000 ppm. The current still was constructed out of 4 mm thick glass; this did not insulate the internal still environment and disallowed still basin solar energy absorption. The proposed boiler still would be made of stainless steel sheet metal and glass. These operational and design changes allowed for increased evaporative water temperature 20.56 % and 17.20 % according to the analytical and computational models respectively. The glass cover temperature rose from 30.26 °C to 39.67 °C, through computational analysis and 36.67 °C, via analytical analysis.

System autonomy was maintained through a design that could be integrated with the existing desalination test rig. The still inlet will be controlled by a solenoid valve that maintains a constant still basin depth and prevents system flooding. The distillate collection and transport is facilitated by a collection trough and outlet piping. As such, no user interface is required unless there is an issue that arises during operation. The ability to be integrated with the current design also satisfied the final objective of the project, that the new boiler setup should be able to be integrated with existing test rig.

A direct comparison between the current system and improved system performance characteristic was carried out. This was enabled through a quantitative approach that encompassed an analytical, computational and experimental model. The analytical and computational model measured new system performance while the experimental model verified current system performance. It was clearly noted that the proposed double slope solar still design increased system performance i.e. still temperatures and productivity.

The literature review noted the main desalination methods available and how commonly utilised each was across the world in largescale projects. Reverse osmosis and solar distillation were found to be the two most widely used methods. Reverse osmosis is better suited to largescale projects as the cost per litre of potable water produced significantly decreases as the volume of water desalinated increases. This is however not the case for solar distillation, as the cost per litre of potable water produced remains constant. Solar distillation thus is a more obvious choice for the method of household (small scale) desalination systems.

The methodology carried out during the research and design phase of the project deviated from the traditional heavily weighted quantitative approach. A qualitative approach was used which included a feasibility study and market analysis. The feasibility study surveyed 100 members of the population while the market analysis investigated three existing double slope boiler still designs and a SWOT analysis was completed. Desalination was perceived as the answer to possible future water shortages according to 85% of individuals who completed the survey. The feasibility study found that a large proportion of respondents would be willing to purchase desalination devices and become independent of current municipal water supply but were would be influenced by the initial startup cost of procuring these devices. 79% of survey respondents chose solar energy as the way in which desalination devices should be powered. The market analysis allowed for the limitations of current designed to be mitigated or eliminated. It also allowed for a suggested placement of the device in the best suited niche and region. Africa, the Middle East and Australia were identified as areas in which a strong market share could be developed – these areas are water scarce, some are still developing and there has been investment in water desalination in recent years.

The quantitative approach attempted to encompass the fundamental models i.e. analytical, computational and experimental. This allowed for a much better comparison with respect to boiler still performance characteristics. Two MATLAB programs were utilised to solve the double slope still mathematical model by iteration – the mathematical model accounted for real world parameters such as wind, solar irradiance scattering and clearness. The 2018 ANSYS® Fluent

DTRM academic version was used to set up the simulation on this three-dimensional heat and mass transfer model. The computational simulation provided a direct contrast to the results achieved through the analytical approach which provided good insight into the consistency of results between the two modelling methods.

The first issue that was identified through the research and design process is that solar distillation is largely dependent on the area of the solar still. A significant increase in output productivity is contingent on the still size, which leads to major problems beyond a certain threshold as the system becomes too large. It is suggested that smaller stills in parallel be used as opposed to one large still while reheat/recovery systems could be introduced in series with a still design.

The second problem identified is that the method of solar distillation is not equipped to deal with larger non dissolved solids/contaminants in the basin water. These solids may clog the pipework or damage the inside of the boiler still. It is proposed to enforce inlet pretreatment of basin water through a solar powered filtration system.

Lastly, the models carried out were for the Durban region of South Africa which normally experiences greater average temperatures than numerous other cities across the country. Therefore, performance results may be skewed as ambient temperatures and available solar radiation is higher for this region. Furthermore, humidity in Durban is higher than in inland cities which meant a smaller likelihood of leakage of moist air out of the boiler still. It is recommended that modelling be carried out for other geographical regions in South Africa to gain a more comprehensive results set.

Future research should be conducted to test the validity of the recommendations made or research alternative solutions regarding the problems noted. It is important for these to be tackled before household solar powered desalination plants can be implemented and manufactured. It is believed that there is a viable market for such devices in the potable water production industry as the niche is evident through an undeveloped market segment. South Africa is more aware of the need for research, development and investment into solar desalination especially after the water crisis that hit the Western Cape in 2018. Solar desalination has been shown to be an efficient, reliable and effective alternative for potable water production.

Appendix A – Confirmation of Publications

A.1 Publication 1 – Solar Desalination: A Critical Review

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INTERNATIONAL JOURNAL OF MECHANICAL ENGINEERING & TECHNOLOGY (IJMET)

www.iaeme.com/ijmet/index.asp

Paper ID: IJMET_10_08_021 **Date: 28-August-2019**

Certificate of Publication

This is to certify that the research paper entitled **"SOLAR DESALINATION: A CRITICAL REVIEW"** authored by **"Devesh Singh and Freddie L. Inambao"** had been reviewed by the Editorial Board and published in **"International Journal of Mechanical Engineering & Technology (IJMET), Volume 10, Issue 8, August 2019, pp. 244-270; ISSN Print: 0976-6340 and ISSN Online: 0976-6359; Journal Impact Factor (2019): 10.6879 Calculated by GISI (www.jifactor.com)"**.

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Journal Impact Factor (2019): 10.6879 Calculated by GISI (www.jifactor.com)

ISSN Print: 0976 - 6340 ISSN Online: 0976 - 6359

Official Acceptance of Research Paper

Paper ID: IJMET/10/07/2019/IJMET_44145 **Date:** 20-July-2019

Dear **Devesh Singh and Freddie L. Inambao**

We would like to inform you that your paper titled **"SOLAR DESALINATION: A CRITICAL REVIEW"** has been accepted for publication in **International Journal of Mechanical Engineering and Technology (IJMET),** Volume 10, Issue 07, (July 2019) issue of the journal based on the Recommendation of the Editorial Board without any major corrections in the content submitted by the researcher.

This letter is the official confirmation of acceptance of your research paper.

Your research paper will be appearing in IJMET, Volume 10, Issue 07, July 2019.

International Journal of Mechanical Engineering and Technology (IJMET)
Journal Impact Factor (2019): 10.6879 Calculated by GISI
ISSN Print: 0976 – 6340
ISSN Online: 0976 – 6359

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ISSN Print: 0976 - 6340 ISSN Online: 0976 - 6359

Review Report

Date: **20-July-2019**

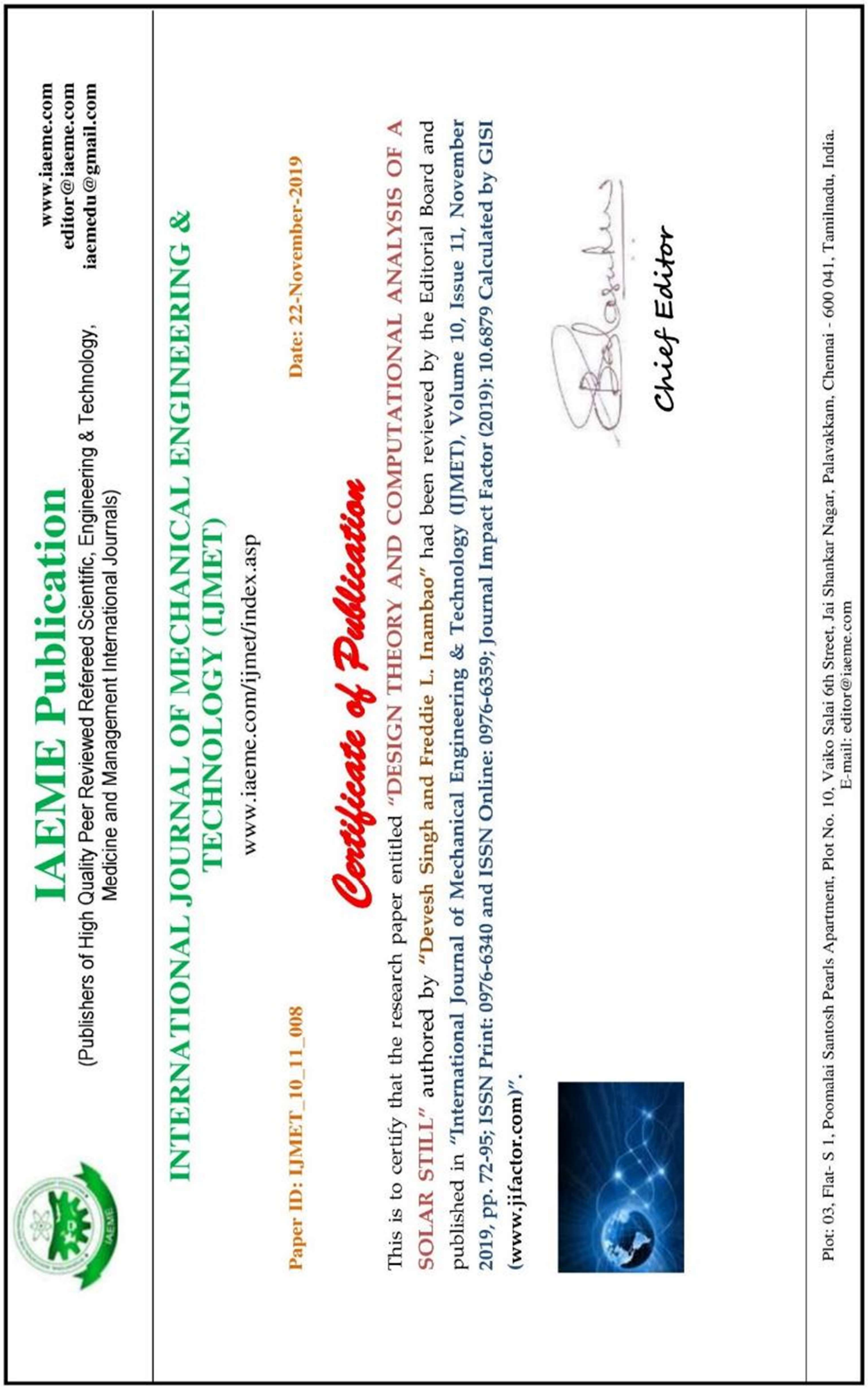
Title: **SOLAR DESALINATION: A CRITICAL REVIEW**

Authors: **Devesh Singh and Freddie L. Inambao**

Evaluation	Poor	Fair	Good	Very Good	Outstanding
Originality					√
Innovation				√	
Technical merit					√
Applicability					√
Presentation and English					√
Match to Journal Topic					√
Recommendation to Chief Editors					
	Strongly Reject	Reject	Marginally Accept	Accept	Strongly Accept
Recommendation					√

Review Comments: The paper reviews the need for research into alternative water purification methods in general, desalination methods in particular, their working principles and mathematical modelling. The economics of thermal and membrane based desalination is noted. **Analytical study.** **Paper Accepted for publication in IJMET.**

A.2 Publication 2 – Design Theory and Computational Analysis of a Solar Still



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Paper ID: IJMET_10_11_008 **Date: 22-November-2019**

Certificate of Publication

This is to certify that the research paper entitled **"DESIGN THEORY AND COMPUTATIONAL ANALYSIS OF A SOLAR STILL"** authored by **"Devesh Singh and Freddie L. Inambao"** had been reviewed by the Editorial Board and published in **"International Journal of Mechanical Engineering & Technology (IJMET), Volume 10, Issue 11, November 2019, pp. 72-95; ISSN Print: 0976-6340 and ISSN Online: 0976-6359; Journal Impact Factor (2019): 10.6879 Calculated by GISI (www.jifactor.com)".**

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ISSN Print: 0976 - 6340 **ISSN Online**: 0976 - 6359

Official Acceptance of Research Paper

Paper ID: IJMET/10/10/2019/IJMET_44589 **Date:** 10-Oct-2019

Dear **Devesh Singh and Freddie L. Inambao**

We would like to inform you that your paper titled **"DESIGN THEORY AND COMPUTATIONAL ANALYSIS OF A SOLAR STILL"** has been accepted for publication in **International Journal of Mechanical Engineering and Technology (IJMET),** Volume 10, Issue 10, (October 2019) issue of the journal based on the Recommendation of the Editorial Board without any major corrections in the content submitted by the researcher.

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ISSN Print: 0976 - 6340 ISSN Online: 0976 - 6359

Review Report

Date: **10-October-2019**

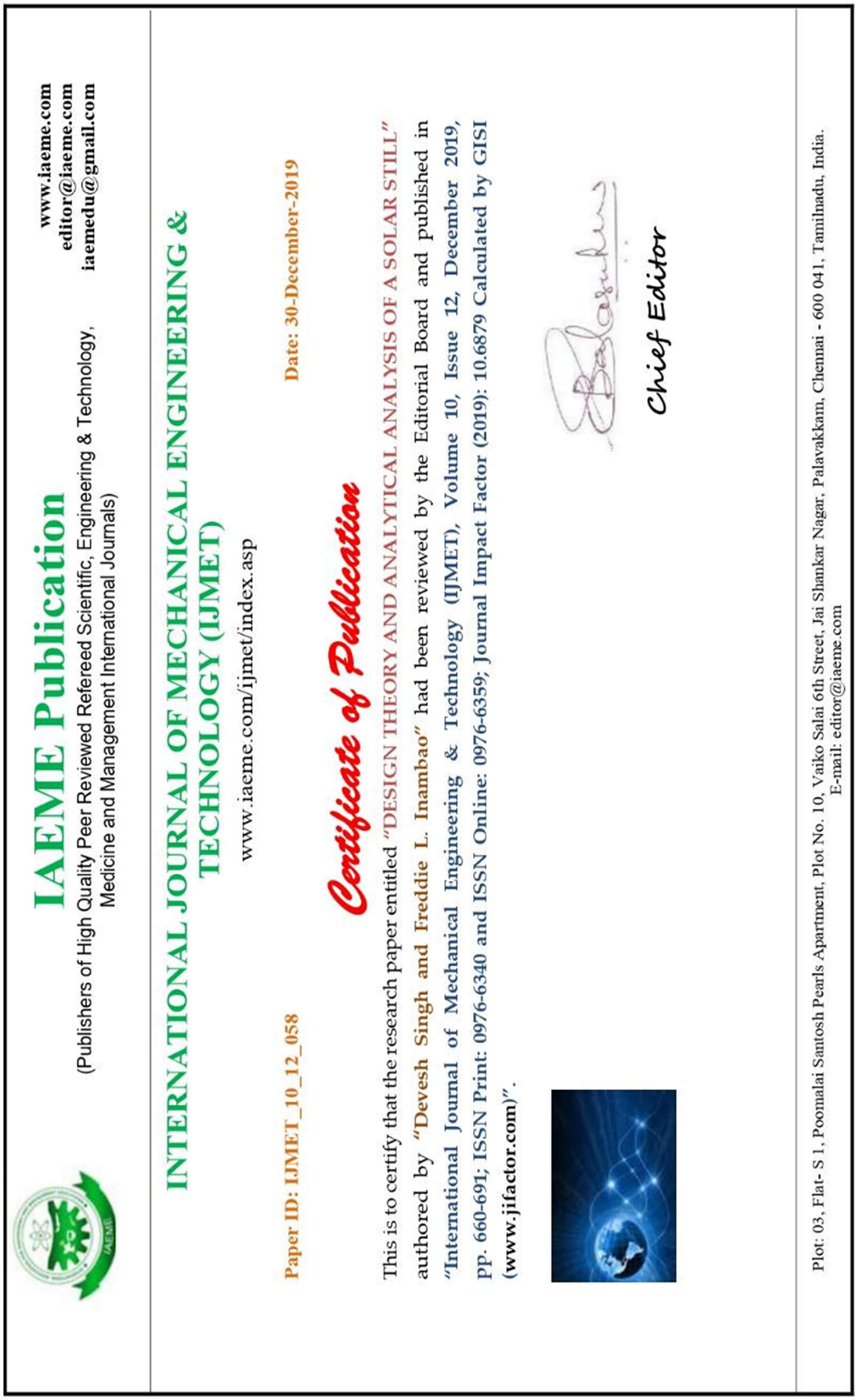
Title: **DESIGN THEORY AND COMPUTATIONAL ANALYSIS OF A SOLAR STILL**

Authors: **Devesh Singh and Freddie L. Inambao**

Evaluation	Poor	Fair	Good	Very Good	Outstanding
Originality					√
Innovation				√	
Technical merit					√
Applicability					√
Presentation and English					√
Match to Journal Topic					√
Recommendation to Chief Editors					
	Strongly Reject	Reject	Marginally Accept	Accept	Strongly Accept
Recommendation					√

Review Comments: This paper article describes the design theory, mathematical model employed by computational software and modelling process utilized in the three dimensional multiphase heat and mass transfer model of a double slope solar still. The double slope solar still performance results obtained from the computational analysis are summarized and graphed. **Analytical study. Paper Accepted for publication in IJMET.**

A.3 Publication 3 – Design Theory and Analytical Analysis of a Solar Still



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Paper ID: IJMET_10_12_058 **Date: 30-December-2019**

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ISSN Print: 0976 - 6340 **ISSN Online**: 0976 - 6359

Official Acceptance of Research Paper

Paper ID: IJMET/10/09/2019/IJMET_44417 **Date:** 12-Sep-2019

Dear **Devesh Singh and Freddie L. Inambao**

We would like to inform you that your paper titled **"DESIGN THEORY AND ANALYTICAL ANALYSIS OF A SOLAR STILL"** has been accepted for publication in **International Journal of Mechanical Engineering and Technology (IJMET),** Volume 10, Issue 09, (September 2019) issue of the journal based on the Recommendation of the Editorial Board without any major corrections in the content submitted by the researcher.

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Review Report

Date: 12-September-2019

Title: DESIGN THEORY AND ANALYTICAL ANALYSIS OF A SOLAR STILL

Authors: Devesh Singh and Freddie L. Inambao

Evaluation	Poor	Fair	Good	Very Good	Outstanding
Originality					√
Innovation				√	
Technical merit					√
Applicability					√
Presentation and English					√
Match to Journal Topic					√
Recommendation to Chief Editors					
	Strongly Reject	Reject	Marginally Accept	Accept	Strongly Accept
Recommendation					√

Review Comments: This paper reviews the theory behind still design, mathematical models used to analyze system performance. The system performance results obtained through the numerical solution of the mathematical model using MATLAB are for a double slope solar still operating in Durban, South Africa. **Analytical study. Paper Accepted for publication in IJMET.**

Appendix B – Qualitative Approach

B.1 Feasibility Study

Research Survey

My name is Devesh Singh. I am completing a Master of Science in Mechanical Engineering degree at the University of KwaZulu-Natal through a design and research project. I am tasked with designing, modelling and analyzing a Solar Powered Water Desalination System.

As part of the qualitative approach to my methodology I am attempting to survey members of the general population. The survey includes basic information about yourself, your knowledge on water usage and scarcity in the region, alternative means of water supply and implementation within South Africa and lastly, your views on the viability of desalination systems for everyday use.

Please remember that the answers you provide are your opinions and are based on your own knowledge, as such, if you do not know or are unsure of the answer there is no need to research it. I need to gauge the understanding of the general population on these key issues.

The questionnaire should take approximately 10 - 12 minutes to complete.

Thank you for your help.

* Required

1. **Email address** *

Personal Information

Please note that all personal information will be treated as confidential. Information will only be used for research purposes. No personal information will be supplied to or handled by any third party without attaining your prior consent.

2. **First Name** *

3. **Surname** *

4. **Age** *

5. **Occupation** *

6. **Organisation** *
   Name of company or learning institution to which you belong.

7. **Highest Qualification** *
Mark only one oval.

- Did not complete grade 12
- Grade 12
- Higher certificate / Diploma
- Bachelors degree (Including Honours)
- Post graduate degree (Masters/PhD)

8. **City of Residence** *

____

9. **Number of individuals in your household** *

____

State of Water Resources

Opinions, knowledge and biographic based questions regarding water resources in your region.

10. **1) What is your understanding of what potable water is?** *
Please limit your description to less than 10 words. If you are unsure, please state "Do not know" as your answer.

____
____
____
____
____

11. **2) What is the primary source of drinking water at your residence?** *
Mark only one oval.

- Municipality
- Borehole
- River/Lake
- Rainwater
- Bottled water
- Other: _______________________________

12. **3) On a scale of 1 to 10 - how safe for consumption is the water supplied by your municipality?** *
Mark only one oval.

	1	2	3	4	5	6	7	8	9	10	
Not safe for consumption	◯	◯	◯	◯	◯	◯	◯	◯	◯	◯	Extremely safe for consumption

13. **4) On a scale of 1 to 10 - how scarce are water resources in South Africa?** *
Mark only one oval.

	1	2	3	4	5	6	7	8	9	10	
Extremely scarce	⬭	⬭	⬭	⬭	⬭	⬭	⬭	⬭	⬭	⬭	Not scarce at all

14. **5) How many litres of water do you drink per day?** *
Include water used in beverages such as tea and coffee.
Mark only one oval.

- ⬭ Less than 1 litre
- ⬭ 1 litre - 1.99 litres
- ⬭ 2 litres - 2.99 litres
- ⬭ 3 litres - 3.99 litres
- ⬭ Greater than 4 litres

15. **6) How many litres of water, would you estimate, do you use per day in total to complete everyday tasks?** *
Tasks may include; bathing, ablution, laundry, garden, etc.
Mark only one oval.

- ⬭ Less than 10 litres
- ⬭ 10 litres - 24.99 litres
- ⬭ 25 litres - 49.99 litres
- ⬭ 50 litres - 74.99 litres
- ⬭ 75 litres - 99.99 litres
- ⬭ More than 100 litres

16. **7) What percentage of South Africa's population has access to a supply of safe drinking water?** *
Mark only one oval.

- ⬭ Less than 30%
- ⬭ 30% - 49.99%
- ⬭ 50% - 69.99%
- ⬭ 70% - 89.99%
- ⬭ 90% - 94.99%
- ⬭ More than 95%

17. **8) On a scale of 1 to 10 - how much do you attempt to conserve water during your daily activities?**
Mark only one oval.

	1	2	3	4	5	6	7	8	9	10	
Not conservative at all	⬭	⬭	⬭	⬭	⬭	⬭	⬭	⬭	⬭	⬭	Extremely conservative

18. **9) Do you believe that there are sufficient measures in place to ensure the delivery of safe drinking water for current/future generations in South Africa?** *

These measures may be put in place by the municipality or provincial/national government.
Mark only one oval.

- Yes
- No

Alternative Sources of Water

These questions relate to alternative sources of water and are opinion and knowledge based.

19. **10) Which means of water supply is the best alternative to the municipal water supply?** *

Mark only one oval.

- Borehole
- River/Lake
- Rainwater
- Reclaimed/gray water
- Atmospheric water generation
- Desalination
- Other: ____________________

20. **11) Which method of potable water production do you prefer?** *

Potable water is water that can be deemed as safe for consumption (drinking and food preparation).
Mark only one oval.

- Filtration
- Boiling
- Chemical treatment
- Ultraviolet irradiation
- Other: ____________________

21. **12) What is your understanding of desalination?** *

Please limit your description to less than 20 words. If you are unsure, please state "Do not know" as your answer.

____
____
____
____
____

22. **13) Which do you believe is the most effective and efficient method of desalination?**

If your answer to question 12 was "Do not know" please select "Do not know" as your answer for this question.
Mark only one oval.

- Reverse Osmosis
- Solar Distillation
- Electrodialysis
- Humidification-dehumidification
- Do not know
- Other

23. **14) Are there any large scale desalination plants in South Africa supplying drinking water to the general population?** *

If your answer to question 12 was "Do not know" please select "Do not know" as your answer for this question.

Mark only one oval.

- Yes
- No
- Do not know

24. **15) Do you believe there is sufficient investment in finding and implementing alternative means of supplying water in South Africa?** *

Mark only one oval.

- Yes
- No

Future of Desalination

Desalination is a general term for a process of removing salt and other minerals from seawater to make it suitable for human consumption (potable). Most desalination systems can produce potable water from both fresh and seawater. Given the aforementioned, please answer the following.

25. **16) If given the opportunity, would you purchase a desalination device for your household/business to become partially or completely independent of the municipal water supply?** *

Mark only one oval.

- Yes
- No

26. **17) What would be the deciding factor guiding your above decision?** *

Mark only one oval.

- Startup costs
- Volumetric output
- Input energy requirements
- Size, noise and aesthetics
- Maintenance requirements
- Output water quality
- Other: ______________________

27. **18) Do you believe desalination is the answer to current/future water shortage issues that may arise in South Africa?** *

Mark only one oval.

- Yes
- No

28. **19) What alternative energy source, do you believe is the best means of powering desalination systems?** *

Mark only one oval.

- Solar
- Wind
- Geothermal
- Wave power
- Other

29. **20) If solar energy was used to power a desalination system, do you believe South Africa receives sufficient solar irradiation on average per year to make the process viable?** *

Mark only one oval.

- Yes
- No
- Do not know

Send me a copy of my responses.

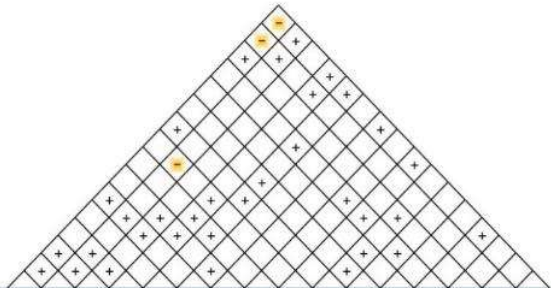
B.2 Quality Function Deployment

QFD: House of Quality
Project: Solar Still Design
Revision: 1.0
Date: 13 May 2019

Correlations	
Positive	+
Negative	−
No Correlation	

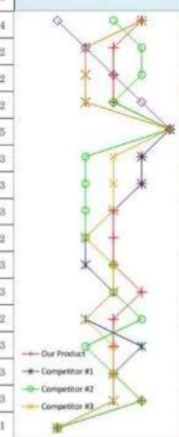
Relationships	
Strong	●
Moderate	○
Weak	▽

Direction of Improvement	
Maximize	▲
Target	◇
Minimize	▼



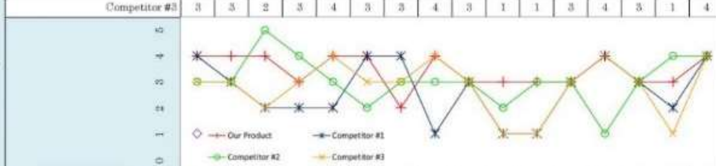
Row #	Relative Weight	Customer Importance	Maximum Relationship	Customer Requirements (Explicit and Implicit) \ Functional Requirements	1 Materials	2 Manufacturing techniques	3 Insulation	4 Dimensions	5 TDS of input water	6 Coating of materials	7 Weight	8 Basin depth	9 Roof Slope	10 Input and output water tanks	11 Valves used	12 Orientation of still	13 TDS of output water	14 Reflectivity of glass cover	15 Length of input pipe	16 Shape of still	Our Product	Competitor #1	Competitor #2	Competitor #3	Row #
				Direction of Improvement	▲	▲	▲	▲	▼	▲	▼	▼	◇	◇	◇	◇	▼	▼	▲						
1	11%	10	9	Start up costs	●	●	●	○	▽	●	●	○	○	●	○	▽	▽	○	○	●	4	4	3	4	1
2	10%	9	9	Volumetric output	○	▽	●	▽	○	○	▽	●	●	○	○	●	○	●	○	●	3	2	4	2	2
3	4%	4	9	Input energy requirements	▽	▽	●	○	○	○	▽	●	●	○	○	●	○	●	●	●	3	2	4	2	3
4	3%	3	9	Size	○	▽	▽	●	▽	▽	○	○	○	●	▽	▽	▽	○	○	○	3	2	3	2	4
5	5%	5	3	Noise	○	▽	○	▽	▽	▽	▽	▽	▽	○	▽	▽	▽	▽	▽	○	5	5	5	5	5
6	6%	6	9	Maintenance requirements	○	○	○	○	●	●	○	○	○	○	○	▽	○	○	▽	●	4	4	2	3	6
7	9%	8	9	Maintenance cost	●	○	○	○	●	●	○	○	○	○	○	▽	○	○	▽	●	4	4	2	3	7
8	9%	8	9	Water taste	▽	▽	○	▽	●	▽	▽	●	○	▽	▽	▽	●	○	▽	○	3	3	2	3	8
9	5%	5	9	Device working life	●	▽	○	▽	○	●	○	○	○	▽	▽	○	▽	○	○	○	3	2	2	2	9
10	3%	3	9	Autonomy	▽	▽	○	○	○	○	▽	▽	○	○	●	▽	▽	▽	▽	○	3	2	3	3	10
11	9%	8	9	Safe drinking water	○	▽	○	▽	●	▽	▽	●	○	○	○	○	●	●	▽	○	4	3	3	3	11
12	2%	2	9	Thermal Efficiency	●	▽	●	▽	○	●	▽	●	○	○	●	●	○	●	●	●	3	2	4	2	12
13	4%	4	9	Aesthetics	●	●	○	●	▽	●	▽	○	●	●	○	○	▽	○	○	●	3	4	2	3	13
14	6%	6	3	Reliable (365 days a year)	○	○	▽	▽	○	○	▽	▽	▽	○	▽	○	○	○	○	○	3	3	3	3	14
15	6%	6	9	Consistency of volumetric output	▽	▽	●	▽	●	▽	▽	●	○	○	○	○	●	●	○	○	4	3	4	3	15
16	7%	7	9	Pretreatment of input water	▽	▽	▽	▽	●	▽	▽	▽	▽	●	●	▽	●	▽	○	○	1	1	1	1	16

Customer Competitive Assessment



Column #	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
Target	Low cost and readily available materials	Low cost and lead time manufacturing methods	High thermal insulation	Maximise solar energy absorption while minimising material costs	TDS of approximately 600 ppm	Minimal surface coating to prolong service life	Minimise weight, less than 100 kg	Minimise basin depth to between 20 mm and 50 mm	Roof Slope of 15 degrees	Tanks to collect and supply water	Valves to prevent vapour leakage	North - South orientation of still	Minimise to approximately 30 ppm	Minimise reflectivity through proper material selection	Find balance	Breath should be greater than or equal to length
Max Relationship	9	9	9	9	9	9	9	9	9	9	9	9	9	9	9	9
Technical Importance Rating	425.5	261.7	463.8	225.5	527.7	444.7	231.9	491.5	370.2	425.5	319.1	289.4	421.3	453.2	257.4	574.5
Relative Weight	7%	4%	8%	4%	9%	7%	4%	8%	6%	7%	5%	5%	7%	7%	4%	9%
Weight Chart																
Our Product	4	4	4	3	4	4	2	4	3	3	3	3	4	3	3	4
Competitor #1	4	3	2	2	2	4	4	1	3	1	1	3	4	3	2	4
Competitor #2	3	3	5	4	3	2	3	3	3	2	3	3	1	3	4	4
Competitor #3	3	3	2	3	4	3	3	4	3	1	1	3	4	3	1	4

Technical Competitive Assessment



Column #	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16

B.3 Failure Modes and Effects Analysis

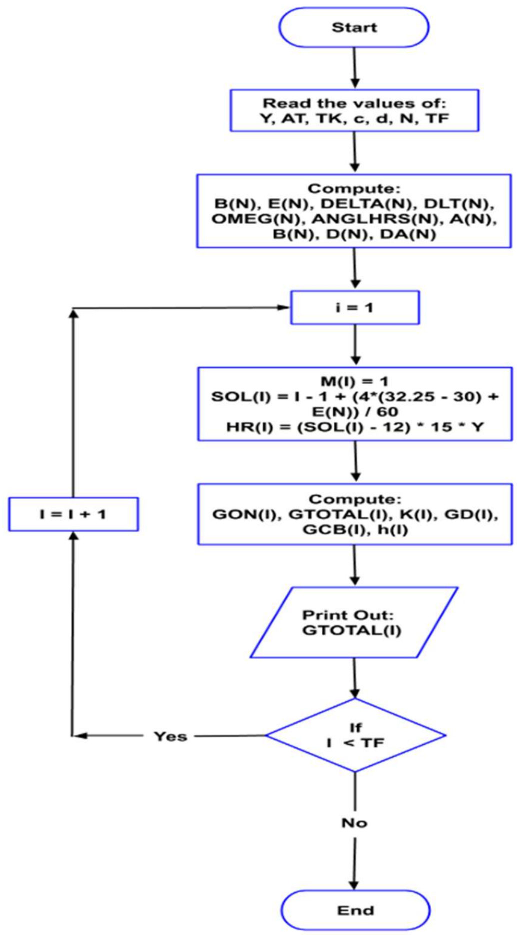
Failure Modes and Effects Analysis for the double slope solar still

Evaluation										Action	Re-evaluation				
Item / Function	Potential Failure Mode(s)	Potential Effect(s) of Failure	S	Potential Cause/ Mechanism of Failure	O	Detection/ Design Controls	D	RPN	Crit	Action(s)	New S	New O	New D	New RPN	New Crit
Glass cover	Fouling	Reduced thermal efficiency	5	Insufficent maintenance by user	5	Periodical service	5	125	25	Provide maintenance guideline	5	4	5	100	20
			5	TDS of input water too high	6	User observation	7	210	30	Specify TDS operating range for users	5	5	7	175	25
Support stand	Corrosion	Structural instability	5	No/insufficent surface treatment of material	4	User observation	4	80	20	Coat support structure in long lasting corrosion protection	5	2	7	70	10
			5	Mechanical damage	5	None	4	100	25	None	5	5	4	100	25
Basin	Leaking	Flooding of still	7	Physical damage to basin tray	4	None	4	112	28	Select more durable basin material	7	3	4	84	21
			7	Incorrect orientation of still or basin	5	User observation	4	140	35	Recommend installation steps for still	7	4	4	112	28
	Fouling	Decrease evaporation	4	Brine outlet blocked	6	Flooding of basin/still	5	120	24	Provide maintenance guideline	4	5	5	100	20
			4	TDS of input water too high	6	User observation	7	168	24	Specify TDS operating range for users	4	5	7	140	20
Pipes	Blockage	Reduced volumetric output	4	Debris in input water	6	Filtration of input water	4	96	24	Add strainer to input tank outlet	4	4	3	48	16
			4	Pipe kinks	5	User observation	4	80	20	None	4	5	4	80	20
			4	Malfunctiong valve	4	Periodical Maintenance	6	96	16	Provide maintenance guideline	4	4	6	96	16
Distillate trough	Fouling	Poor output water quality	5	Insufficent maintenance by user	5	Periodical service	5	125	25	Provide maintenance guideline	5	4	5	100	20
			5	TDS of input water too high	6	User observation	7	210	30	Specify TDS operating range for users	5	5	7	175	25
			5	Holes in still	4	Drop in volumetric output	5	100	20	None	5	4	5	100	20
Inlet brine tank	Empty	Halt solar distillation	6	Leak in tank	3	User observation	4	72	18	None	6	3	4	72	18
			6	Insufficient brine filled into tank	3	User observation	4	72	18	Specify tank should be filled	6	2	4	48	12
Outlet distillate tank	Overflowing	No drainage of distillate from collectiong trough	6	Not emptying tank	3	User observation	4	72	18	Specify tank should be emptied once a day	6	2	4	48	12

Appendix C – Quantitative Approach

C.1 Analytical Model

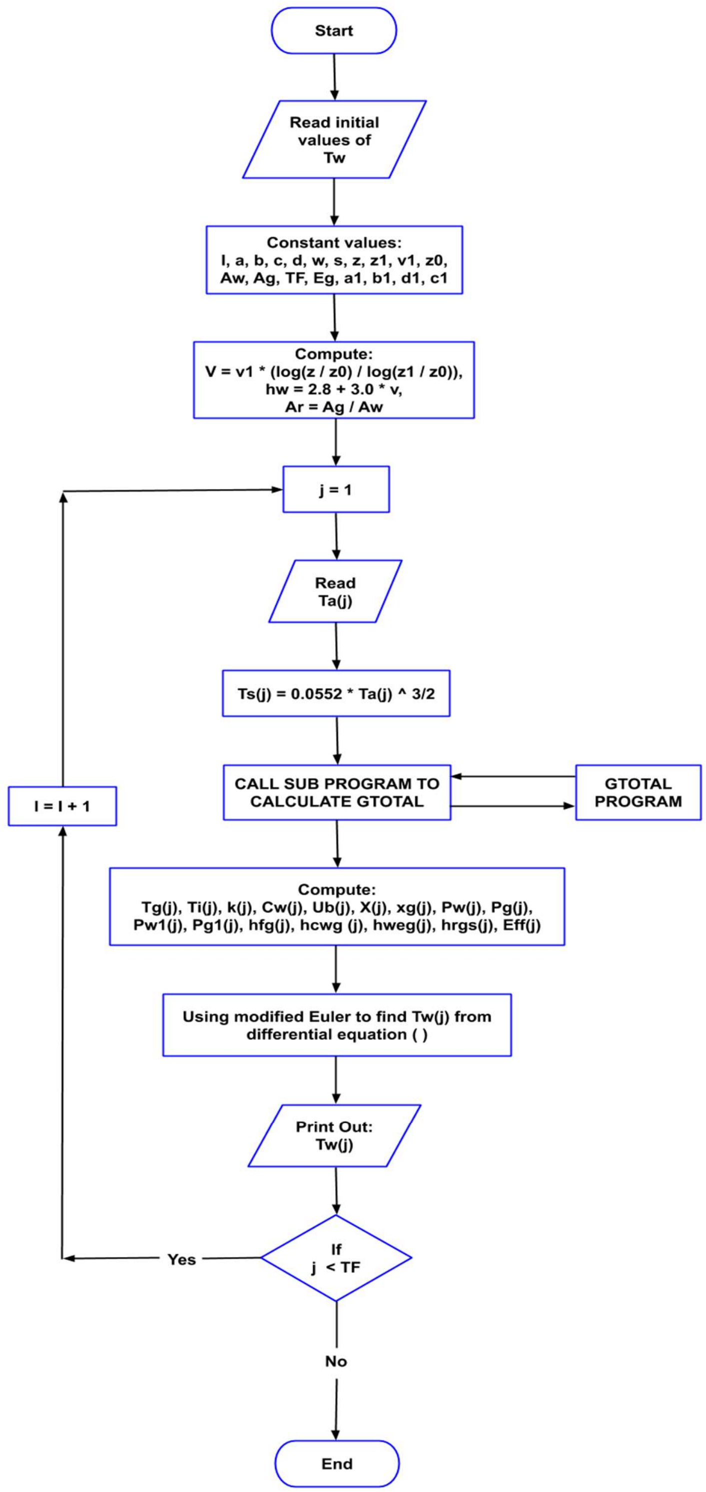
Supplementary Program – g_t.m



Code	Description
function GTOTAL=g_t(); global N;	Start program
Y=3.1415927/180; AT=15.5; TK=0.61; c=3600; d=10^6	Read values of constants

B(N)=(N-1)*360*Y/365; E(N)=229.2*(0.000075+0.001868*cos(B(N))-0.032077*sin(B(N))-0.014615*cos(2*B(N))-0.04089*sin(2*B(N))); DELTA(N)=23.45*sin(360*Y*(284+N)/365); DLT(N)=DELTA(N)*Y; OMEG(N)=cos(-tan(AT*Y)*tan(DLT(N))); ANGLHRS(N)=OMEG(N)*1/Y; A(N)=0.409+0.5016*sin((ANGLHRS(N)-60)*Y); B(N)=0.6609-0.4767*sin((ANGLHRS(N)-60)*Y); D(N)=(2/15)*cos(-tan(AT*Y)*tan(DLT(N))); DA(N)=D(N)*1/Y;	Calculate defined equations
for I=1:11 J=7+1;	Iteration
M(I)=I; SOL(I)=J-1+(4*(32.25-30)+E(N))/60; HR(I)=(SOL(I)-12)*15*Y;	
GON(I)=1367*(1+0.033*cos(360*N*Y)/360)*((cos(AT*Y)*cos(DLT(N))*cos(HR(I)))+(sin(AT*Y)*sin(DLT(N)))); GTOTAL(I)=TK*GON(I)*(A(N)+(B(N)*cos(HR(I)))); Kt(I)=GTOTAL(I)/GON(I); GD(I)=GTOTAL(I)*(0.9511-0.1604*Kt(I)+4.388*Kt(I)^2-16.638*Kt(I)^3+12.336*Kt(I)^4); GCB(I)=GTOTAL(I)-GD(I); h(I)=GD(I); end	Calculate defined equations
function SS=Tww() global ee; GTOTAL=g_t();	Display values of GTOTAL
for I=1:11 SS(I)=GTOTAL./(10*sqrt(1.602)); end	Decision
SS(1)=ee; end	Iterate to using next value
end	End program

Principal Program – Main_Program.m



Code	Description
global N;	Start Program

global ee;	

dt=1;
tf=24;
t(1)=0;
np=(tf-t(1))/dt;
dt1=(t(1)+1)/dt;
Tw0(1)=0;
l=0.05;
a=0.02612;
b=15.76;
c=2392;
d=0.048;
e=3.8213;
w=0.0;
s=5.67*10^-8;
Ta1=[27 29.5 31 33.5 35 35 36 36.5 36 35.5 34.5];
Ta2=[23.5 26.5 28 29.5 30.5 31 32 32 27 27 26.5];
Ta3=[17 19.5 22.5 24 25 26 27 27 27.5 27 26.5];
Ta4=[23 23 24 25 28 29.5 30.5 31 32 32 31];
Ta5=[27 28 29 32 33.5 33.5 34 34 33 32 31];
Ta6=[17.5 19 22 23.5 25 26 28 29 28 26.5 25];
T7=[14 17.5 19 20 23 25 25.5 24 24 24.5 24];
Ta8=[9 10.5 12 16.5 18 20 21 21 20.5 19.5 18];
Ta9=[13 17 19.5 22.5 23.5 24 26 26 25.5 25 24];
Ta10=[19.5 23.5 26 29 31 31 31.5 32 31 30 28];
Ta11=[23.5 27 29 31 32.5 32.5 32.5 33 32.5 32.5 32];
Ta12=[24 26.5 28.5 31 32.5 33.5 35 35.5 35 34 33.5];
RR=[15 46 74 05 35 166 181 212 243 273 304 349];
sw=[20 23 24 25 28 28 25 25 25 25 23 20];
Z=1;
Z1=10;
V1=4;
Z0=0.03;
Aw=1;
Ag=1.46;
	Read values of constants

V=(log2(Z/Z0)/log2(Z1/Z0))*V1; hw=2.8+3*V; Ar=Ag/Aw;	Compute defined equations
for L=1:12; N=RR(L);	Iteration
GTOTAL=g_t();	Call up g_t.m

if L==1
  disp(['Variation of temperature productivity and solar intensity'])
  disp(['of January'])
Ta=Ta1';
elseif L==2
  disp(['Variation of temperature productivity and solar intensity'])
  disp(['of February'])
Ta=Ta2';
elseif L==3
   disp(['Variation of temperature productivity and solar intensity'])
   disp(['of March'])
Ta=Ta3';
elseif L==4
   disp(['Variation of temperature productivity and solar intensity'])
   disp(['of April'])
Ta=Ta4';
elseif L==5
   disp(['Variation of temperature productivity and solar intensity'])
   disp(['of May'])
Ta=Ta5';
elseif L==6
   disp(['Variation of temperature productivity and solar intensity'])
   disp(['of June'])
Ta=Ta6';
elseif L==7
   disp(['Variation of temperature productivity and solar intensity'])
   disp(['of July'])
Ta=Ta7';
elseif L==8
   disp(['Variation of temperature productivity and solar intensity'])
	Read defined values of Ta

disp(['of August']) Ta=Ta8'; elseif L==9 disp(['Variation of temperature productivity and solar intensity']) disp(['of September']) Ta=Ta9'; elseif L==10 disp(['Variation of temperature productivity and solar intensity']) disp(['of October']) Ta=Ta10'; elseif L==11 disp(['Variation of temperature productivity and solar intensity']) disp(['of November']) Ta=Ta11'; elseif L==12 disp(['Variation of temperature productivity and solar intensity']) disp(['of December']) Ta=Ta12'; end Ts=0.0552*Ta.^(1.5);	

ee=sw(L);
Tw(1)=ee;
for xx=1:12;
kk=xx+7;
q(xx)=xx;
Tg(xx)=(((a*Tw(xx)^2-
b*Tw(xx)+c)*Tw(xx)+(Ar*Ta(xx)*hw)+Ar*Ts(xx)*(0.048*Ta(xx)-9))
/((a*Tw(xx)^2-b*Tw(xx)+c)+(Ar*hw)+Ar*(0.048*Ta(xx)-9))-e);
Ti(xx)=Tw(xx)/2.0+Tg(xx)/2.0;
K(xx)=0.0244+0.7673*10^-4*Ti(xx);
Cw(xx)=999.2+0.1343*Ti(xx)+0.01*10^-4*Ti(xx)^2-6.758*10^-8*Ti(xx)^3;
Ub(xx)=K(xx)/1;
Eg=0.98;
x=647.27-(Tw(xx)+273.15);
a1=3.2437814;
b1=5.86826*10^-3;
	Compute defined equations

c1=1.1702379*10^-8;
d1=2.1878462*10^-3;
xg(xx)=647.27-(Tg(xx)+273.15);
Pw(xx)=165960.72*10^-(x*(a1+b1*x+c1*x^3)
/((Tw(xx)+273.15)*(1+d1*x)));
Pg(xx)=165960.72*10^(-
(xg(xx)*(a1+b1*x+c1*xg(xx)^3))/((Tg(xx)+273.15)*(1+d1*x)));
Pw1(xx)=(101300/760)*Pw(xx);
Pg1(xx)=(101300/760)*Pg(xx);
y=Tw();
hfg(xx)=3044205.5-1679.1109*(Tw(xx)+273)-1.1425*(Tw(xx)+273)^2;
hrwg(xx)=0.9*s*(Tw(xx)^2+Tg(xx)^2)*(Tw(xx)+Tg(xx));
hcwg(xx)=0.884*((Tw(xx)-Tg(xx))+((Pw1(xx)-Pg1(xx))/(268900-
Pw1(xx)))*Tw(xx))^(1/3);
hewg(xx)=(9.15*10^-7*hcwg(xx)*(Pw1(xx)-Pg1(xx))*hfg(xx))
/(Tw(xx)-Tg(xx));
hrgs(xx)=Eg*s*(Tg(xx)^2+Ts(xx)^2)*(Tg(xx)+Ts(xx));
hcgs(xx)=hw*(Tg(xx)-Ta(xx))/(Tg(xx)-Ts(xx));
Ui(xx)=hrwg(xx)+hcwg(xx)+hewg(xx);
Uo(xx)=hw*(Tg(xx)-Ta(xx))/(Tg(xx)-Ts(xx))+hrgs(xx);
Ut1(xx)=(1/(Ui(xx)+1/(Ar*Uo(xx))));
Ut(xx)=1/Ut1(xx);
Eue(xx)=(hewg(xx)/Ut(xx))*Ui(xx)*(Tw(xx)-Tg(xx));
Mw(xx)=(Eue(xx))*10^8/hfg(xx);
p(xx)=Eue(xx);
Eff(xx)=Mw(xx)*hfg(xx)*10^-6/GTOTAL(xx);
Tw(xx+1)=(10+(Ta(xx)+Tw(xx))/2)+(Tw(xx)+(Eff(xx)*GTOTAL(xx))+(Ut(xx)*T
s(xx)))+(Ub(xx)*Ta(xx))/((Cw(xx)/Aw)+Ut(xx)+Ub(xx))*w;
z11(xx)=Tw(xx);
t(xx+1)=t(xx)+dt
dx1b(xx)=Aw/Cw(xx)*(Eff(xx)*GTOTAL(xx)-Ut(xx)*(Tw(xx)-Ts(xx))-
Ub(xx)*(Tw(xx)-Ta(xx)));
Tw(xx+1)=Tw(xx)+dx1b(xx)*dt1;
Tw1(xx)=(Tw(xx)*Tw0(1)+y(xx))*dt1;
dx1e(xx)=Aw/Cw(xx)*(Eff(xx)*GTOTAL(xx)-Ut(xx)*(Tw(xx+1)-Ts(xx))-
Ub(xx)*(Tw(xx+1)+Ta(xx)));	

dTw(xx)=(dx1b(xx)+dx1e(xx))/2; Tw(xx+1)=Tw(xx)+dTw(xx)*dt; Tw(xx+1)=Tw1(xx); end	

format short;
Tg1=Tg'
Tw2=Tw1';
dd=kk';
Mw1=Mw'*10^-5;
disp(['Time(hr); WatTemp; GlasTemp; ambienttemp; SkyTemp; Productivity']);
disp([dd'; Tw2; Tg1; Ta; Ts; Mw1]);
if L==1
figure(11),plot(dd,Tw2,'-kd',dd,Tg1,'-bs',dd,Ta,'-ro')
figure(12),plot(Mw1,Ta,'-kd',Mw1,Tw2,'-bs')
figure(13),plot(dd,GTOTAL,'-
kd','LineWidth',2,'MarkerEdgeColor','k','MarkerFaceColor','r','MarkerSize',5)
figure(14),plot(dd,Eue,'-
kd','LineWidth',2,'MarkerEdgeColor','k','MarkerFaceColor','r','MarkerSize',5)
figure(15),plot(dd,Mw1,'-
kd','LineWidth',2,'MarkerEdgeColor','k','MarkerFaceColor','r','MarkerSize',5)
 	
elseif L==2
figure(21),plot(dd,Tw2,'-kd',dd,Tg1,'-bs',dd,Ta,'-ro')
figure(22),plot(Mw1,Ta,'-kd',Mw1,Tw2,'-bs')
figure(23),plot(dd,GTOTAL,'-
kd','LineWidth',2,'MarkerEdgeColor','k','MarkerFaceColor','r','MarkerSize',5)
figure(24),plot(dd,Eue,'-
kd','LineWidth',2,'MarkerEdgeColor','k','MarkerFaceColor','r','MarkerSize',5)
figure(25),plot(dd,Mw1,'-
kd','LineWidth',2,'MarkerEdgeColor','k','MarkerFaceColor','r','MarkerSize',5)
 	
elseif L==3
figure(31),plot(dd,Tw2,'-kd',dd,Tg1,'-bs',dd,Ta,'-ro')
figure(32),plot(Mw1,Ta,'-kd',Mw1,Tw2,'-bs')
figure(33),plot(dd,GTOTAL,'-
kd','LineWidth',2,'MarkerEdgeColor','k','MarkerFaceColor','r','MarkerSize',5)
	Plot desired system parameters

```
  figure(34),plot(dd,Eue,'-
kd','LineWidth',2,'MarkerEdgeColor','k','MarkerFaceColor','r','MarkerSize',5)
  figure(35),plot(dd,Mw1,'-
kd','LineWidth',2,'MarkerEdgeColor','k','MarkerFaceColor','r','MarkerSize',5)

 elseif L==4
  figure(41),plot(dd,Tw2,'-kd',dd,Tg1,'-bs',dd,Ta,'-ro')
  figure(42),plot(Mw1,Ta,'-kd',Mw1,Tw2,'-bs')
  figure(43),plot(dd,GTOTAL,'-
kd','LineWidth',2,'MarkerEdgeColor','k','MarkerFaceColor','r','MarkerSize',5)
  figure(44),plot(dd,Eue,'-
kd','LineWidth',2,'MarkerEdgeColor','k','MarkerFaceColor','r','MarkerSize',5)
  figure(45),plot(dd,Mw1,'-
kd','LineWidth',2,'MarkerEdgeColor','k','MarkerFaceColor','r','MarkerSize',5)

 elseif L==5
  figure(51),plot(dd,Tw2,'-kd',dd,Tg1,'-bs',dd,Ta,'-ro')
  figure(52),plot(Mw1,Ta,'-kd',Mw1,Tw2,'-bs')
  figure(53),plot(dd,GTOTAL,'-
kd','LineWidth',2,'MarkerEdgeColor','k','MarkerFaceColor','r','MarkerSize',5)
  figure(54),plot(dd,Eue,'-
kd','LineWidth',2,'MarkerEdgeColor','k','MarkerFaceColor','r','MarkerSize',5)
  figure(55),plot(dd,Mw1,'-
kd','LineWidth',2,'MarkerEdgeColor','k','MarkerFaceColor','r','MarkerSize',5)

 elseif L==6
  figure(61),plot(dd,Tw2,'-kd',dd,Tg1,'-bs',dd,Ta,'-ro')
  figure(62),plot(Mw1,Ta,'-kd',Mw1,Tw2,'-bs')
  figure(63),plot(dd,GTOTAL,'-
kd','LineWidth',2,'MarkerEdgeColor','k','MarkerFaceColor','r','MarkerSize',5)
  figure(64),plot(dd,Eue,'-
kd','LineWidth',2,'MarkerEdgeColor','k','MarkerFaceColor','r','MarkerSize',5)
  figure(65),plot(dd,Mw1,'-
kd','LineWidth',2,'MarkerEdgeColor','k','MarkerFaceColor','r','MarkerSize',5)

 elseif L==7
```

```
    figure(71),plot(dd,Tw2,'-kd',dd,Tg1,'-bs',dd,Ta,'-ro')
    figure(72),plot(Mw1,Ta,'-kd',Mw1,Tw2,'-bs')
    figure(73),plot(dd,GTOTAL,'-
kd','LineWidth',2,'MarkerEdgeColor','k','MarkerFaceColor','r','MarkerSize',5)
    figure(74),plot(dd,Eue,'-
kd','LineWidth',2,'MarkerEdgeColor','k','MarkerFaceColor','r','MarkerSize',5)
    figure(75),plot(dd,Mw1,'-
kd','LineWidth',2,'MarkerEdgeColor','k','MarkerFaceColor','r','MarkerSize',5)

  elseif L==8
    figure(81),plot(dd,Tw2,'-kd',dd,Tg1,'-bs',dd,Ta,'-ro')
    figure(82),plot(Mw1,Ta,'-kd',Mw1,Tw2,'-bs')
    figure(83),plot(dd,GTOTAL,'-
kd','LineWidth',2,'MarkerEdgeColor','k','MarkerFaceColor','r','MarkerSize',5)
    figure(84),plot(dd,Eue,'-
kd','LineWidth',2,'MarkerEdgeColor','k','MarkerFaceColor','r','MarkerSize',5)
    figure(85),plot(dd,Mw1,'-
kd','LineWidth',2,'MarkerEdgeColor','k','MarkerFaceColor','r','MarkerSize',5)

  elseif L==9
    figure(91),plot(dd,Tw2,'-kd',dd,Tg1,'-bs',dd,Ta,'-ro')
    figure(92),plot(Mw1,Ta,'-kd',Mw1,Tw2,'-bs')
    figure(93),plot(dd,GTOTAL,'-
kd','LineWidth',2,'MarkerEdgeColor','k','MarkerFaceColor','r','MarkerSize',5)
    figure(94),plot(dd,Eue,'-
kd','LineWidth',2,'MarkerEdgeColor','k','MarkerFaceColor','r','MarkerSize',5)
    figure(95),plot(dd,Mw1,'-
kd','LineWidth',2,'MarkerEdgeColor','k','MarkerFaceColor','r','MarkerSize',5)

  elseif L==10
    figure(101),plot(dd,Tw2,'-kd',dd,Tg1,'-bs',dd,Ta,'-ro')
    figure(102),plot(Mw1,Ta,'-kd',Mw1,Tw2,'-bs')
    figure(103),plot(dd,GTOTAL,'-
kd','LineWidth',2,'MarkerEdgeColor','k','MarkerFaceColor','r','MarkerSize',5)
    figure(104),plot(dd,Eue,'-
kd','LineWidth',2,'MarkerEdgeColor','k','MarkerFaceColor','r','MarkerSize',5)
```

figure(105),plot(dd,Mw1,'- kd','LineWidth',2,'MarkerEdgeColor','k','MarkerFaceColor','r','MarkerSize',5) elseif L==11 figure(111),plot(dd,Tw2,'-kd',dd,Tg1,'-bs',dd,Ta,'-ro') figure(112),plot(Mw1,Ta,'-kd',Mw1,Tw2,'-bs') figure(113),plot(dd,GTOTAL,'- kd','LineWidth',2,'MarkerEdgeColor','k','MarkerFaceColor','r','MarkerSize',5) figure(114),plot(dd,Eue,'- kd','LineWidth',2,'MarkerEdgeColor','k','MarkerFaceColor','r','MarkerSize',5) figure(115),plot(dd,Mw1,'- kd','LineWidth',2,'MarkerEdgeColor','k','MarkerFaceColor','r','MarkerSize',5 end;	
end	End Program

Appendix D – Editing Certificates of Publications and Dissertation

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EDITING CERTIFICATE

Re: **Devesh Singh**
UKZN Master's dissertation: **Design of an Improved Solar Powered Water Desalination Plant**

I confirm that I have edited this dissertation and the references for clarity, language and layout. I returned the document to the author with track changes so correct implementation of the changes and clarifications requested in the text and references is the responsibility of the author. I am a freelance editor specialising in proofreading and editing academic documents. My original tertiary degree which I obtained at the University of Cape Town was a B.A. with English as a major and I went on to complete an H.D.E. (P.G.) Sec. with English as my teaching subject. I obtained a distinction for my M.Tech. dissertation in the Department of Homeopathy at Technikon Natal in 1999 (now the Durban University of Technology). I was a part-time lecturer in the Department of Homoeopathy at the Durban University of Technology for 13 years.

Dr Richard Steele
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per email

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EDITING CERTIFICATE

Re: **Devesh Singh**
Journal article: **Solar Desalination: A Critical Review**

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To: **Devesh Singh**
For editing article: **Design Theory and Computational Analysis of a Solar Still**

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08 September 2019
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