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THE POTENTIAL FOR SOLAR HEAT IN THE CAPE FOOD AND BEVERAGE INDUSTRY

by

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in

Mechanical Engineering

Dissertation Supervisor:

Denis Van Es

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ABSTRACT:

This report investigates whether or not current solar water heating technology has the potential to supplement conventional energy use within the Western Cape food and beverage industry. In order to achieve this, two things need to be investigated, namely, the potential for such technology in terms of market size and the cost of rolling it out. The report also states at what energy price and under what constraints solar water heating will be feasible as a bulk energy source.

DECLARATION

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SIGNATURES:

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EXECUTIVE SUMMARY

The main purpose of this dissertation *is to establish whether there is potential for solar heat to provide energy to the food and beverage industry, using the Western Cape as the focal point* of this study. To fulfil this task, two objectives have to be achieved, namely, quantifying the market potential for the technology in this industry and calculating the costs involved in implementing such technology.

Background and Introduction

In the Western Cape, 47% of primary energy is consumed by the industrial sector, and a large portion of this is for thermal heat. The food and beverage industry (F&BI) is one of the largest industries in this province and, hence, consumes a considerable amount of energy.

Historically, energy costs in the F&BI have been low, i.e. less than 10% of production costs (DME 2002), but in the current energy climate, these costs are due to rise sharply. Companies need to adapt, either by initiating energy efficiency measures (CCT 2003) or by using renewable energy technologies.

Solar heating systems offer a way for industry to reduce their reliance on fossil fuels. Many of the processes in industry run continuously and are therefore well suited to augmentation with solar heat. The F&BI consumes a large proportion of thermal energy, much of which (60%) is demanded at temperatures below 250°C, which can easily be provided for by solar water heaters (Vannoni, Battisti and Drigo 2008).

Using solar heat to cater for part of this demand will not only have benefits for the company concerned but will also offer a way of reducing peak demand and relieving stress on the national grid. Solar water heating technologies can also reduce the GHG emissions of a company considerably. Investing in a solar water heating system is therefore a good way for companies to hedge the risk of future carbon taxes and/or regulatory measures.

PROCEDURE AND THEORY

In order to achieve the aim of this dissertation, local food and beverage companies were contacted to participate in the study. Energy consumption data was gathered from these companies to decide which processes might be suitable to augment with solar heating systems. The pre-heating of boiler make-up water was deemed a suitable example to demonstrate the economics of the technology, as it was a common process to many of the respondents.

The energy analysis software RETScreen (Natural Resources Canada 2010) was used to model the solar systems. Actual data from solar collector manufacturers was gathered. Three different types of solar collectors were investigated, namely, flat plate collectors, evacuated tube collectors and parabolic trough concentrators. The relevant solar radiation data for each site was used in RETScreen. The solar radiation data was extracted from the NASA *Surface meteorology and Solar Energy* website. The process load data was extracted from the information received from the companies.

The economic payback of the solar heating systems was then analysed using the lifecycle cost analysis. With this analysis, the net present value of the systems can be compared to alternative investments, to determine whether solar systems would be a good investment choice.

A sensitivity analysis was conducted on the results to see what effects future price increases would have on the net present value of the solar systems. A large range of future scenarios was explored, utilising six different fuel prices for each of the two fuels (coal and electricity). HFO was also considered, but none of the participants in the study had boilers that run on HFO.

RESULTS OF LIFECYCLE COST ANALYSIS

The main results of the analysis are presented below:

- The technical potential for solar heat in the Western Cape is ***12 PJ*** of total primary energy, which is equivalent to 9% of the total industrial consumption in the Western Cape.
- This is 60% of the consumption of paraffin, HFO and coal within the F&BI within the province and is roughly equivalent to ***2.3 million*** square meters of flat plate collectors, if each collector yields 1.439 MWH/m^2 per year.
- The two most important factors to consider before implementing a solar heating system are: the annual utilisation of the process and the price of the fuel being supplemented.
- Systems that are used for less than six months of the year are generally not feasible.
- Under the current fuel prices, none of the systems analysed paid back in less than 14 years, and the largest net present value was R 705 000, which was for a system with an investment cost of R8 million.
- The systems are deemed to be feasible when annual payback of the systems is less than five years.
- The flat plate collector systems show the best performance under the lifecycle cost analysis, and become feasible at an electricity price of 52 c/kWh where the annual utilisation is above 8 months.

- Parabolic trough system and evacuated tube systems only become feasible where electrical resistance heaters are used and the electricity price rises above 0.75 c/kWh and 65 c/kWh respectively (with high annual utilisation).
- Parabolic trough concentrators show good thermal performance at higher temperatures and offer a good way of producing medium temperature steam, although at high cost. They produce the most energy per area out of the three collector types modelled and therefore offer larger potential GHG emissions savings.

CONCLUSIONS AND RECOMMENDATIONS

- Solar heating systems offer a very affordable way for the province to meet its GHG emission reductions. The capacity cost of implementing solar heating systems is far lower than concentrated solar power (CSP) and wind power. It is therefore recommended that future government subsidies be aimed at industrial size solar water heater systems.
- If large projects could be stimulated by government investment, the industry would stand to benefit from large economies of scale in the manufacturing process.
- It is recommended that local municipalities within the Western Cape collect more disaggregated energy consumption statistics to make calculating the potential for new technologies more efficient. Currently, there is a lack of energy statistics in the province.
- Factories using electricity to generate thermal energy, where the energy required is below 100°C, should definitely investigate the possibility of solar water heating systems.
- Factories utilising coal boilers should only consider solar heating systems when the annual utilisation is more than 10 months of the year and the cost of coal is 1250 R/tonne; even in this scenario, they should only use flat plate collector systems.
- Apart from the economic benefits of fuel savings, SWH systems offer a more risk averse investment of capital, in view of the possible implementation of regulatory measures to reduce GHG emissions. If one believes that civilization is gradually becoming a carbon constrained society, investment in SWH also offers an advantage over the business as usual (BAU) scenario. Companies exporting goods to overseas markets where carbon constraints already exist need to be especially cautious.

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LIST OF ACRONYMS

Collector Types

CPC	compound parabolic trough concentrators (*a truncated piece of sheet metal is formed into the shape of a parabola, this acts as the backing of the collector, which reflects rays onto a central tube)*
ETC	evacuated tube collectors *(the common long glass tubes found on roofs across the country)*
EFPC	evacuated flat plate collectors *(a flat plate collector with an evacuated space between glazing and absorber plate of the collector sometimes filled with an inert gas i.e. krypton)*
FPC	flat plate collectors *(the ordinary collector found on many house around South Africa)*
LFC	linear fresnel collectors *(a concentrating collector consisting of long rows of parallel mirrors, usually flat that reflect light onto a central tube located above the mirrors)*
PTC	parabolic trough concentrators *(a series of long mirrors or sheet metal shaped into a parabola when viewed in profile, they concentrate the sun's energy onto a central tube located above the mirrors)*

General

3-D	three dimensional
AFPC	advanced flat plate collectors
ARS	absorption refrigeration system
BAU	business as usual
CCT	City of Cape Town
CIF	cost, insurance and freight
CIP	cleaning-in-place
COMA	Company A
COMB	Company B
COMC	Company C
COP	coefficient of performance
CRF	capital repayment factor
CSP	concentrated solar power
DLR	Deutsches Zentrum für Luft und Raumfahrt e.V.
EU	European Union
ERI	Energy Research Institute (University of Cape Town)
F&BI	food and beverage industry
FEC	final energy consumption
FFPS	future fuel price scenario

GCV	gross calorific value
GHG	greenhouse gas
HFO	heavy fuel oil
HHV	higher heat value
HTF	heat transfer fluid
IEA	International Energy Agency
IDAE	Instituto para la Diversificacion y Ahorro de la Energia
IGES	Institute for Global Environmental Strategies
INETI	Inst. Nacional de Engenharia e Tecnologia Industrial
IPCC	International Panel for Climate Control
IPPs	independent power producers
IRR	internal rate of return
JSE	Johannesburg Stock Exchange
LCA	lifecycle cost analysis
NCV	the net calorific value
NEP SOLAR	New energy partners SOLAR
NERSA	the National Energy Regulator of South Africa
NREL	National Renewable Energy Laboratory
NPV	net present value
O&MC	operating and maintenance costs
PC	parasitic costs
RFO	residual fuel oil
SCOP	solar coefficient of performance
SEGS	solar electricity generating systems
SHC	solar heating and cooling
SHS	solar heating system
SPES	Institut Catala d’Energia and Sociedade Portuguesa de Energia
SWH	solar water heating
TI	transparent insulation
TMY	typical meteorological year
UPH	useful process heat
US	United States
USA	United States of America
USH	useful supply heat
VAT	value added tax
ZAE	Bayern Zentrum für Angewandte Energieforschung e.V. (Bavarian Centre for Applied Energy Research)

LIST OF SYMBOLS

Nomenclature

a_1	First order heat loss coefficient
a_2	Second order heat loss coefficient
A_c	Area of the collector (either gross or aperture)
A_{fh}	Energy content of the fuel
A_{fm}	Energy content of the fuel on a mass basis
b_o	Angle of incidence modifier coefficient (used to calculate the angle of incidence modifier)
°C	Temperature in degrees Celsius
C_{energy}	Cost of energy
CH_4	Chemical symbol for methane
C_{load}	Cost of powering a conventional heating system
CO_2	Chemical symbol for carbon dioxide
CO_2e	A quantity of emissions equivalent to an amount of carbon dioxide emissions
C_p	Specific heat capacity of a substance expressed in J/kg.K
d	Discount rate
F	Future value of a cash flow
F_{ch}	The carbon emissions factor of a fuel based on the fuel's energy content
F_R	The heat removal factor, a term used in the efficiency equation of solar collectors
F_{ox}	The oxidation factor of a fuel to account for the particulate matter emitted by a combustion event
GJ	Gigajoules, a unit of energy equal to a billion joules.
G_T	The amount of solar radiation falling on a collector
GW	Gigawatt, one billion watts, a unit of power or installed capacity of an energy consuming device/s
H_m	Gross calorific value of a fuel on a mass basis
kg	kilogram, or one thousand grams
kJ	Kilojoule, one thousand joules
K_θ	The angle of incidence modifier of a collector
kW	Kilowatt, one thousand watts
kWh	A kilowatt-hour, a measure of energy equivalent to 3600 kilojoules
L/d	Litres per day
L/m^2	Litres per square meter
m^2	meters squared
$\dot{m}$	Mass flow rate, [kg/s]
MW_{th}	Megawatt thermal, the installed capacity of an energy consuming/producing device where the output is thermal energy

MWh	Megawatt-hours
n	Number of years
N_2O	The chemical symbol for nitrous oxide
NO_x	The chemical symbol for the oxides of nitrogen i.e. nitrogen oxide and nitrogen dioxide
	Rate of heat or energy consumption in kJ/hour
Q_u	The useful heat available from a solar collector
Q_L	The desired cooling load from a refrigerator or cooling unit
Q_{load}	The amount of energy used in a heating system
P	The present value of a future cash flow
PJ	Petajoule, one trillion kilojoules
R	Rand
R/kWh	Rand per kilowatt-hour
S	Solar radiation absorbed by a collector
ΔT	A difference in temperatures measured in degrees Kelvin
ΔT_m	The true mean fluid temperature difference in a solar collector
T_a	The ambient temperature
T_i	The fluid inlet temperature
U_L	Thermal heat loss coefficient, [W/m^2.K]
W/m^{2}K^2	The units for the second order temperature dependent coefficient of a solar collector
W_{net}	The net work input required by a refrigeration or cooling unit

Greek Symbols

η_i	The instantaneous efficiency of a solar collector
η_0	The efficiency of a collector without heat losses, i.e. optical efficiency multiplied by the global irradiation falling on the collector
η_{Boiler}	The efficiency of a boiler
$\eta_{Supply\ System}$	The efficiency of a supply system
$(\tau\alpha)_n$	The optical efficiency of a solar collector (for normal irradiation) equal to the product of the absorptance and emittance of a collector

GLOSSARY OF TERMS

Attenuation	A physics definition: a decrease in a property, such as energy, per unit area of a wave or a beam of particles, that occurs as the distance from the source increases as a result of absorption, scattering, spreading in three dimensions, etc.
Boiler make-up water	Is the water from the municipal supply that is added to water returning to the boiler for reheating' certain process will lose water or will use the water directly and hence it cannot be returned for reheating.
Diffuse radiation	Is that part of the incoming solar radiation that has been reflected, transmitted or diffused through particles in the earth's atmosphere
Extraterrestrial	Not originating from within the limits of the earth
Insolation	Another term used to describe incoming solar radiation
Installed Capacity	The installed capacity of a device is the amount of power that it can produce or consume, depending on its function. Power is a measurement of the rate of energy consumption, watts (W), kilowatts (kW), megawatts (MW) and gigawatts (GW) are all units of power and not to be confused with kilojoules (kJ) and kilowatt-hours (kWh) which are units of energy.
Solar Heat	Refers to the solar thermal energy output from a single solar collector or an array of collectors
Solar Radiation	This is the incoming energy from the sun, which travels as electromagnetic waves. Heat travels from the sun in this form at a wavelength smaller than that of visible light, i.e. the infrared part of the spectrum
Solar Irradiance	This is the rate at which solar radiation reaches an area on earth and is fundamentally different to the amount of solar radiation reaching an area. The latter is the summation of the solar irradiance over a given period of time.
Vapourisation	The process by which a liquid is transformed into a vapour

1. INTRODUCTION

1.1 OVERVIEW AND BACKGROUND

Over the past few years, the once infallible national energy supplier, Eskom, has found it increasingly difficult to ensure a stable and secure supply of electricity to the country. As a result, there is uncertainty around the future of the energy supply within the country. Three other significant factors have added to the lack of confidence in the energy supply sector: the uncertainty around the future cost of electricity, the government's pledge to reduce greenhouse gas (GHG) emissions, and the failure of the National Energy Regulator of South Africa (NERSA) to incorporate independent power producers (IPPs) into the national energy supply mix.

Over the last year, demand for power decreased considerably, solely due to the global economic recession: 8.1% for the first four months of 2009 compared with the same period in 2008 (Statistics South Africa 2009). Ironically, this has given the country some leeway, as the rolling blackouts that occurred in 2008 have abated. As a result, however, there are still no clear answers to the three main questions being asked by the electricity consumer: What will be the price of electricity? Who will be supplying the electricity, and in what form? And will climate change targets be imposed on the consumer?

What has become apparent in this time, however, is that the days of cheap energy are over, and that companies will have to take responsibility in some way for their GHG emissions. Fifty-five companies listed on the Johannesburg Stock Exchange (JSE) have already disclosed their carbon emissions last year in the third annual Carbon Disclosure Project (Groenewald 2009).

Industry in South Africa consumed 36% of primary energy supplies in 2004 (DME 2009), which is about double that of the residential sector, which consumed 17.9%. Of the 36% energy consumed by industry, coal and petroleum make up about 90% of the supply mixture (DME 2009). South Africa has a high energy intensity per GDP compared to that of developed nations (DME 2002). Whilst the Western Cape does not have many of the mining and mineral processing industries that account for this high energy intensity, industry is still the second largest consumer of energy in the province besides the transport sector. Of the 47% of total primary energy supply consumed by industry, the food and beverage industry (F&BI) consumes a large proportion of this (Department of Environmental Affairs and Development Planning: Western Cape 2008, Sustainable Energy Africa, UCT's Energy Research Centre 2010).

Historically, energy costs in the F&BI have been low, i.e. less than 10% of production costs (DME 2002), but in the current energy climate, these costs are due to rise sharply. Companies need to adapt, either by initiating energy efficiency measures (CCT 2003) or by using renewable energy technologies.

Renewable energy sources, such as solar water heating (SWH), can ensure a stable supply of energy whilst concurrently reducing carbon emissions by displacing conventional energy supplies. Solar heating technologies have been around for many years, and the use of non-concentrating collectors has been well established locally within the residential sector since the 1970's (Holm 2005). Both non-concentrating and concentrating collectors[1] offer benefits to industry, but are not being used extensively for two reasons: they have high upfront capital costs (especially concentrating collectors) and there is a clear lack of understanding surrounding the implementation of such technology within industry. Internationally, there have been studies to quantify the potential for solar heat[2] in industry (Vannoni, Battisti and Drigo 2008, Benz, Gut, et al. 1999), but not much is known about the potential for solar heat within industry in South Africa. According to Vannoni et al (2008), there are only 90 plants worldwide that produce process heat from solar energy; collectively, these plants have a total installed capacity of 25 MW_{th}.

The F&BI uses a large proportion of energy on refrigeration and process heat. According to Vannoni et al (2008), 60% of process heat in the F&BI is required at temperatures below 250˚C (with the remaining 40% needed at temperatures above 250°C). Thanks to ongoing research, currently both non-concentrating and concentrating collectors can readily supply heat at temperatures up to 250°C (Weiss and Rommel 2008). Conventional energy supplies for these processes can be augmented with solar heat by incorporating modern SWH systems in parallel with the existing conventional energy supplies. According to the study done by Vannoni et al (2008), 3-4% of the industrial process heat demand of the European Union (EU) could be replaced by solar heat, translating to 100-125 GW_{th} of installed SWH capacity.

This dissertation aims to gain a clearer understanding of how much solar heat could potentially be used within the Western Cape region by monitoring the power used by a few of the large industrial food and beverage manufacturers. As an added benefit, the data collected will also demonstrate the potential environmental impacts such measures could have.

1.2 HYPOTHESIS AND RESEARCH OBJECTIVES

The goals of this dissertation are:

First, to quantify the potential contribution of solar energy to the aggregate energy demand of the food and beverage industry in the Western Cape.

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[1] Currently no examples of this type of collector exist in South Africa, apart from small scale demonstrations in academic institutions.

[2] Solar heat is used here and in the rest of the document in place of solar thermal energy; this refers specifically to the energy gained from solar collectors and is not to be confused with solar heating. Solar heating is the use of solar heat or solar thermal energy for heating. Solar heat can also be used for cooling and electricity generation.

Second, to consider the relative financial viability of three types of solar heating systems in servicing that demand.

In order to achieve these objectives, the power used by large food and beverage manufacturers will be monitored to establish exactly how much energy is being used for refrigeration and the generation of process heat. A few large consumers within this industry will be targeted. This research will in no way be able to cover all the food and beverage manufacturers in the Western Cape, however, and is not intended as an exhaustive study. But the data will nonetheless give an indication of the order of magnitude of the potential, i.e. whether it is in the region of kW or GW.

Once the power consumption data has been arranged into end use temperature ranges, as demanded by the various processes, suitable solar heating solutions can be assigned to meet these end use temperature demands. Thus, the second goal of this dissertation is to determine the cost of implementing solar heating systems[3] (SHSs) to supplement the conventional energy supplies within the factories monitored. The cost of implementing the SHS will be compared to the price of conventional energy supplies, and the point at which the use of SHSs becomes economically competitive will be established.

There are limitations with regard to how much conventional energy a SHS can displace, namely, the available roof space at a facility, and the availability of solar insolation[4] at a site etc. These limitations, and the rationale behind any assumptions made, will be discussed in Chapter 7, which presents the results[5].

Once the total amount of conventional energy displaced by the implementation of the SHS has been calculated, this study also aims to establish the amount by which GHG emissions are reduced when the proposed systems are used. Given government's current stance on climate change, it is important for companies to know exactly where they stand with regard to GHG emissions, so that they will thus be ready for any binding reduction measures.

1.3 METHODOLOGY

This dissertation essentially involves a review of the literature on solar heating and cooling for industrial processes. Both local and international literature has been consulted. Whenever possible, literature

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[3] A solar heating system (SHS) is a system that uses solar insolation to generate solar heat, which can then be used for heating, cooling or power generation. The heat transfer fluid (HTF) may not necessarily be water, as is the case with a SWH system.

[4] This is another term for solar radiation.

[5] The first part of Chapter 7 presents the results of the project whereas the second part of the chapter discusses them.

specifically pertaining to the F&BI has been sought; using the information obtained from these sources, the project aims to discover the potential of solar heating within the South African context, using the F&BI within the Western Cape as a focal point. Consequently, users that have been identified as large consumers of power in the particular industry have been approached for permission to carry out an energy audit. These audits reveal exactly how much power is being consumed in processes that could be augmented with a SHS.

With detailed knowledge of the energy consumption within these large factories, the three main objectives of the project can be explored. The methodology behind these objectives is discussed below.

The initial step in establishing if there is potential for the use of solar heat in the Western Cape's F&BI is to monitor the power that is currently being used in this industry for processes that could be substituted and/or augmented with solar heat. In the literature, there are many papers describing the potential applications of solar heat (Norton 1999, Kalogirou 2004). Other authors have used computer modelling tools to simulate how SHSs would perform in existing factories (Benz, Gut, et al. 1999, Kalogirou 2003, Kulkarni, Kedare and Bandyopadhyay 2008), specifically within the F&BI. Although the results are theoretical and the designs were not actually built, the results of these modelling tools have been shown to be accurate within 10% (Kalogirou 2004).

In order to monitor accurately how much power a facility consumes over a given time period, a year for argument's sake, one would ideally need to perform the energy audit over the full period. But in reality, this is often not possible due to time constraints and unavailable equipment. Often one has a small window period to set up the current loggers; this can only be done, for example, during a maintenance shutdown, as many processes run continually otherwise[6]. Although long periods of power monitoring may not be feasible, it is still imperative to determine the load characteristics of the plant being monitored. The load characteristics of a plant vary according to the production patterns followed by the plant.

The current logger thus records the voltage and current drawn by machinery while they are in operation; it records this information in a digital format that can be downloaded onto spreadsheet tools. Although the loggers can take measurements every single minute, this would result in an unnecessarily large volume of captured data. It is important to choose a suitable period between recordings in order to capture the electricity consumption of a machine correctly, whilst at the same time keeping the amount of data recorded to a minimum. This is especially important in studies conducting many audits simultaneously, where data volumes can become very large.

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[6] Some loggers can be set up on live machinery; this depends on the type of equipment available to the user.

Utility bills and load profiles are other tools that the surveyor can use in conjunction with the current loggers in order to gain a relatively accurate picture of an organisation's power consumption. Load profiles for large users are furthermore available from electricity suppliers. These profiles break down exactly how a consumer uses electricity over a given time period. For instance, a cold storage warehouse would normally use the most electricity at the sun's zenith on a hot summer's day.

Once the existing processes have been identified and surveyed, the potential for solar heat in a facility can be established. The magnitude of this potential will be a fraction of the total power consumed in the processes audited. It is often not feasible to supply a process with a solar fraction of unity[7], as this involves the use of thermal storage during periods of insufficient solar insolation or night time production. It is often far more economical to supply a process with an auxiliary heating system to cover periods of insufficient solar insolation than it is to provide back-up in the form of thermal storage (Norton 1999, Kulkarni, Kedare and Bandyopadhyay 2008). The aim is to supply solar heat at the least cost possible, so that the overall system is as competitive as possible in relation to existing energy supplies. Typically, industry is only concerned with investments that can repay themselves in short periods, such as over one-and-a-half years (DME 2002).

As previously mentioned in Section 1.2, the processes surveyed will be sorted into differing temperature ranges and aligned with a suitable SHS. There are many studies in the literature that indicate the costs of SHSs (Kulkarni, Kedare and Bandyopadhyay 2007, Kulkarni, Kedare and Bandyopadhyay 2008, Benz, Gut, et al. 1999, Kalogirou 2003). Costs for evacuated tube collectors (ETC) and flat plate collectors (FPC), for instance, can be gathered from local distributors and manufacturers respectively. For other collector types, the information will have to be gathered from international suppliers, as only the two previously mentioned collector types are currently commercially available in South Africa. There are a few international companies already offering SHS as prefabricated modular units (Heliodynamics 2009, Sopogy 2002, NEP Solar 2010) with information accessible from the internet.

The lifecycle cost analysis (LCA) method will be employed in order to establish the total cost involved in implementing a typical SHS. For the analysis to be valuable, this would need to be a process common to most plants in the F&BI, e.g. boiler make-up water supply[8]. The point at which the SHS becomes economically competitive in relation to the existing energy supplies can be forecast. Obviously, the accuracy of this analysis is dependent on the integrity of the cost data supplied by manufacturers and the accuracy of the data extracted from the literature. The LCA is a well documented method for

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[7] A solar fraction of unity means that all the energy input to a process comes from solar energy and none from a conventional supply. In most cases, this is impossible to implement, let alone feasible.

[8] Boiler make-up water is the water that comes from the municipal water supply to "make up" for water lost in the process heat supply system for a given plant. Water is lost as condensate in steam traps, when there is no condensate return for a process, through leaks, blowdown and when water/steam is used directly in a process.

comparing the costs of different energy producing technologies (Kalogirou 2004, Kulkarni, Kedare and Bandyopadhyay 2008, Duffie and Beckman 2006). In his paper, Kalogirou documents very clearly how this methodology can be used optimally. For instance, the LCA takes into account the time value of money as well as all the costs associated with the design, including future operating costs.

The GHG emissions that are avoided by the design are directly proportional to the amount of electricity and/or other forms of primary energy that the SHSs would displace. With regard to the savings in electricity, figures for GHG emissions avoided on a kWh basis are readily available from Eskom (Eskom 2008). In respect of other types of fuel, there is published data on emissions associated with these fuels, i.e. gas, coal, petroleum etc. Other useful tools such as the *RETScreen Clean Energy Project Analysis Software,* which is a freely available software package, easily allow one to calculate the reductions in emissions that arise from savings on conventional fossil fuels (Natural Resources Canada 2010).

Having identified the research questions and explained the methodology behind the research, the next section will now outline the structure of the report.

1.4 REPORT STRUCTURE

This dissertation is structured as follows:

Chapter 1 introduces the topic, outlines the hypothesis and other research questions that are explored, explains the methodology behind the research, and then summarises the structure of the report.

Chapter 2 is the literature review, which presents the supporting literature on the topic. The literature review begins by considering the local F&BI in the Western Cape and the amount of data that is available with regard to the energy consumption of this industry. The chapter then explores the different types of solar collectors available on the market, focusing on the collectors that show promise for future commercialisation. Sources for costing the SHSs are also examined. Lastly, the chapter explores the issues and limitations surrounding the integration and use of SHSs in existing factories.

Chapter 3 reveals the theory behind the solar radiation data available to the South African public and the limitations of this data.

Chapter 4 covers the solar collectors considered for this study including the cost and performance data for these collectors.

Chapter 5 outlines the theory used in the LCA and the GHG emissions analysis.

Chapter 6 discusses the values and methods used in the calculations that are presented in the results chapter. The assumptions used in the calculations are shown in this chapter.

Chapter 7 presents the results of the energy surveys. The results of the LCA and GHG emissions analysis are introduced. The processes that are the most economically competitive to supplement with solar heating are identified. The future costs of the SHS are plotted against the electricity prices, in order to identify and forecast the point at which solar heating becomes competitive with conventional energy supplies. The second part of Chapter 7 looks objectively at the results and assesses the potential of SHSs to supply energy in the Western Cape F&BI. Questions around the accuracy of the energy audits are explored. Furthermore, the limitations to implementing the chosen solar solutions are discussed. Lastly, the sensitivity of the results to the solar fraction chosen for the processes is examined.

Chapter 8 presents the conclusions and recommendations based on the objectives and results obtained. The solutions for each temperature range are proposed, based on the theory presented in Chapter 2.The validity of the hypothesis, as formulated in the introductory chapter, is assessed. Recommendations are made as to how future research in the field may help to create awareness for the use of solar heat in industrial processes.

Chapter 9 lists the references and bibliographic details of all the works cited. The calculations performed and details of the energy audits are contained in the appendices.

2. LITERATURE REVIEW

The purpose of this chapter is to define the *Potential for Solar Water Heating in the Cape Food and Beverage Industry.* Through a review of the available literature, this chapter thus sets out to identify the processes that would be suitable for supplementation with solar energy and in turn the solar technologies that could be used to supply this energy.

Literature from European studies relating to the potential of using solar heat for industry is also consulted in order to create a comparison with the results of this study. The manufacturing techniques used in the South African F&BI do not differ much from those used in Europe, and therefore one would expect the relative potential on a percentage basis to be much the same, with the exception that the overall quantity of energy considered would differ (the EU, being a much larger economic zone, has a much larger F&BI than South Africa). The European studies thus provided a backdrop against which the results of this study could be compared.

2.1 ENERGY CONSUMPTION WITHIN THE FOOD AND BEVERAGE INDUSTRY

There are numerous studies that contain statistics and data on the amount of total primary energy consumed within South Africa (DME, Eskom, Energy Research Institute 2002, DME 2009). They quantify the total primary energy consumed within the country, including crude oil, natural gas, coal and nuclear fuel. Other studies contain statistics primarily with regard to the electricity supply, and its distribution and consumption (NER 2004, NERSA 2005).

Most of these studies, listed above, provide disaggregated energy balances for the primary economic sectors, namely residential, commercial, industrial (including mining), agricultural, transport and non-energy use. The latter takes into account energy feed stocks that are used to produce chemicals and other non-energy feed stocks, i.e. wood for paper (DME, Eskom, Energy Research Institute 2002).

This study focuses on the F&BI, which is an industrial subsector. Some studies provide consumption data disaggregated into the subsectors of industry (DME 2002, DME, Eskom, Energy Research Institute 2002, Winkler, et al. 2006). But it is hard to find sources that disaggregate energy use to a provincial level.

The main texts used to gauge the energy consumption within the F&BI of Cape Town are, firstly, “The State of Energy Report 2003*”* published by the City of Cape Town (CCT) municipality (CCT 2003) and, secondly, ”Policies and scenarios for Cape Town’s energy future: Options for sustainable city energy development”*,* which builds on the report released by the CCT (Winkler, et al. 2006). Although these reports do not establish a baseline for energy consumption within the industrial subsectors of the Western Cape economy, the figures are the only ones available.

The Department of Minerals and Energy (DME) collaborated with the Energy Research Institute (ERI) and Eskom to produce the report "Energy Outlook for South Africa: 2002" (DME, Eskom, Energy Research Institute 2002), which provides a very detailed breakdown of energy consumption within the industrial sector. This report gives a good indication of the overall size of the F&BI within South Africa and the amount of energy consumed within this industrial subsector.

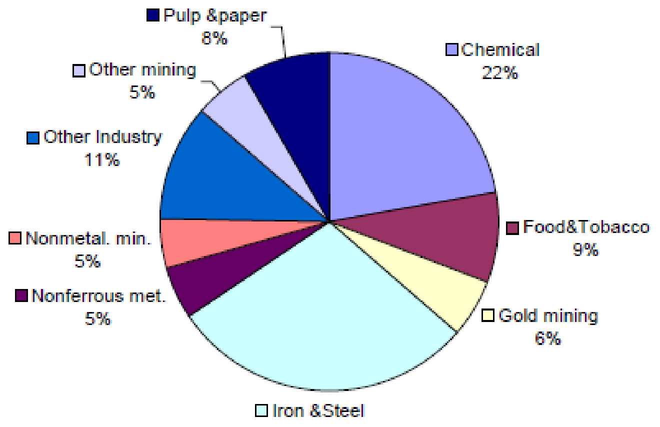

Figure 2.1: Industrial final energy demand by subsector (DME, Eskom, Energy Research Institute 2002)[9]

Industry consumed 42% of the total 3054 PJ of energy demanded within South Africa in 2000. This has decreased to 36% in the latest DME publication (DME 2009), reflecting South Africa's move towards being a service based economy. Of this total, the F&BI consumed 9%, which equates to 113 PJ of energy. To put this in perspective, this is more energy than is consumed within the gold mining industry.

To get a better picture of the energy consumption of the F&BI in the Western Cape, it is useful to refer back to the report by Winkler et al (2006). The total primary energy consumption for industry in Cape Town, for the year 2000, was 25.4 PJ (Winkler, et al. 2006). This equates to 24% of the total energy demand in Cape Town. Of this 24% demand, the F&BI consumes 2.7 PJ or 11% of the industrial demand. Figure 2.2 compares the demand of the large industrial users within Cape Town.

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[9] The Food & Tobacco Industry in Figure 2.1 is another name used in some texts to describe the F&BI.

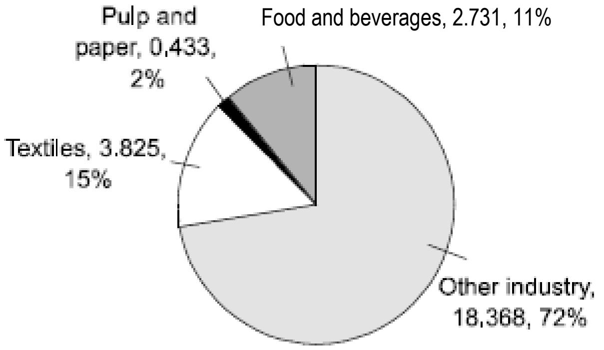

Figure 2.2: Energy consumption of the industrial sub-sectors: the first figure is the PJ/year consumption and the second is the percentage share of the total (Winkler, et al. 2006)

However, the report by Winkler et al (2006) falls specifically within the boundaries of the City of Cape Town and is therefore not reflective of the entire Western Cape.

In a study done for the Western Cape Department of Economic Development and Tourism (Kowalik and Coetzee 2005), the total industrial energy demand for the Western Cape was calculated as 27.8 PJ, thus slightly higher than that of Cape Town's (25.4 PJ). Kowalik and Coetzee (2005) acknowledge that this figure is not accurate[10] and that it is difficult to obtain a disaggregated balance of energy use in the Western Cape[11]. There is no breakdown of the industrial subsectors within this report. The energy consumption within the Cape Town F&BI no doubt forms the largest part of this figure, but there is a lack of precise data when trying to ascertain the energy consumption on a provincial level.

According to the DME's "Energy Efficiency Baseline Study*"*, energy costs have historically formed less than 10% of production costs (DME 2002) within the F&BI. Typically, the energy intensity of this industry has been low and therefore not targeted by energy efficiency programmes. Nonetheless, there is the potential to save 15 PJ of energy, of which 13.7 PJ could be realised merely by implementing more efficient thermal measures (DME 2002). This gives an indication that a large proportion of the processes that consume energy within the F&BI could in fact be supplemented by solar heat, i.e. thermal measures, and that there is much potential for using such technology in this industry.

This section has highlighted what the levels of potential are for solar heat within the F&BI. It has shown that a gap exists in the energy consumption figures for the Western Cape's industrial subsectors. We also know from previous studies that a large proportion of energy consumed within this industry is expended on thermal measures.

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[10] They state that: "All data in these energy balances was unclassified and therefore to a certain degree inaccurate" (Kowalik and Coetzee 2005).

[11] The last disaggregated figures for provincial energy balances were released in 2000 by the DME (Kowalik and Coetzee 2005).

2.2 STUDIES ON THE POTENTIAL OF SOLAR HEAT FOR INDUSTRIAL PROCESSES

Locally, studies on SWH have limited themselves to calculating the demand from residential and commercial sectors (Holm 2005) and to assessing the state of the local solar water heater manufacturing industry (Holm 2005, Theobald and Cawood 2009).

Two studies from the international literature stand out in the field of solar heat for industrial processes. The first is a comprehensive survey carried out in respect of industrial companies in the Iberian Peninsula (AIGUASOL Enginyeria 2001). The report defines the potential for solar heat within industry in Spain and Portugal, and it includes a more detailed analysis on three case studies. The study was conducted by AIGUASOL Enginyeria of Barcelona in conjunction with other major European research institutes and societies[12]. The early findings of the report were presented at the 2000 Eurosun conference in Copenhagen in a separate paper (Schweiger, et al. 2000).

The second report is a study conducted for the entire European Union by the International Energy Agency (IEA). The aim of the report was to establish the potential of solar heat in industrial processes (Vannoni, Battisti and Drigo 2008). The study is one part of a list of tasks under the solar heating and cooling (SHC) programme run by the IEA. It was intended to serve as a guide, which would enable local authorities to develop the necessary policies and instruments to help implement the use of solar thermal energy within the industrial sectors of their respective countries.

The report highlights some interesting facts that are pertinent to this study. About 30% of all heat used in industrial processes, for the countries surveyed, is at temperatures below 100˚C. Furthermore, these figures are broken down into the different industrial subsectors. In the food, wine and beverage industry, for instance, over 60% of heat used is at temperatures below 250˚C.

The report by Vannoni et al (2008) also states that there is currently only 25 MW_{th} of installed solar capacity being used in industrial facilities worldwide. This is insignificant compared to the 145 GW_{th} of installed solar capacity in the residential and commercial sectors (REN21 2009). This is a surprising result, considering that the industrial sector consumes 28% and 42% of all primary energy consumed within the EU and South Africa respectively.

Vannoni et al (2008) conclude that 3.8% of the EU's industrial energy demand could be supplied by solar heat, which equates to 258.2 PJ/year or between 100-125[13] GW_{th} of installed capacity. AIGUASOL

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[12] Inst. Nacional de Engenharia e Tecnologia Industrial (INETI); Bayern Zentrum für Angewandte Energieforschung e.V. (ZAE); Deutsches Zentrum für Luft und Raumfahrt e.V. (DLR); Instituto para la Diversificacion y Ahorro de la Energia (IDAE); Institut Catala d'Energia and Sociedade Portuguesa de Energia Solar (SPES).

[13] The upper and lower boundaries are based on the solar radiation levels of 500 kWh/m^2year and 400 kWh/m^2year respectively.

Enginyeria concludes that the potential in Spain and Portugal alone is 3.6% of industrial consumption, which equates to 0.209 PJ. The figure from Vannoni et al (2008) may not seem large, i.e. 3.8%, in terms of total industrial energy consumption within the EU, but it is more than double the total amount of energy consumed in the South African F&BI.

Both these studies give a clear indication of the market potential for solar thermal heat in the industrial sector. The former also sets out clearly what the current system costs are and what they need to be in order to be competitive with conventional heating systems (AIGUASOL Enginyeria 2001).

2.3 PROCESSES SUITABLE FOR SUPPLEMENTATION WITH SOLAR HEAT

Many of the processes found in today's manufacturing facilities that use steam, hot water and air as heat transfer fluids (HTF) can be supplemented with solar heat (Benz, Beikircher and Aghazadeh 1996, Kalogirou 1996, Benz and Beikircher 1999, Benz, Gut, et al. 1999, Kalogirou 2003, Kalogirou 2004). Heat can be supplied directly in the form of steam, hot water, air or by using a heat exchanger, in which case oils and other fluids can be heated indirectly. The use of a heat exchanger prevents fouling and scale build-up (calcium from water) within the solar loop (Kalogirou 2004).

The most suitable processes for conversion were identified as: cleaning, drying, evaporation and distillation, blanching, pasteurisation, sterilisation, cooking, melting, painting, and surface treatment (Vannoni, Battisti and Drigo 2008). Table 2.1 below shows typical temperatures demanded by various industrial processes.

Table 2.1: Industrial heat demand, categorised by industry, process and temperature range, adapted from (Kalogirou 2003)

Industry	***Process***	***Temperature (C˚)***
Dairy	*Pressurisation*	*60–80*
	Sterilisation	*100–120*
	Drying	*120–180*
	Concentrates	*60–80*
	Boiler feed water	*60–90*
Tinned food	*Sterilisation*	*110–120*
	Pasteurisation	*60–80*
	Cooking	*60–90*
	Bleaching	*60–90*
Textile	*Bleaching, dyeing*	*60–90*
	Drying, degreasing	*100–130*
	Dyeing	*70–90*
	Fixing	*160–180*
	Pressing	*80–100*

Paper	*Cooking, drying*	*60–80*
	Boiler feed water	*60–90*
	Bleaching	*130–150*
Chemical	*Soaps*	*200–260*
	Synthetic rubber	*150–200*
	Processing heat	*120–180*
	Pre-heating water	*60–90*
Meat	*Washing, sterilisation*	*60–90*
	Cooking	*90–100*
Beverages	*Washing, sterilisation*	*60–80*
	Pasteurisation	*60–70*
Flours and by-products	*Sterilization*	*60–80*
Timber by-products	*Thermodifussion beams*[14]	*80–100*
	Drying	*60–100*
	Pre-heating water	*60–90*
	Preparation of pulp	*120–170*
Bricks and blocks	*Curing*	*60–140*
Plastics	*Preparation*	*120–140*
	Distillation	*140–150*
	Separation	*200–220*
	Extension	*140–160*
	Drying	*180–200*
	Blending	*120–140*

Most factories today generate medium temperature steam in order to transport heat to processes in the factories. In most of these cases, the process itself requires heat at a much lower temperature. Therefore, supplementing process heat with solar heat would avoid the losses associated with steam generation and distribution.

Cooling can also be supplemented with solar heat via the use of absorption refrigeration systems (Winston, et al. 1999, ETSU and ENVIROS 1999, Soto-Gomez, et al. 1999, Cengel and Boles 2002, Kalogirou 2004, Mittal, Kasana and Thakur 2005, Syed, et al. 2005, Duffie and Beckman 2006, Desideri, Stefania and Sdringola 2009) and solar mechanical cycles[15] (Klein and Reindl 2005, Syed, et al. 2005).

The main advantage of using solar heat for cooling in the South African climate is that the period of peak cooling demand, summer, coincides with the period of highest annual solar radiation, from November through to March.

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[14] This is a curing process used in the production of timber by-products.

[15] Solar heat is used to drive a prime mover (based on a Rankine cycle) to create mechanical rotation, which can be used in conjunction with an ordinary vapour compression cycle refrigeration system.

The most common types of absorption systems are those used in air-conditioning applications and of these the lithium bromide-water type is the most predominant. This type of absorption system can only supply cooling down to 5°C (ETSU and ENVIROS 1999). This is insufficient for use in the F&BI where temperatures of +0.5°C are needed for fruit and vegetable preservation and lower temperatures for freezing applications (Cengel and Boles 2002). Ammonia-water systems can readily reach temperatures of -60˚C (ETSU and ENVIROS 1999), but their drawback is that they do not come off-the-shelf and have to be manufactured to the specific system's needs. Lithium bromide-water systems, in contrast, can be bought as off-the-shelf units ranging from 100kW to 1000's of kW (ETSU and ENVIROS 1999) in cooling capacity.

The absorption systems characteristically have high upfront capital costs but are cheaper to operate than conventional vapour compression refrigeration systems. One study found that the cheapest form of solar absorption cooling is as much as three times the cost of a conventional vapour compression system (Syed, et al. 2005). The large upfront capital costs of absorption system, in general, are seen as the main barrier preventing their large-scale adoption. The solar collectors make up the largest part of the total system costs (Syed, et al. 2005).

2.4 PROCESS HEAT

This section briefly discusses the literature surrounding the different types of solar collectors and their suitability for different processes. In order to understand better which processes are suited to the different collector types, it is necessary to define the three main operating temperature ranges that exist within industry. The suitability of a collector depends significantly on the required operating temperature of the process.

An important part of this project involves modelling SHSs for the preheating of boiler make-up water, and therefore it is necessary to have a good understanding of the different solar technologies available to the designer. This section thus identifies and examines the most pertinent types of solar collector considered for this project.

2.4.1 TEMPERATURE RANGE DISTINCTIONS AND COLLECTOR TYPES

Process heating demands can be divided up into three main temperature ranges, namely, low (up to 80°C), medium (up to 250°C) and high (above 250°C) (AIGUASOL Enginyeria 2001, Vannoni, Battisti and Drigo 2008).

The boundaries of the temperature ranges described above roughly coincide with the temperatures at which different solar technologies need to be implemented. Most flat plate collectors (FPC) are suitable up to 80°C. The lower portion of the medium temperature range, i.e. below 150°C, is suitable for advanced flat plate collectors (AFPC), whereas concentrating collectors, e.g. parabolic trough concentrators (PTC), are required in the upper part of this range. At temperatures above 250°C, only concentrating collectors will be feasible.

The point at which one type of collector is more suitable than another is dependent on but not limited to the following: the local solar radiation levels and climatic conditions, the thermal characteristics of the collector, the optical efficiency of the collector, and the load placed on the collector. It is important to note the difference between collector types and the temperature ranges in which they operate at their maximum solar output.

Kalogirou's paper, "The potential of solar industrial process heat applications", is a very good source of information on the suitability of different collector types for industrial processes (Kalogirou 2003). In his approach, Kalogirou (2003) takes a set of design parameters and shows how various collector types perform, given this problem set. From this, he determines the limitations for each type of collector. He also concludes that water pre-heating is the most effective use for low temperature process heat collectors, such as FPCs, as the water entering the collectors is at a low temperature, which allows the panels to impart the maximum amount of energy to the water (for a given flow rate).. Essentially, the performance of a collector is a weak function of load temperature in this instance (often water in a system with a return is at high temperatures, and therefore the collector cannot impart as much energy to it as where the inlet water temperature is at ambient conditions).

The most economical way of generating low temperature process heat is by using the ordinary FPC. South Africa has a well established local flat plate manufacturing sector (Holm 2005). Recently, a local mine installed a 42 000 litre hot water system for the ablution facilities of its employers (Forder 2009). FPCs adequately provide energy up to temperatures of around 80 - 90˚C (Kalogirou 2003, Weiss and Rommel 2008). Above this temperature, the convective heat losses become unacceptably high, and the efficiency of FPCs drop to below 40% (AIGUASOL Enginyeria 2001).

Benz et al (1996) have conducted a case study on AFPCs and their suitability in producing process heat for the beverage industry. Four large solar thermal designs are modelled and analysed for a small brewery, large brewery, malt factory and a milk processing plant respectively. These collectors have high efficiencies at temperatures above 100˚C, performed well at generating heat up to 180˚C, and are therefore well suited to the medium temperature range. The authors of this study are an authority on AFPCs: three of the now commercial types of AFPCs were developed at the Bavarian Centre for Applied Energy Research (ZAE Bayern) where the authors are based. Many papers have been authored or co-authored by researchers from this institution on the development of solar collectors (Benz and Beikircher 1999, Benz, Beikircher and Aghazadeh 1996, Muschaweck, et al. 2000) that perform well in the medium temperature range.

Figure 2.3 below shows the efficiency curves (Benz, Gut, et al. 1999) for the four types of collectors used in their study. Due to the increased efficiency of these collectors, a SHS would potentially take up less area than ordinary FPCs. This is very important because roof space is often the main limitation to the size of SHS that can be installed at a factory. In the figure below *TI-collector* refers to a flat plate collector with transparent insulation on the back and side walls.

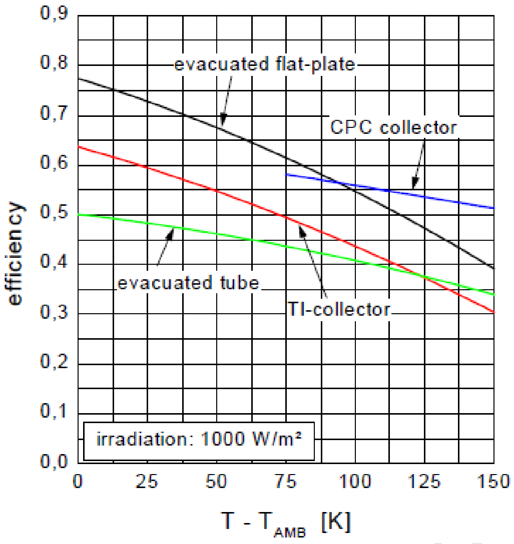

Figure 2.3: Efficiency curves for various AFPCs (Benz, Gut, et al. 1999)[16], irradiation of 1000 W/m²

2.4.2 THE MEDIUM AND HIGH TEMPERATURE RANGES

The most suitable collectors for medium temperature process heat applications are AFPC[17], evacuated tube collectors (ETC), compound parabolic trough concentrators (CPC) and PTCs (Schweiger, et al. 2000, Kalogirou 2003, Kalogirou 2004, Weiss and Rommel 2008). These are all seen as important technologies in producing thermal heat up to temperatures of 180˚C. The CPC (Weiss and Rommel 2008) and evacuated flat plate collectors (EFPC) are especially good (Benz, Gut, et al. 1999).

For temperatures above 200˚C, concentrating collectors are needed e.g. Linear Fresnel Collectors (LFC) and PTCs .These show good performance for temperatures far exceeding 250°C. The cost of producing heat above 150°C with solar collectors escalates rapidly when compared with the cost

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[16] Transparent Insulation (TI).

[17] The types developed at ZAE Bayern fall into this category.

of energy provided by conventional heating systems. Thermal heat in South Africa is normally generated from coal, heavy fuel oil or biomass (bargasse and woodchips), all of which are relatively cheap compared to electricity. It is a general rule of thumb that, the higher the operating temperature of a SHS, the higher the capital costs of the system will be (Duffie and Beckman 2006).

PTCs can provide heat from 50˚C up to 400˚C and are the most mature solar technology used to produce high temperature thermal heat (Kalogirou 2003, Kalogirou 1996, Kalogirou 2002). They have been used extensively in the SEGS I – IX power plants in the USA, where there is over 354 MW of installed capacity. LFCs are used in applications ranging from 50 kW_{th} to 5 MW_{th}. They operate very efficiently between 150˚ and 200˚C, using water as the HTF, but higher operating temperatures can be achieved when different thermal fluids[18] are used (Weiss and Rommel 2008).

2.4.3 THE COST IMPLICATIONS OF VARIOUS COLLECTOR TYPES

In order to understand the cost implications of a SHS, one has to model the system according to the local climatic conditions. It is also important for the model to capture the typical operation of the SHS, thus ensuring that the analysis is accurate. Once this has been done, accurate energy prices can be extracted from the model.

Kulkarni et al (2007 and 2008) present two papers that outline procedures used to model and optimise the design of a solar thermal system. In their analysis, they select a set of design parameters, showing how the SHSs perform under these parameters; they then go a step further and optimise the system in order to obtain the lowest cost energy output from the system. They demonstrate this for a low temperature system as well as for a pressurised hot water system operating at above 100˚C (Kulkarni, Kedare and Bandyopadhyay 2008, Kulkarni, Kedare and Bandyopadhyay 2007). These two papers also explore the relationship between cost and solar fraction and the trade-off of employing an auxiliary heating system in conjunction with the SHSs.

Cost is one of the most important variables when choosing a collector. A certain collector may be exactly suited to a task, but if it is too expensive, the cost of the energy it supplies can never be justified. Therefore, it is important to choose a suitable collector based on cost as well as on performance characteristics. There are many papers in the literature that provide details of collector cost. Most sources agree that for low temperature process heat the FPC is by far the most economical choice (AIGUASOL Enginyeria 2001, Kalogirou 2003, Weiss and Rommel 2008).

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[18] The thermal fluids referred to here are thermal oils specifically designed for heat transfer applications.

Please note Figure 2.4 below contains one typographical error, EPFC is meant to be EFPC and stands for evacuated flat plate collector, and is an error by the authors of the paper. For a full list of the acronyms please refer to the List of Acronyms on page xii.

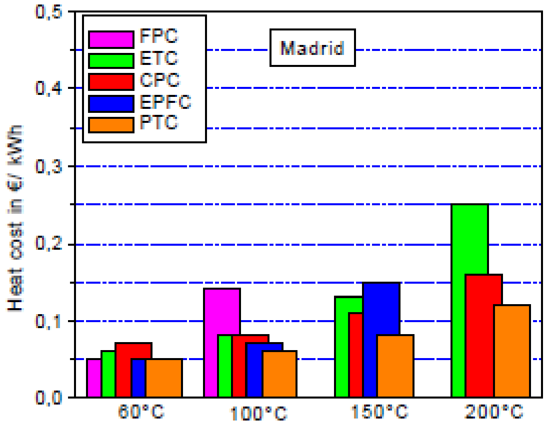

Figure 2.4: Heat costs versus output temperatures for various collector types (AIGUASOL Enginyeria 2001)

For temperatures above 100˚C, the POSHIP report reveals that PTCs are the most economical for the climatic conditions present in the Iberian Peninsula[19]. Their increased efficiency at medium temperatures makes them more than competitive with the AFPCs (Schweiger, et al. 2000, AIGUASOL Enginyeria 2001), even though they do on average have a higher upfront capital cost. Figure 2.4 above is an excerpt from the report showing the cost of solar heat for Madrid. Clearly, the PTC (orange bar on chart) is very competitive. The cost of heat from fossil fuels for the same region is on average 0.01 €/kWh, in 2000 Euros (Schweiger, et al. 2000).

Although CPCs have the best performance in the medium temperature range, the most economical collectors in this range are the AFPCs (Kalogirou 2003). This result is confirmed by Benz et al 1999.

The most economical way to generate high temperature process heat is thus with either LFCs or PTCs. Both types of collector are available commercially as modular units (Weiss and Rommel 2008, Heliodynamics 2009, NEP Solar 2010).

2.5 ABSORPTION COOLING

This section examines the basic concept of absorption refrigeration systems in order to establish how they are used in conjunction with solar heating. This section is not intended to explain the exact

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[19] Out of all the areas in Europe, the Iberian Peninsula has radiation levels that most closely match the radiation levels present in South Africa.

workings of an absorption refrigeration system (ARS), but a basic knowledge of the system's components is necessary to understand how they work in conjunction with SHSs. The performance of ARSs and types of commercially available units is also discussed. The potential role of these systems in the F&BI is explored, which clarifies why they are considered for this project.

2.5.1 ABSORBTION REFRIGERATION: BASIC THEORY

ARSs have many of the same components as do the ordinary vapour compression cycle. Figure 2.5 below shows the basic set-up of an ARS. The system still has an evaporator, condenser and expansion valve. The additional components are the generator, absorber, pump, distiller/deflegmator and additional heat exchangers (Klein and Reindl 2005, Vicatos 2006). The other major difference is that the refrigerant is replaced by a working pair of fluids; the one fluid acts as the refrigerant, while the other fluid is a transport medium. The fluids must have a strong affinity to absorb one another[20].

In the generator, a hot strong solution of the refrigerant is boiled off; this solution is then distilled to ensure that the refrigerant is separated from the other substance, transport medium. The refrigerant is then condensed, expanded and evaporated just as in the vapour compression cycle. Once the refrigerant has removed heat from the refrigerated space, it exits the evaporator (as a warm vapour), where it is cooled within the absorber so that it more readily combines[21] with the other substance to form a weak solution of the two fluids. Heat exchangers can be added as illustrated in Figure 2.5 below to preheat and precool the weak and strong solutions in the cycle respectively. A cooling tower is used in order to provide cooling for both the evaporator and the absorber.

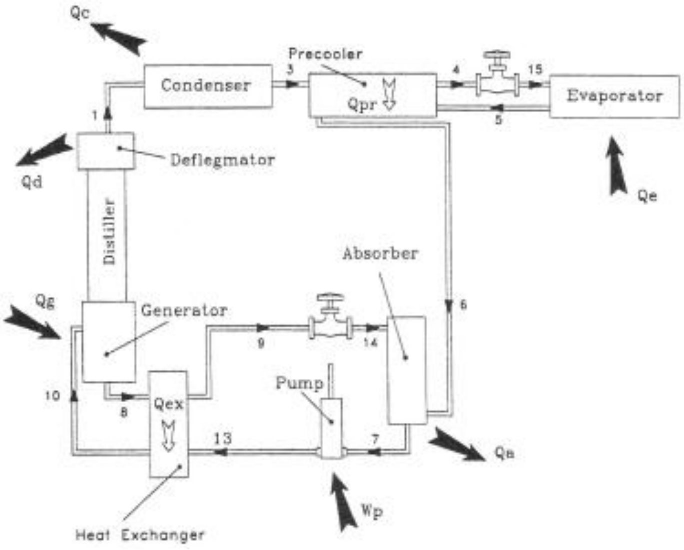

Figure 2.5: An absorption refrigeration system's components (Vicatos 2006)

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[20] Once the warm refrigerant gas is passed out of the evaporator, it must be reabsorbed by the other substance to form a weak solution made up of the two substances.

[21] The reaction in the absorber is exothermic, therefore cooling is needed to facilitate the reaction (Klein and Reindl 2005).

There are two predominant types of absorption systems available, namely, ammonia-water and lithium bromide-water. In the case of the ammonia-water systems, the ammonia is the refrigerant and the water the transport medium. With the lithium bromide-water type, water is the refrigerant. Currently only the lithium bromide-water type is available commercially as a prefabricated unit. Ammonia-water systems have to be custom built.

In order for the system to function, a constant supply of (thermal) heat is needed in the generator to boil off the refrigerant. Also, heat must be continually removed from both the absorber and condenser. The heat input to the generator can be supplied by solar collectors. A system running off solar collectors would need to have an auxiliary heat supply to run at night.

The quality of heat needed depends on the system's configuration as well as on the working pair of fluids used. In typical modern lithium bromide-water ARSs, input heat to the generator is required to be between 70 and 95°C where the systems are water cooled (Mittal, Kasana and Thakur 2005, Duffie and Beckman 2006). In a typical ammonia-water system, heat is required at between 120 and 130°C to facilitate the reaction (Klein and Reindl 2005). The temperature of the heat needed will determine the type of solar collector that can be used.

As with vapour compression cycle refrigeration systems, cascading can be used in absorption systems, in which case they are known as double effect systems. Double effect systems essentially use some of the heat discarded in the absorber to begin the heating process in a second generator, much like a cascaded refrigeration system, where the heat rejected by the condenser in the second stage is absorbed by the evaporator in the first stage. The more vapour generated per unit heat input, the greater the cooling capacity and coefficient of performance (COP) will be. But the drawback is that a higher generator temperature is needed around 155˚C (Winston, et al. 1999), which is substantially higher than the 70 - 90˚C operating temperature of single effect chillers.

2.5.2 PERFORMANCE AND LIMITATIONS

Systems employing the lithium bromide-water working pair are generally only used in air conditioning applications, as the cooling temperatures need to be above freezing (in fact the practical limit is 5˚C). This is because water is used as the refrigerant, and water will start freezing at temperatures below 5˚C. The lithium bromide-water systems have the highest COP of any other working pair. This is typically 0.6 for a single effect chiller[22] (ETSU and ENVIROS 1999, Duffie and Beckman 2006) and 1.2 for a double effect chiller (ETSU and ENVIROS 1999, Winston, et al. 1999,

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[22] The term chiller is used to refer to absorption systems of the lithium bromide-water type, as they are limited to temperatures above 5˚C.

Duffie and Beckman 2006). For comparison, see Table 2.2 below with COPs for vapour compression cycles.

Table 2.2: Some typical COPs with corresponding operating temperatures of large industrial vapour compression cycle refrigeration plants

Refrigerant	*Refrigerated Space Temperature*	*COP*
Ammonia	*+ 5°C*	*5.16*
Ammonia	*+0.5°C*	*4.41*
Ammonia	*-10°C*	*3.17*

The figures above are based on a screw compressor delivering ±2300 kW of refrigeration and an evaporating temperature 8°C below the refrigerated space temperature (Käsner 2010).

Ammonia-water systems can readily reach temperatures of -60˚C. The COP of a single stage ammonia-water absorption system providing cooling at -10˚C with a condensing temperature of 35˚C is 0.5 (Klein and Reindl 2005). This is much lower than that of a vapour compression cycle using ammonia as a refrigerant, see Table 2.2. Another important aspect of ARSs is that the output figures supplied by manufacturers are always based on the condition that the condenser water exit temperature[23] is at a certain temperature.

The actual performance of a solar driven ARS will be lower than the figures quoted above. The efficiency of the solar collectors still has to be accounted for, which will lower the overall system efficiency. Syed et al (2005) have established a term known as the solar coefficient of performance (SCOP). This term is defined as the product of the solar collector efficiency and the coefficient of performance. The term is important, as it gives an indication of the overall plant efficiency and capital cost, because collector and heat removal component size and hence cost are significantly affected by SCOP (Syed, et al. 2005).

It is clear to see that the overall system efficiencies of solar driven ARSs will be much lower than will be the COP of conventional vapour compression cycles. Therefore, even though thermal heat supplied from the sun is free and the cost of electricity is avoided, the drastically decreased efficiency may mean that the systems take a long time to pay back the high upfront capital costs of a solar ARS.

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[23] Between 29.4˚C and 35˚C is the normal operating temperature range.

2.5.3 COST IMPLICATIONS OF SOLAR ABSORPTION REFRIGERATION SYSTEMS

According to the UK's *Energy Efficiency Best Practice Programme* (ETSU and ENVIROS 1999), absorption refrigeration systems are only worth considering economically speaking if one of the following applies to the site under consideration: if excess heat is available (i.e. a combined heat and power plant), if there is a cheap source of fuel for heat (e.g. a landfill site), if upgrading the electrical load to the site would be extremely expensive (e.g. a remote site far from major distribution points), or if the vibration and/or noise associated with the compressor of a vapour compression cycle is a problem.

Syed et al (2005) put the cost of a conventional vapour compression system at around 125 £/kW of refrigeration. The cheapest solar driven system is around 375 £/kW (2005 Pounds), which is a FPC supplying a lithium bromide-water system (Syed, et al. 2005). Desideri et al (2009)present a case study for a meat curing plant, in which 35 kW of cooling is supplied at around 1700 €/kW (2009 Euros); again, this is for a single stage lithium bromide-water system. These costs include heat rejection equipment, chillers and solar collectors (Desideri, Stefania and Sdringola 2009).

Lithium bromide-water systems can be bought as off-the-shelf units ranging from 100kW to 1000's of kW (ETSU and ENVIROS 1999) in cooling capacity. Well-known off-the-shelf manufacturers include Hitachi and Yazaki (used in the first solar driven air-conditioning system in South Africa[24]). These are the most economically competitive systems currently available: they can operate with solar heat as the thermal input at temperatures between 70-75˚C, which means that FPCs can be used to generate heat. These are the cheapest of all the available solar collectors (see Section 2.4.3 above). Most food and beverage companies require cooling at temperatures below the level that can be supplied by lithium bromide-water systems, and therefore an ammonia system would need to be used.

Ammonia-water absorption systems have not been financially competitive in the past because they are mainly not off-the-shelf and because the more expensive solar collectors are needed to supply the medium temperature heat needed to drive the system. These ammonia based systems are not nearly as commercialised as lithium bromide systems. There are a handful of small systems in place in the UK and other countries around the world (ETSU and ENVIROS 1999, Napolitano and Sparber 2009) but again larger systems are only available as custom built systems.

Soto-Gomez et al (1999) presented a paper on a small solar driven custom built ammonia absorption plant. The plant uses 16 kW of heat generated by 32 ETCs (57.55m^2). The system allows a pull-down load of 200kg of fish in 24 hours, up to a total capacity of 2 tons. The total cost

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[24] The system is a 35 kW off-the-shelf Yazaki lithium bromide-water chiller. It supplies chilled air for the Moot hospital in Pretoria (Aitchison 2009).

of the plant was $95 000 (1999 US Dollars) excluding installation and, according to the authors, would take 23 years to pay itself off at 1999 energy costs (Soto-Gomez, et al. 1999).

The absorber, rectifying (distillation) column and generator add large additional upfront capital costs to the costs of ARSs. However, in the latest systems being developed, chemical inhibitors have been successfully employed to separate the strong solution vapours from the liquid carrier (i.e. ammonia vapour from water, for example). This means that costs can be saved on the rectifying column (Vicatos 2010). If a cheap source of heat is not readily available, one has to be installed, in our case a SHS, which again drives up the system costs.

With this in mind, many food and beverage factories have heat supplies in the forms of boilers, and therefore an absorption system maybe financially viable when used in conjunction with a SHS and the excess heat from these boilers[25]. The payback of such a system would be determined by calculating the fuel savings of generating thermal energy. But this project is concerned with the costs of a purely solar driven system.

A large amount of work is involved in costing a custom built ARS, and this is beyond the scope of this project. The literature survey has revealed, however, that the technology is available, albeit still at a high cost. The cooling requirements of factories may in future be supplemented with solar heat when the systems become more commercialised. This will reduce the upfront capital costs. This has already happened for lithium bromide-water systems because of their potential for air conditioning applications, which is a major energy consumer in western countries, such as the US, which have higher summer load profiles. This is the opposite to the phenomenon in South Africa, however, where the load profile is far higher in winter; there is thus less of a driver to develop solar cooling in this country, even though the peak demand period for cooling conveniently coincides with the periods of highest annual solar radiation.

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[25] At night, many factories have a reduced production, therefore there may be even more heat available during these periods.

3. SOLAR RADIATION DATA

3.1 SOLAR RADIATION BASICS

South Africa has an abundance of sunshine, with some of the highest solar radiation levels in the world (DME 2003). The DME's White Paper on Renewable Energy clearly states that there is considerable potential for SWH, and that they foresee potential savings in the urban residential sector of 5 900 GWh alone. At any given time, there is 1.367 kW (Stine and Geyer 2001) of solar energy falling on the earth for every square meter of earth directly facing the sun. This quantity is known as the solar constant and is the maximum amount of energy available to the earth, from the sun, before the radiation has entered the atmosphere. Not all of this radiation reaches the ground; there are three main phenomena that decrease this figure, namely: the rotation of the earth, the earth's asymmetrical orbit around the sun, and the interaction with the earth's atmospheric particles (Stine and Geyer 2001).

We are only concerned with the last of these interactions, as we can, to some extent, compensate for the effects of the earth's atmosphere by appropriately selecting a solar design.

On average, the mean daily global radiation received by tilted surfaces is more than that of horizontal surfaces. The reason for this is that a horizontal surface receives only the direct part of solar radiation, known as normal radiation, and some diffuse radiation[26], whereas a tilted surface receives a reflected component of the diffuse radiation that a horizontal surface would not receive. The net effect of this is that, on partly cloudy days, when more radiation is diffused and scattered, tilted surfaces pick up a greater amount of radiation.

The following paragraph describes how a solar collector should be tilted in order to collect the maximum amount of solar energy over a given period of time. For a solar collector, the angle of incidence is defined as the angle between the normal to its surface and the solar irradiance[27] hitting its surface; the cosine of this angle determines the amount of irradiance hitting the horizontal surface. This is known as the "cosine effect" (Stine and Geyer 2001), which can be seen in Figure 3.1 below. Hence collectors that lie normal to the sun's radiation will receive more irradiance per square meter. Since the sun's position constantly changes throughout the day, only a collector that tracks the sun will have its aperture normal to the sun for the entire day. In the absence of such a tracking mechanism, i.e. in the case of stationary collectors, empirical research has shown that collectors facing the equator tilted to an angle equal to the local latitude will receive the most irradiance over a given period of time, this is a

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[26] Diffuse radiation is that part of the solar radiation that has been reflected, transmitted or diffused through particles in the earth's atmosphere.

[27] Solar irradiance is the rate at which a unit of solar energy reaches a unit of area of earth (W/m^2), whereas solar radiation is the summation of irradiance incident on a surface over a given time period (kJ/m^2).

generalized rule that is true to most locations. Local weather patterns in a given area, may alter this trend, requiring a different orientation to gain maximum solar radiation.

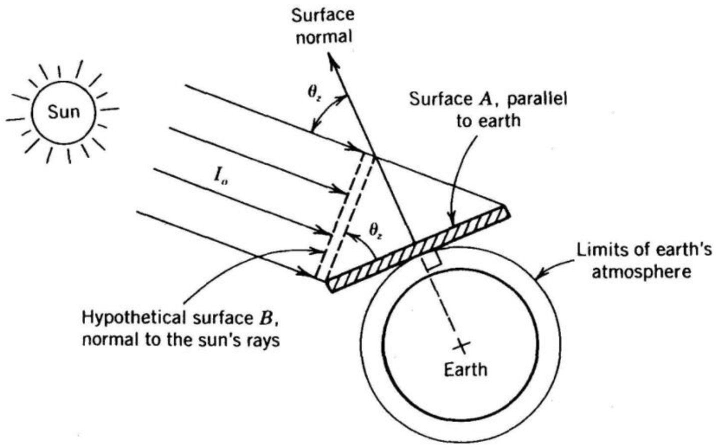

Figure 3.1: Diagram showing the "cosine" effect (Stine and Geyer 2001)

Collectors must face north in the southern hemisphere. Some collectors are tilted 10°-15° more or less than the angle of latitude (Kalogirou 2003) depending on the time of year at which more energy is desired, i.e. this creates winter/summer biases when compared to total energy collected.

3.2 GATHERING SOLAR RADIATION DATA

In order to get the most energy possible out of a SHS, it is important to know what the local solar resources are. There are three ways in which one could obtain this information, namely, by direct measurement, from previous studies or from satellite data.

The cheapest method by far is to obtain the information from previous studies. But then one has to be certain about the methodology used to compile the relevant data and the time period over which the data was collected. If the study was compiled over a year, for instance, it is necessary to know whether this year is typical of the long-term average of available radiation. The following section will briefly examine the three options open to someone who is interested in determining the amount of solar radiation available in a given area.

3.2.1 DIRECT MEASUREMENT

The most obvious way of assessing the amount of irradiance received by an area is by directly measuring the solar resources available in that area by using pyrheliometers and pyranometers. Pyrheliometers measure the direct or normal beam radiation, and they must be kept normal to the sun. Pyranometers can be set up to measure either global radiation, i.e. the diffuse and direct normal radiation, or just the diffuse part via the use of a shading ring. Depending on what the solar design entails, multiple instruments may need to be used. Very precise metering stations can be purchased, and these measure each component of the solar radiation separately.

The accuracies of the instruments vary by manufacturer and type of instrument employed. Table 3.1 below lists the uncertainty associated with some of the common instruments used to measure irradiance levels.

Table 3.1: Uncertainty associated with solar radiation instruments (Hoyer-Klick 2010)

Instrument Type	***Uncertainty***
Absolute Cavity Pyrheliometer	*1%*
Pyranometer	*2%-5%*
Photoelectric Pyranometer	*±5%*
Shaded Pyranometer	*4%-8%*
Rotating Shadow-band Pyranometer	*2%*

Accuracies listed assume that the instruments are calibrated correctly and that they are cleaned regularly. These requirements mean that an operator is needed to visit the instruments almost daily.

There are rugged stations that have been developed for very tough climatic conditions and that are fully automated for use in remote sites. Again, this comes at a high premium. The cost of a Solar Millennium Meteostation[28] is in the range of € 25000 – 30000 (2010 Euros) (Hoyer-Klick 2010).

Of course, a single instrument on its own may suffice for solar irradiance measurements, i.e. a pyranometer measuring global irradiance, but again care needs to be taken to ensure that the machine is regularly calibrated and cleaned.

A further factor that needs to be taken into account with direct measurement is that data is only available from when the recording period started, therefore the data obtained may not be indicative of the long term solar irradiance inherent in a specific area. Direct measurements should only be employed in the absence of data for a specific area, when data is not trusted or when a high degree of high accuracy is needed in the case of locating a solar thermal power plant.

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[28] This is a self-contained station that is fully automated and records direct normal, global and diffuse irradiation, as well as temperature, relative humidity, wind speed, wind direction and atmospheric pressure.

3.2.2 SATELLITE DATA

An alternative to direct measurement is solar radiation data from orbital satellites. The advantages of satellite data are that there is long term data (more than 20 years) available, that there is no soiling of the equipment and thus no cleaning required, and that the spatial resolution allows whole regions to be mapped (Hoyer-Klick 2010). The data from these satellites is free from some sources. The more accurate and long term data from the more established satellites costs in the order of € 8000 (2010 Euros) (Hoyer-Klick 2010), which is considerably less than a metering station would cost.

Table 3.2 below summarizes the satellite sources available to a solar developer. It includes the period over which the data was recorded, as well as the area covered, spatial resolution, costs, temporal resolution[29] and the provider.

Table 3.2: Currently available satellite data sources adapted from (Hoyer-Klick 2010)

Product	*Area Covered*	*Period of Data*	*Temporal Resolution*	*Spatial Resolution*	*Cost*	*Provider*
NASA SSE	*World*	*1983-2005*	*Daily Average Profile*	*100 km*	*Free*	*NASA*
Meteonorm	*World*	*1981-2000*	*Synthetic Hourly/min*	*1km*	*€ 400*	*Meteotest*
Solemi	*Certain Longitudes Only*	*1991-present*	*1 hour*	*1km*	*±€ 8000*	*DLR*
Helioclim	*Certain Longitudes Only*	*1985-present*	*15min/30min*	*30km/3-7km*	*Older data free/newer data € 5000*	*École de Mines*
EnMetSol	*Certain Longitudes Only*	*1995-present*	*15min/1hour*	*3-7km/1-3km*	*±€ 8000*	*University Of Oldenburg*
Satel-light	*Europe*	*1996-2001*	*30min*	*5-7km*	*Free*	*ENTPE*[30]
PVGIS Europe	*Europe*	*1981-1990*	*Daily Average Profile*	*1km*	*Free*	*JRC*
ESRA	*Europe*	*1981-1990*	*Daily Average Profile*	*10km*	*€ 100*	*École de Mines*

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[29] This defines the time period in between readings.

[30] (ENTPE) École Nationale Des Travaux Publics De L'État and (JRC) the European Commission's Joint Research Committee.

The synthetic and average data uses interpolation between periods of recording to generate high resolution output, whereas the other three satellites actually record data at a high resolution. The reason why some entries in the table have more than one value is that the satellites have been upgraded over the years, i.e. Helioclim 1, 2 and 3 etc.

The disadvantages of satellite data are that it is not as accurate as ground based measurements and that it has a lower time or temporal resolution. Data that has a high spatial resolution may not be very accurate for a given site. Also important to note is that the different satellites produce data that deviates from other satellites. It may be necessary to compare data from different sources to check for uncertainty.

3.2.3 DATA FROM STUDIES: CAPE TOWN

The last route available to obtain solar radiation data is by using a study that encompasses the area in question. The important thing to note about such a study is that there may be uncertainties in the data, because of the type of model employed to interpolate the irradiance values for areas where there were no data measurements, i.e. between weather stations. It may also be a good idea to check the values of a study against locally available ground measurement and satellite data.

One such study for South Africa, by Anton Eberhard, is the "*Solar Radiation Data Handbook for Southern Africa"* (Eberhard 1990). The data used is from the South African Weather Bureau (SAWB)[31]. Data for Cape Town has been collected for over 19 years for global irradiance and 6 years for diffuse irradiance (this was at the time of printing in 1990). The SAWB has an entire radiation network consisting of pyranometers used to measure "*solar radiation on unobstructed horizontal surfaces on each site*" (Eberhard 1990). Linked to this, the SAWB has an absolute cavity pyrheliometer with an uncertainty of less than 0.2%, which can be directly linked to the World Standard Group.

The following data comes from Eberhard's study for the city of Cape Town (Lat: 33° $59^{'}$ Long: 18° $36^{'}$). Cape Town is particularly well endowed with sunshine. The amount of sunshine varies from 6 hrs/day in winter to 11 hrs/day in summer (taking into account weather conditions) (Eberhard 1990).

Cape Town furthermore receives an annual mean global radiation level of 1915 kWh.m^{-2}.year^{-1} which is on average the equivalent of 5.25 kWh.m^{-2} per day[32]. The mean annual diffuse radiation component is 548 kWh.m^{-2}.year^{-1} (Eberhard 1990). Clearly one can see (from Table 6) that, for a

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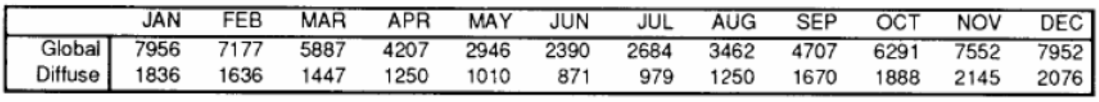
[31] Now known as the South African Weather Service (SAWS).

[32] This figure comes from dividing the annual mean global radiation figure by 365 days in the year; in addition, there are mean daily values by month given in the tables below.

tilted surface, the best angle is 30 - 35° for Cape Town[33], because the annual mean global radiation for these angles is 6.029 kWh.m^{-2} per day respectively (Eberhard 1990). This is slightly higher than the figure quoted above for the average daily global radiation for horizontal surfaces. This corresponds to the theory (explained in Section 3.1), as Cape Town's latitude is 33° 59', which lies in the range of 30° - 35°.

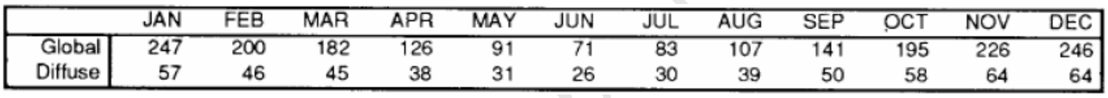
Below are four tables (Tables 3.3 to 3.64) with monthly and daily averages for radiation on tilted and horizontal surfaces.

Table 3.3: Mean daily radiation (Wh m^{-2} day^{-1}) (Eberhard 1990)



	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
Global	7956	7177	5887	4207	2946	2390	2684	3462	4707	6291	7552	7952
Diffuse	1836	1636	1447	1250	1010	871	979	1250	1670	1888	2145	2076

Table 3.4: Mean monthly radiation (kWh m^{-2} month^{-1}) (Eberhard 1990)



	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
Global	247	200	182	126	91	71	83	107	141	195	226	246
Diffuse	57	46	45	38	31	26	30	39	50	58	64	64

For a simple analysis, to find out the potential energy supply from a solar thermal system, it is sufficient to use the supplied tables in conjunction with a suitable mathematical analysis to come up with an estimate. But to obtain a more accurate picture of the potential of a SHS, one would need to set up a transient model. This model would encompass the thermal performance of all the system's components, i.e. collector, receiver, storage, piping, etc., as well as the typical meteorological data of the area.

Meteorological data is compiled into a typical meteorological year (TMY) for the area concerned. From the literature it can be seen that the TMY is either based on a year that is very characteristic of the weather conditions of the area concerned or it is based on long periods of observation of the local weather conditions compiled into an "average year" (Kalogirou 2003). The advantages of such a model, one incorporating a TMY, are that it shows how sensitive a design is to changes in solar irradiance levels and that it gives a clearer understanding of the interactions between all the different variables in such a system with respect to the radiation data. The TMY will give a good indication of long term system performance, either if the design is not sensitive to changes in the solar irradiance or if the TMY is a good indicator of the typical characteristics of the area (Kalogirou 2003).

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[33] This is the methodology to follow if the goal is to collect the most solar irradiance in a year. An angle of 45° might be better for collecting more energy in winter but less on an annual basis.

As mentioned before, the data in Eberhard's study is a good indication of the long term average of the solar irradiance levels. The data has been recorded over many years and hence the effects of local climatic conditions will reflect in the numbers. Therefore, in an indirect way, the data in the study does encompass the idea of the TMY.

Table 3.5: Mean daily global radiation on tilted surfaces (Wh m^{-2} day^{-1}) (Eberhard 1990)

Degrees	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	Annual Mean
5	7964	7297	6131	4536	3245	2684	2989	3742	4961	6443	7591	7927	5459
10	7948	7407	6363	4860	3554	2989	3304	4033	5198	6589	7611	7882	5645
15	7881	7470	6554	5152	3841	3276	3599	4298	5402	6693	7587	7786	5795
20	7780	7484	6702	5411	4103	3542	3871	4535	5572	6754	7523	7652	5911
25	7630	7450	6805	5635	4338	3785	4118	4743	5706	6771	7411	7477	5989
30	7432	7367	6864	5821	4545	4002	4337	4921	5803	6745	7252	7256	6029
35	7187	7237	6878	5969	4721	4193	4528	5066	5862	6676	7048	6989	6029
40	6896	7060	6846	6076	4866	4356	4688	5177	5884	6563	6800	6679	5991
45	6563	6837	6769	6143	4977	4489	4816	5254	5867	6410	6511	6330	5914
50	6190	6571	6648	6169	5056	4591	4912	5297	5812	6215	6181	5942	5799
55	5795	6264	6483	6153	5100	4662	4975	5304	5720	5981	5817	5548	5650
60	5383	5918	6275	6096	5109	4702	5003	5275	5591	5711	5442	5129	5469
65	4941	5544	6028	5997	5083	4708	4998	5211	5425	5405	5036	4682	5255
70	4473	5148	5741	5859	5024	4683	4958	5113	5225	5066	4604	4212	5009
75	3982	4723	5418	5681	4930	4626	4885	4981	4992	4706	4148	3723	4733
80	3491	4271	5061	5466	4802	4536	4778	4816	4728	4323	3674	3271	4435
85	3030	3798	4673	5215	4643	4416	4639	4619	4434	3917	3220	2819	4119
90	2563	3310	4258	4929	4452	4266	4469	4392	4114	3492	2777	2387	3784

Table 3.6: Mean monthly global radiation on tilted surfaces (kWh m^{-2} month^{-1}) (Eberhard 1990)

Degrees	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	Annual Total
5	246	204	190	136	100	80	92	116	148	199	227	245	1989
10	246	207	197	145	110	89	102	125	155	204	228	244	2057
15	244	209	203	154	119	98	111	133	162	207	227	241	2112
20	241	209	207	162	127	106	120	140	167	209	225	237	2154
25	236	208	210	169	134	113	127	147	171	209	222	231	2183
30	230	206	212	174	140	120	134	152	174	209	217	224	2197
35	222	202	213	179	146	125	140	157	175	206	211	216	2198
40	213	197	212	182	150	130	145	160	176	203	204	207	2184
45	203	191	209	184	154	134	149	162	176	198	195	196	2156
50	191	184	206	185	156	137	152	164	174	192	185	184	2114
55	179	175	200	184	158	139	154	164	171	185	174	171	2060
60	166	165	194	182	158	141	155	163	167	177	163	159	1995
65	153	155	186	179	157	141	154	161	162	167	151	145	1917
70	138	144	177	175	155	140	153	158	156	157	138	130	1827
75	123	132	167	170	152	138	151	154	149	145	124	115	1727
80	108	119	156	163	148	136	148	149	141	134	110	101	1618
85	93	106	144	156	143	132	143	143	133	121	96	87	1503
90	79	92	131	147	138	127	138	136	123	108	83	74	1381

3.3 RADIATION DATA FOR THIS STUDY

For this study two sources of data have been consulted, namely, the "*Solar Radiation Data Handbook for Southern Africa"* (Eberhard 1990) and NASA's "*Surface meteorology and Solar Energy"* website, which makes use of both satellite and ground data obtained over the past 22 years (NASA 2009). The data from the NASA site is freely available and is very detailed. All types of meteorological to solar data can be accessed, from wind speed to direct normal radiation. The data is also used by the modelling software RETScreen (Natural Resources Canada 2010) in the solar energy modelling spreadsheets, which are used in the analysis of data for this project. The data used from the NASA site is available in the appendices. See Appendix A.

4. SOLAR COLLECTORS

This chapter examines the costs used in the financial analysis of the solar collector systems. The assumptions and breakdowns used in structuring the system costs are also discussed. The section also takes a brief look at the materials and workings of each of the three collector types chosen for this project.

4.1 SUMMARY OF SOLAR COLLECTORS CONSIDERED FOR THIS STUDY

The following table consists of the three collectors types considered for this study. The cost and performance data from the manufacturers have been shown. Whenever possible, local manufacturers were consulted first, then local distributors, and finally (when nothing was available locally), international suppliers were approached. Many local manufacturers are only SABS tested, and the collector performance parameters necessary for RETScreen are not supplied in these tests.

Table 4.1: Comparison of commercially available solar collectors

Collector Model	***Efficiency Data***				***Collector Area***		***Collector Cost (Rand)***	
	a_1	***a_2***	***η_0***	***K_θ(34°)***	***Gross***	***Aperture***	***Collector***	***Large Installation***
	W/m²K	*W/m²K²*	*%*		*m²*	*m²*	*R/m²*	*R/m²*
Flat Plate Collector								
Atlantic Solar	-	-	-	-	4.0[34]	±3.6	±1300	4320-6500
Solarzone TS-300	3.943	0.008	75.1	0.95[35]	2.03	1.845	-	5000 - 6500[36]
Sonnenkraft RK 2300 Mediterano	4.269	0.0413	73.3	0.986	2.34	2.238	1304	4320- 6500
Solar Heat Exchangers	5.860	-	86.96	-	2.09	2.000	2138	7120-10700
Evacuated Tube Collector								
EFA Solar	1.487	0.014	64.9	1.328[37]	2.34	1.39	2451	6130 - 8170
Parabolic Trough Collector								
NEP-Solar	0.4	0.0015	68.5	?	28.8	28.8[38]	-	12450 - 15320

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[34] Upon request, larger panels could be manufactured for large installations (Hertzog 2010); the panels manufactured by Atlantic Solar carry the SABS 1307 mark of approval, but the SABS tests do not cover the efficiency data listed in Table 4.1.

[35] This figure is for an angle of incidence equal to 50° and is the standard used in European testing.

[36] This figure is for an entire system including all the categories listed in Table 4.2, and it was furnished directly by the distributor.

[37] The incidence angle modifiers for evacuated tubes are biaxial, as the covers of these collectors are optically non-symmetrical. For Cape Town's latitude (33° 59'), the angle of incidence modifier (beam irradiance) for the longitudinal $(K\tau\alpha)l$ and transverse $(K\tau\alpha)t$ axes of the evacuated tubes in question are 0.99 and 1.267 respectively. The angle of incidence modifier for diffuse irradiance is 1.328.

[38] This is the aperture area of a module consisting of 12 mirror segments of 2.4 m².

Collectors tested by European and American authorities are supplied with the necessary parameters. The parameters needed for this project form part of Equation 5.8, see Section 5.2.1. The performance parameters needed to model the output from a solar system are listed under efficiency data in Table 4.1 above.

It is important to note that the efficiency data listed in Table 4.1 comes directly from test reports supplied by the manufacturers/distributors and that it is therefore in the format of the country where the testing took place. RETScreen uses the efficiency data in the American format and hence any efficiency data from European testing stations needs to be converted.

It must be stated that there are many other types of solar collectors available on the international market. These types of collectors may in fact be better suited to use in the F&BI, but none are currently available locally. Importing collectors from overseas is definitely an option, but one that needs to be weighed up carefully in light of import duties and shipping cost, which can add significantly to the cost of the collectors.

Sometimes it may be easier to base calculations when planning SHSs on a Rand per capacity basis, for the three collector types modelled in RETScreen in this project, the cost on a capacity basis is listed in Table 4.2. The costs have been listed as a range, with a lower and upper bound respectively. The capacity of a system is a function of the collector efficiency data.

Table 4.2: Capacity cost and area cost for the three collector types used in this study

Collector Type	*Capacity Cost (R/kW)*	*Area Cost (R/m²)*
Flat Plate Collector	*6 134 – 9 285*	*4 230 – 6 500*
Evacuated Tube Collector	*8 757 – 11 671*	*6 130 – 8 170*
Parabolic Trough Concentrator	*17 786 – 21 886*	*12 450 – 15 320*

4.2 FLAT PLATE COLLECTORS

This section discusses the basic operation of FPCs and the different components used in manufacturing these collectors. A detailed breakdown of the system costs for a FPC system is presented in the second part of this section.

4.2.1 BASIC CONCEPTS OF THE FLAT PLATE COLLECTOR

The basic FPC is a mature technology, as it is by far the most widely used solar collector in the world with a proven track record (AIGUASOL Enginyeria 2001). At the end of 2001, there was a total capacity of 70 GW_{th} of installed solar water heaters worldwide; 34 GW_{th} of this total consists of flat plate collectors, compared to 15 GW_{th} of ETCs (ESTIF 2004). The basic FPC model has remained the same over the years; a schematic is given in Figure 4.1 below.

The glazing is usually an iron free glass[39] that can withstand hail impact. In some climates, where greater efficiency is desired, an anti-reflective coating is applied to the glass substrate. Sometimes, two layers of glazing are used, as this further increases the collector's efficiency. The absorber plate is usually a thin copper or aluminium plate that is permanently fixed to the copper risers. Heat conductive paste, braising, wiring, clips or clamps are used to fix this joint to ensure good thermal conductivity between absorber plate and the copper risers (Kalogirou 2004). If this joint is not properly manufactured, the collector will lose efficiency. The header pipes are copper pipes of a larger diameter to which the risers are joined; the header pipes are connected to the inlet and outlet supplies of the collector on the solar loop. The water inlet and outlets are connected to the bottom and top of the solar panel respectively. This is due to the increased buoyancy of the water, as it is heated.

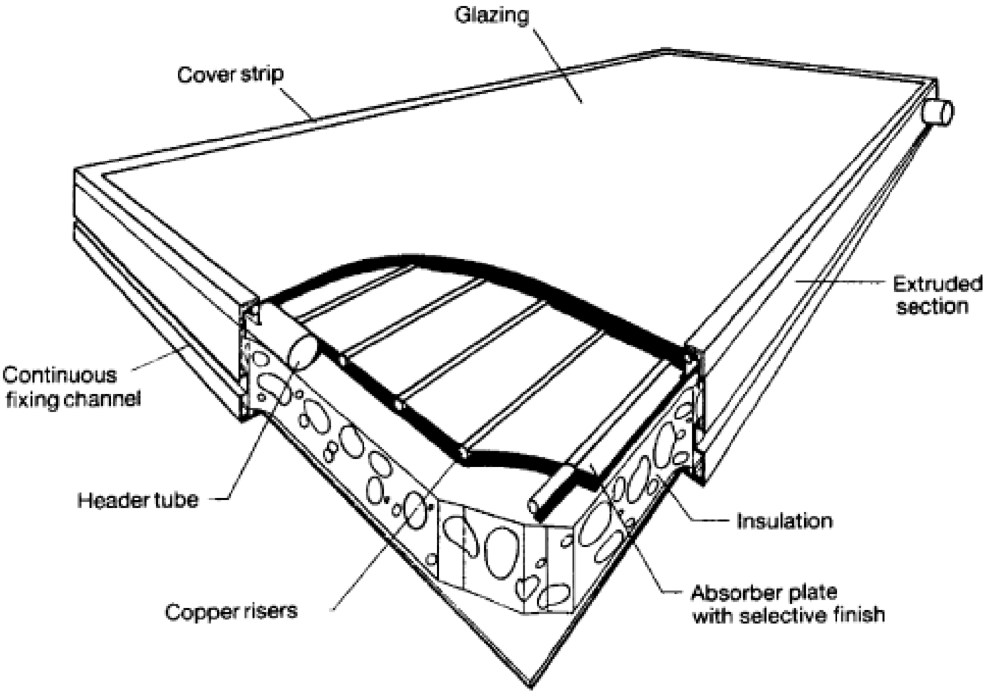

Figure 4.1: Basic elements of a flat plate collector (Kalogirou 2004)

Some systems employ the thermosyphon principle to feed water between the collector and the geyser, which is raised above the level of the panel for the thermosyphon to function. Direct thermosyphon systems cannot be used in areas where freezing is a problem. During one cold night on the Highveld in 1982, temperatures reached -4.2°C in a matter of hours and wiped out millions

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[39] Low iron glass, also known as *float* glass, has a lower reflectivity than ordinary glass and allows more solar radiation to pass through it.

of Rands worth of direct flow thermosyphon systems. This caused many manufacturers to go out of business, and it resulted in a loss of confidence in the SWH market (Holm 2005). Indirect flow systems employ a pump, which delivers fluid to the collector in a closed solar loop containing a water glycol mixture; this type of collector is used in areas where freezing is a problem. It is imperative to choose the correct system to match the local climatic conditions of a region.

Insulation is placed behind the absorber/riser sub-assembly to ensure that the heat loss is minimised from the underside of the sub-assembly. A backing board and frame secure all these items and ensure that the entire assembly is both water- and dust-proof.

Figure 4.2 below shows the main mechanisms in which solar irradiance is lost by the average FPC. The efficiency given in this example for the collector is 60%. According to a study done by Holm, the average efficiency of FPCs within South Africa is 66% (Holm 2005). It is important to note that this is the collector efficiency, which is different to the overall thermal efficiency of the system (losses in the geyser and piping are not taken into account under the former).

There is a well-established local FPC manufacturing industry, and the technology is widely used and understood. But manufacturing processes remain very labour intensive, and the volumes produced are low. For reductions in cost to occur, these two things need to change.

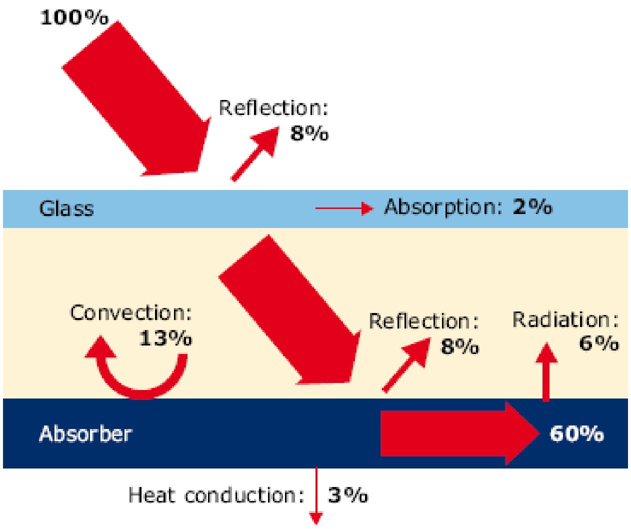

Figure 4.2: The main mechanisms of solar insolation loss (both optical and thermal losses) for an average FPC (Weiss and Rommel 2008)

4.2.2 COST BREAKDOWN FOR A FLAT PLATE COLLECTOR SYSTEM

The costs listed in Table 4.3 have been built up from the cost per square meter of collector aperture i.e. Rand/m^2. Following consultation with a local mechanical and process design firm, the cost of the collectors was estimated to be between 20% and 30% of the total system costs (De Beer 2010).

From this and the cost per square meter of collector aperture, the cost (per square meter) for a system can be worked out, e.g. R/m^2 4320. The rest of the system costs have been estimated from previous project experience of this firm which designs plant equipment for the F&BI in the Western Cape.

Table 4.3: Cost breakdown for a flat plate collector system (2010 Rands)

Description	Percentage of Total Cost (%)		Cost (Rand/m^2)	
	Low	High	Low	High
Panel Costs	30%	20%	R 1300	R 1300
Installation	12.5%	17%	R 430	R 975
Piping & Fittings	7.5%	7.5%	R 325	R 487
Heat Exchanger (1 Of)	3.5%	3.5%	R 195	R 290
Frame and/or Supports[40]	10%	11%	R 325	R 650
Assembly & Fasteners	2.5%	2.5%	R 105	R 160
Insulation for pipes	1.5%	1.5%	R 215	R 330
Pumps (2 Of)	3%	3%	R 130	R 195
Engineering Fees	8%	12.5%	R 540	R 975
Electrical Panels & Controls	14.5%	14.5%	R 540	R 810
Contingency	7%	7%	R 215	R330
TOTAL	100%	100%	4320 R/m^2	6500 R/m^2

The insulation costs are based on R39/m in respect of galvanised steel piping, whereas the heat exchanger costs are based on a plate heat exchanger with a 750 kW capacity, costing in the range of R80 000 (of course, this is dependent on the manufacturer).

4.3 EVACUATED TUBE COLLECTORS

This section begins by briefly examining the basic principles of ETCs. The materials used in the manufacturing of the tubes as well as the manufacturing techniques employed are also briefly discussed. The second part of the section breaks down the cost of an ETC system, as used in the financial analysis of this project.

4.3.1 BASIC CONCEPTS OF THE EVACUATED TUBE COLLECTOR

Originally, the average single glazed FPC was designed for areas with warm climates. The efficiency of collectors in these regions is not paramount, as the solar resources of these areas more than make up for the lack of efficiency of the solar systems (Kalogirou 2004). ETCs, however,

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[40] Most sites will need a frame to ensure that the collectors are at the best possible angle to maximise the solar yield. Others may need some roof support.

were designed for colder and more temperate climates that often experience windy, rainy and overcast conditions. The design of ETC is meant to minimize the convective losses from the collector, whilst simultaneously allowing the tube to collect more energy over a given time period. The collector frame, consisting of a glass tube, can accept more sunlight when the sun is at low angles of incidence, i.e. in the morning and the evening. Therefore, an ETC should give better performance over a given period than a FPC (Kalogirou 2003).

As the temperature of a solar collector increases, the thermal losses due to convection increase too. The vacuum in the ETCs suppresses this convective heat loss, effectively allowing the tubes to operate at higher efficiencies at elevated temperatures. Under similar conditions, the thermal losses of a FPC would be unacceptably high, leading to a dramatic reduction in the efficiency of the collector.

The design under consideration uses the “heat pipe” type ETC (Weiss and Rommel 2008), where the thermal fluid in each collector tube does not touch the HTF in the header pipe. Situated within the evacuated glass tube assembly is the heat pipe (which is an extremely efficient heat conductor (Kalogirou 2004)); essentially, the heat pipe is a copper tube that has a condenser attached to it. The condenser is inserted into the header tube, either directly, with the HTF flowing over it (a so-called wet connection), or via a manifold, which is situated in the header tube (a dry connection). The latter requires a “heat-conductive paste” (Weiss and Rommel 2008) of some sort to ensure that there is suitable thermal conductivity between condenser and manifold.

The main structure of ETCs consists of two concentric glass tubes. A vacuum separates the two concentric tubes, and the vacuum is in the order of magnitude of $<10^{-2}$ Pa (Weiss and Rommel 2008). To maintain the integrity of the vacuum, a barium getter is inserted between the two glass tubes. The getter is a deposit of reactive material (barium in the case of most ETCs) that is coated on the inner surface of the tube, and is designed to supply a dosage of barium to any particles that collide with it, for the lifetime of the tube. The barium absorbs out-gassing substances that are formed due to the high temperatures reached inside the tubes, which would otherwise degrade the performance of the tubes over time (Mahjouri 2009).

The internal space of the heat pipe is kept at low pressure, which is not for insulation purposes, but rather to help the primary working fluid inside the tubes to change its state. Lowering the pressure allows boiling to take place at lower temperatures. The solar heat collected provides the latent heat needed for vapourisation. The hot gases then rise to the condenser, which acts like a heat sink; the fluid within the secondary loop absorbs this latent heat from the vapour, causing it to condense back into the liquid state. The liquid then flows back down the tube under gravity, repeating the process.

The absorber plate (usually copper or aluminium) is continuously attached to the heat pipe for the best possible thermal conductivity. This sub-assembly is then coated in a selectively absorbing coating. The inside of the glass tubing (always iron free glass) is also coated with an anti-reflection film. This reduces the amount of light that reflects off the tube. There are many different compounds and methods for coating the absorber plate, heat pipe sub-assembly and glass tubes. Most of these processes are fully commercialised and have been tried and tested over many years (Kalogirou 2004).

Figure 4.3: Evacuated heat pipe collector (ITS Solar 2010)

The common header pipe contains all the individual condensers (wet connection type) or the manifold (dry connection type). Each tube is an individual sealed unit. Once the heat from the tubes has been imparted to the HTF, it is pumped through a heat exchanger, where it transfers its energy to the potable water contained in the storage tank.

The ETCs have two distinct methods that protect them from overheating. Firstly, if the chemical make-up of the mixture and amount of liquid in the heat pipe is carefully chosen, the liquid will be fully vapourised at a desired temperature (Mahjouri 2009). The point where the liquid is fully vapourised, should ideally correspond with the critical point of the substance. There is no discernible phase change once the critical point of the substance has been reached (as more heat is added only the specific volume of the vapour will increase (Cengel and Boles 2002)). At this stage, all the vapour will have risen to the condenser, hence there will be no substance within the heat pipe to absorb the solar flux. Essentially, this means that the collector has reached its stagnation point and that no more heat is transferred to the tubes.

The second way, in which the temperature is limited within heat pipe ETCs, is by using a thermodynamic valve that makes use of a memory metal spring (Mahjouri 2009). The metal is chosen based on its coefficient of thermal expansion. At the desired cut-off temperature, the “memory” of the metal spring is initiated and it expands; this causes a plug to seal the neck between the condenser tube and the heat pipe. Again, this reduces the quantity of fluid within the heat pipe, which leads to a reduction in the amount of heat transfer that can take place.

There are many different types of ETC being produced in various countries, employing different production techniques. The production of the evacuated space within the tube structure is a well-established process that adapts knowledge from the light bulb and TV tube manufacturing industry. The heat pipe technology is also a mature technology that was first developed by NASA decades ago (Mahjouri 2009). The process has become automated and thus benefits from economies of scale, as large volumes are produced, and this has brought about a reduction in the cost of the units (Mahjouri 2009, Weiss and Rommel 2008).The tubes are widely available within South Africa with many local distributors. The majority of the tubes are imported from China, which is by far the world’s leading producer of ETCs.

4.3.2 COST BREAKDOWN FOR AN EVACUATED TUBE COLLECTOR SYSTEM

The costs of the ETC system have been estimated in exactly the same way as the costs of the FPC system. Again, the manufacturer’s price for the evacuated tubes collectors has been used to construct the overall system cost, based on knowing the relative percentage of this price with respect to the overall system cost.

The price includes a manifold for each array of evacuated tubes. These manifolds can be joined together in turn. The relative cost of the ETCs is a larger portion of the overall system costs, 40%-30%, than compared with the FPC systems which are typically between 20%-30% of overall system costs. This reflects their higher price per square meter of collector aperture. ETC systems are more expensive than FPC systems due to the higher collector costs. The distributor’s figure has not been subject to a discount for large orders, which is usually associated with purchases *en masse*. However, it has been indicated that this figure i.e. R 2451 could be reduced, if a large order were placed.

Table 4.4: Cost breakdown for an evacuated tube system

Description	**Percentage of Total Cost (%)**		**Cost (Rand/m^2)**	
	Low	High	Low	High
Panel Cost	40%	30%	R 2451	R 2451
Installation	10%	15%	R 610	R 1225
Piping & Fittings	6.5%	7.5%	R 399	R 610
Heat Exchanger (1 Of)	3.5%	3.5%	R 215	R 285
Frame and/or Supports[41]	7.5%	9.5%	R 460	R 775
Assembly & Fasteners	2.5%	2.5%	R 150	R 205
Insulation for pipes	1.5%	1.5%	R 95	R 125
Pumps (2 Of)	3%	3%	R 185	R 245
Engineering Fees	8%	10%	R 490	R 815
Electrical Panels & Controls	12.5%	12.5%	R 765	R 1020
Contingency	5%	5%	R 306	R410
TOTAL	100%	100%	6130 R/m^2	8170 R/m^2

4.4 PARABOLIC TROUGH CONCENTRATORS

This section, which focuses on PTCs, follows the same format as the previous two sections. PTC systems would need to be imported into South Africa and are therefore subject to the associated duties, taxes and shipping fees etc. For a breakdown of these costs, please consult Appendix C.

4.4.1 BASIC CONCEPTS OF PARABOLIC TROUGH SYSTEMS

The PTC is by far the most mature concentrating solar technology to date. PTCs have been used around the world to generate heat at temperatures up to 400˚C. Many installed plants make use of PTCs in both Europe and the USA. Despite what people may think, the higher costs involved in concentrating solar systems are more than offset by the larger efficiencies achieved at high operating temperatures.

Several companies now sell modular units for applications from 50-250˚C (AIGUASOL Enginyeria 2001, Weiss and Rommel 2008). Brooks (2005) in his master's dissertation built and tested a PTC locally, with aperture 7.5m^2 and optical efficiency off 55%. The design was never commercialised, but the project did prove that these systems could be built and tested locally (Brooks 2005).

The main reason why concentrating technology is employed is that it reduces the large amount of heat loss associated with non-concentrating solar collectors. The concentration ratios of a PTC

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[41] Like with the FPC systems, most sites will need a frame to tilt the ETCs at the best angle possible to maximise the solar yield. Others may need some roof support.

range from 10-26 (for the smaller modular units). This greatly reduces the absorber area of a collector compared to its reflector area (Weiss and Rommel 2008). Reducing the absorber area of a solar collector furthermore greatly reduces the heat losses from the collector; see Table 4.1 for a comparison of the heat loss coefficients. The PTC has a heat loss coefficient an order of magnitude less than the other two types of collector. Nearly all modern PTC designs employ evacuated tubes to cover the receiver element in order to suppress heat losses.

The troughs have a very narrow window of acceptance and hence have to track the sun. They only make use of the normal part of global radiation, and need to track the sun in order to keep this continually focussed on the linear absorber. Any misalignment results in a large loss in efficiency. They can be aligned either north-south or east-west. The loss in optical performance that is inherent when reflecting light with optical devices, such as concentrating technologies, is more than offset by their gain in thermal performance (Weiss and Rommel 2008). Large PTCs with aperture widths of around 6m have been in existence primarily for power generation. Smaller modular units are now available that can be roof mounted, and that are designed to deliver process heat from 50 - 250˚C. The aperture width of these designs ranges from 50cm to 2.5m (Weiss and Rommel 2008).

Figure 4.4: An array of modular parabolic trough collectors (NEP SOLAR 2009) with aperture width 1.2m.

4.4.2 COST BREAKDOWN FOR A PARABOLIC TROUGH SYSTEM

The PTC system costs are obtained from literature on CSP, together with collector costs from Australian manufacturer NEP SOLAR. The collector cost supplied by NEP SOLAR is CIF[42] (cost, insurance and freight) to port in South Africa (Minder, Solar Thermal Research 2010). Once at port in Cape Town, the buyer needs to pay duty, VAT[43] and clearance agent fees (Cronje 2010). All these costs have been taken into account in this analysis. The overall effect of these charges is that the cost of the collectors is increased by 40.71%[44] from the CIF price quoted by the manufacturer. The breakdown of the solar field cost as well as the system costs are given in Tables 4.5 and 4.6.

Table 4.5: Solar collector field costs, for a parabolic trough collector system (518m^2)

Collector Field Costs, 18 modules (518m^2 of collector aperture area)

Description of Item	***Percentage of Total Cost (%)***	
	Low	*High*
Mirror, Receiver, Frame & Drive	*74.00%*	*68.40%*
Piping & Fittings	*8.72%*	*12.47%*
Hydraulic Control System	*1.57%*	*1.27%*
Structural Support	*8.00%*	*10.00%*
Assembly & Fasteners	*0.39%*	*0.32%*
Insulation	*0.39%*	*0.32%*
Pumps	*1.50%*	*1.50%*
Electrical Panels & Controls	*5.43%*	*5.73%*
Total (100%)	*100.00%*	*100.00%*
Total Cost	***R 3,726,545.78***	***R 4,031,643.09***
Cost (Rand/m^2)	***7,194.10***	***7,783.09***

The system percentages have been adapted from a report prepared for the National Renewable Energy Laboratory (NREL) in the USA, which is the national laboratory of the US Department of Energy (Sargent & Lundy LLC 2003, Sargent & Lundy LLC 2005). Much of the data comes from the experience gained in operating the SEGS I – IX (solar energy generating systems) over the past two decades.

In the literature, the cost of the mirrors, receivers and drives are all assigned individual percentages of the total solar field cost. The units from NEP-Solar are modular; and every module (28.8m^2)

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[42] The seller pays for freight by sea, insurance and duties at the port of shipment.

[43] VAT is 14% on top of duty (15%) and 10% upliftment fee. The upliftment fee is not paid out; it is just used to inflate or increase the VAT. Clearance agent fees are 8%.

[44] The full breakdown of import and exchange rates (US Federal Reserve 2010) used in this analysis is presented in Appendix C.

comes complete with mirror, frame, receiver and drive (collector elements). Therefore, the relative percentages assigned to these items collectively make up the first row of Table 4.5. Again, the total cost is constructed based on the relative percentage and cost of the collector elements. Roof installations will not need any civil works, unlike ground installations, but mounting platforms for the base of the frames as well as structural reinforcement for the roof will be necessary due to the extra load of the PTCs. Note that there will be an electrical control system, as well as a hydraulic control system, which will control flow rates through the receiver tubes.

Table 4.6: Parabolic trough system costs

System Costs		
Description of Item	***Percentage of Total Cost (%)***	
	Low	*High*
Solar Field	*58.00%*	*51.00%*
Steam Generator	*2.00%*	*2.00%*
Heat Transfer Fluid	*3.00%*	*3.00%*
Installation	*12.00%*	*17.00%*
Engineering Fees	*8.00%*	*10.00%*
Contingency	*17.00%*	*17.00%*
Total (100%)	*100.00%*	*100.00%*
Total Cost	***R 6,425,078.93***	***R 7,905,182.53***
Cost (Rand/m^2)	***12,451.70***	***15,320.12***

Depending on the temperature of operation, thermal oils are used in parabolic troughs as a heat transfer fluid. Direct steam generation is possible, but it has its associated problems, i.e. extreme temperature variations within the receiver tube, which lead to hot spot activity, and large temperature gradients between different parts of the pipe (Almanza, Lentz and Jimenez 1997), which can lead to fatigue and bending of the receiver pipe. Additional control mechanisms are needed to ensure proper operation of the troughs (Eck, et al. 2003) when using direct steam methods. The upside of using water directly is that the solar-steam heat exchanger (Almanza, Lentz and Jimenez 1997) and thermal oils can be eliminated, which lowers the system costs. By not using thermal oils, there is increased system efficiency due to higher operating temperatures (Almanza, Lentz and Jimenez 1997, Eck, et al. 2003). This is mainly a concern for power generation where temperatures in excess of 400°C are desired, which leads to severe degradation of the thermal oils.

5. THEORY

This chapter is made up of three sections: The first looks at the theory behind the bottom-up modelling approach that has been used to calculate the final energy consumption for each process considered. These aggregated figures will be used to make assumptions about the potential for solar heat in the F&BI. The second section looks at the theory used in the calculations of the solar fractions and of the amount of useful heat added by the SHS systems. Finally, the last section presents the theory used in the GHG emissions analysis and LCA.

5.1 FINAL ENERGY CONSUMPTION: PROCESS HEATING AND COOLING

This section presents the theory used in calculating the primary fuel consumption for each process, and it explains how the technical potential (for SHSs) for each company was found.

5.1.1 USEFUL PROCESS HEAT AND FINAL ENERGY CONSUMPTION

The quantity of product processed by a factory is a known parameter, usually in the form of a mass flow rate , measured in kg/h. Therefore, the rate of heat needed in a process is given by the following simple equation:

(5.1)

where is kJ/h, C_p is the specific heat of the product being heated and is the temperature difference between the product entering and leaving the process in °C. The HTF is often separated from the product via the use of a heat exchanger. The HTF most commonly used by the F&BI is water, either in the form of steam or pressurised hot water.

To get the useful process heat (UPH) needed per annum, the quantity is multiplied by the annual operating time of the process (in hours), 8760 hours being the maximum possible in a year (assuming the system is operational for 24 hours x 365 days without stopping). The equation for calculating the UPH needed per annum is as follows:

(5.2)

UPH is in either MWh or GJ, where 3.6 GJ is equivalent to 1 MWh.

In order to calculate the quantity of final energy consumed in the form of coal or fuel oil, one needs to take into account the energy lost between burning the fuel in the boiler and the energy consumed by the process. The useful supply heat (USH) is the amount of heat dispatched by the boiler to the steam reticulation system. Heat is lost in the reticulation system en route to the process. Measuring the quantity of steam supplied to every process would be a very expensive process; instead, a value of 15% has been used to account for losses in the steam reticulation system, which is the same number used by the researchers in the POSHIP report (AIGUASOL Enginyeria 2001).

Heat from combusted fuel is also lost in the boiler itself. Therefore, to convert the UPH established from Equation 5.2 into final energy consumption, the losses in the supply system and boiler must be taken into consideration. The following formula can be applied to work out the final energy consumption (FEC):

(5.3)

The efficiency of the boiler is dependent on the boiler's construction and method of operation. For this project, typical boiler efficiencies range between 75% and 85%. The second term in Equation 5.3 accounts for the losses in the supply system, i.e. heat losses in the pipes, the condensate and the heat exchangers.

5.1.2 FINAL ENERGY CONSUMPTION: COOLING

Solar heat can provide energy for cooling by using absorption refrigeration systems. In a conventional vapour compression cycle, a compressor provides the work input needed to produce cooling, and the system converts electricity into useful cooling. The conversion efficiency of the refrigeration system in providing the desired cooling is known as the coefficient of performance (COP) of the cooling system. The mathematical description of the COP is given as follows (Cengel and Boles 2002):

(5.4)

The term Q_L is the desired cooling load or cooling effect required, which is expressed in kW. The W_{net} is the required amount of mechanical energy that the cycle needs in order to supply the desired cooling effect. The work input in a vapour compression cycle is the quantity of electricity used by the system[45].

The F&BI makes use of large scale ammonia based vapour compression cycles. The COPs for typical F&BI systems are in the range of 2-5 (Käsner 2010), depending on the application. The lower the temperature of the desired cooling effect, the lower the COP will be for the system. For a

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[45] Apart from the compressors, there are also fans (for blowing air across the evaporator into the cold space), pumps that circulate defrosting water, controllers and other items, which consume power in a vapour compression cycle. The major consumers by far are the compressors.

given cooling effect, the work input will rise, as the desired temperature decreases. This is because the compressor has to supply a greater amount of mechanical work in the form of compression. The increased mechanical work means increased electricity consumption.

Therefore, the final energy consumption of a large industrial refrigeration plant will be determined by the system's COP[46] and the number of operating hours per year. Most systems will cycle on and off as needed, and may not run continuously at the rated capacity the entire time. The cooling load varies, and the system is usually designed to cover the peak cooling requirements of the plant, which often coincides with summer when the ambient temperatures are the highest. Therefore, at other times of the year, when ambient temperatures are cooler or during times when production is not as its peak, the systems may not operate at full rated capacity. Hence, the FEC is not simply calculated as the maximum operating capacity multiplied by the number of hours in a year. Instead, it is calculated as follows:

$$\frac{\quad}{\quad} \qquad (5.5)$$

where the final energy consumption is in MWh. In this case n is the capacity at which the refrigeration operates at for a given period of time. The formula basically states that the FEC is the summation of the different loads at which the system operates at multiplied by the time at which it operates at the specific load. The part load the refrigerator will operate at a different COP_{nR} to its normal COP_R.

The FEC of a refrigeration plant is most accurately measured by monitoring the power consumption of the plant directly with an electricity meter. Failing this, Equation 5.5 can be used together with data or knowledge from the plant's engineer.

5.2 SOLAR THERMAL PROCESSES

This section outlines the theory used to calculate the useful heat gain of the solar collectors; it also describes how the test data from certification authorities is used to calculate this quantity. The principle of solar fraction is discussed too. The first part of this section also deals with the models used by solar modelling tools, such as RETScreen.

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[46] The system COP takes into account the energy used by mechanical blowers, compressors and pumps that are used to circulate water to defrost the evaporator coils etc. The major contributors are obviously the compressors.

5.2.1 COLLECTOR EFFICIENCY AND USEFUL HEAT GAIN

There are many variables in calculating the useful heat gain of a solar collector, namely, radiation intensity, fluid inlet temperatures, wind effects, the sun's changing position in the sky and the changes in ambient conditions. Therefore, it is necessary to have a model that can help designers to predict what the solar gains of a collector will be in a geographic region. As discussed previously, having reliable long term solar radiation data is the key starting point.

There are entire chapters dedicated to explaining the theory behind the mathematical modelling of FPCs (Duffie and Beckman 2006, Kalogirou 2004). But there is one equation that stands out above all others when it comes to predicting the useful heat gains from solar collectors (Duffie and Beckman 2006), namely:

(5.6)

where A_c is the area of the collector in m^2, F_R the heat removal factor, S is the solar radiation absorbed by the collector in J/m^2, U_L is the overall heat loss from the collector[47], and T_i[48] and T_a are the inlet fluid and ambient temperatures respectively. This equation can be applied to most types of collectors.

The useful heat gain is calculated as a function of the collector inlet temperature by using Equation 5.6. This is a convenient method for analysing SHSs, as the inlet fluid temperature is often a known condition. But, by doing so, one underestimates the losses experienced by the solar collector. The temperature of the absorber is not uniform and equal to the inlet fluid temperature along its entire surface. Rather, the temperature of the absorber increases along the fluid's flow path. The heat removal factor F_R therefore adjusts the useful heat gain of the collector from what it would have been if one simply assumed that the absorber was at a constant temperature equal to the fluid inlet temperature, to what it is in reality (Duffie and Beckman 2006).

F_R is dependent on the mass flow rate through the collector. As the flow rate increases, the temperature rise through the absorber decreases and the heat losses decrease correspondingly. The construction of the collector's absorber sub-assembly limits the level to which F_R can increase.

Most testing authorities provide the instantaneous efficiency of a solar collector, which is the ratio of the useful heat gain to the solar radiation falling on the collector area, as follows:

(5.7)

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[47] This term takes into account both the optical losses and heat losses experienced by a solar collector. The term is temperature dependent.

[48] In European testing procedures, the variable T_i is replaced by the true mean fluid temperature across the absorber. Hence the factor F_R is replaced by F' to compensate for the fact that T_i and T_m are not the same. Data for this project is mostly in the European format. It is possible to convert from one form to another.

where η_i is the instantaneous efficiency and S has been replaced by the product of G_T and $(\tau\alpha)$. In this case, $(\tau\alpha)$ is the transmittance-absorptance product of the solar collector. Essentially, it is the transmittance-absorptance product of beam radiation falling on the collector (Duffie and Beckman 2006). A coefficient called the angle of incidence modifier is introduced later; this term adjusts the $(\tau\alpha)$ product to reflect the fact that the sun's position in the sky changes over time, and hence so does the amount of radiation transmitted and absorbed by the absorber surface of the collector. G_T is the total amount of solar radiation falling on a collector's aperture.

The instantaneous efficiency of a collector is a misleading term when used in isolation to determine the amount of heat collected by a solar water system. The above model, Equation 5.7, implies a simple linear relationship between the instantaneous efficiency and the operating conditions ——. But in reality, data plotted using Equation 5.7 can be scattered, and the variables F_R, U_L and $(\tau\alpha)$ are not constant in the operating conditions of the flat plate collector. Scatter in the data is due to temperature dependence, wind effects and angle of incidence changes[49] (Duffie and Beckman 2006). Having said all this, Equation 5.7 is usually sufficient to model the performance of a standard single glazed flat plate collector. But in this project, other collector types are used and hence a more appropriate model is needed to estimate the performance of all the different types of collectors in order to make a valid comparison between them.

This leads to the following equation, which describes the instantaneous efficiency of solar collectors as a function of the operating conditions. The resulting equation implies a quadratic relationship:

—— —— (5.8)

where the equation is in the European format, i.e. the true mean temperature difference between the absorber and ambient conditions is used. In this format, η_o is equivalent to . This equation is used by most solar modelling packages in either of the two forms (European or US), and therefore it is important to make sure the data entered is in the correct form for the corresponding programme. Equation 5.8 can be used to model the performance of stationary FPCs to PTCs that track the sun. For instance, the programme RETScreen uses this equation. However, it does not have an in-built quadratic solver, and hence solves the problem by using a linear interpolation function.

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[49] The tilt of the Earth in conjunction with the Earth's rotation around the sun means that the sun's angle of incidence will change with respect to a fixed collector over the course of a season.

5.2.2 ANGLE OF INCIDENCE MODIFIER

The angle of incidence modifier is a coefficient used to moderate the results of Equations 5.7 and 5.8. It essentially accounts for the fact that the sun's position in the sky changes over the course of the seasons. Because the product (τα) is calculated under test conditions, when beam radiation is strong, it does not give such an accurate approximation of the conditions experienced by the solar collector when the sun is low in the sky or when cloud cover is predominant. At these times, diffuse and reflected radiation make up the larger portion of the heat collected by the absorber.

With the angle of incidence modifier added, Equation 6.6 then becomes (Duffie and Beckman 2006):

(5.9)

where the angle of incidence modifier is given by the following expression for collectors with flat covers[50] e.g. FPCs (Duffie and Beckman 2006):

(5.10)

In this equation, b_0 is known as the angle of incidence modifier coefficient. This coefficient is unique to each type of collector and is dependent on the collector's construction. Some collector types, such as ETCs, require a biaxial angle of incidence modifier, as the cover shapes are non-symmetrical. The angle of incidence modifier is supplied by the testing authority together with the test data for a specific collector. Most solar modelling programmes allow for the angle of incidence modifier.

5.2.3 SOLAR FRACTION

Solar fraction is simply the ratio of solar energy to conventional energy used in a process. For instance, if a process consumes 100 GJ of energy per annum in the form of pressurised hot water derived from burning coal, and 50 GJ of pressurised hot water per annum, directly supplied from a SHS, the solar fraction of the design is simply 33% for that year.

A brief sensitivity analysis was performed on the data to see what the effect is of changing the solar fraction of a design on the economic analysis in terms of the net present worth of a system. Solar fraction is linked to both the initial capital costs and avoided energy costs, which are two conflicting variables in a solar system. Increasing the solar fraction will increase the design and component costs of a solar system, whilst at the same time increasing the avoided energy costs.

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[50] The term flat covers is used here instead of stationary collectors as the ETCs are also stationary but their geometry is unsymmetrical and Equation 5.10 cannot be used in this instance

By analysing the "classical capital-energy trade-off" (Kulkarni, Kedare and Bandyopadhyay 2007), one can work towards finding the optimum solar fraction of a particular design. This will be a design that has the largest ratio of energy savings to initial capital costs. In terms of the F&BI, this is a design that pays back in the shortest period possible whilst at the same having a favourable NPV.

The next section will discuss the theory used in the economic analysis of the solar systems. Optimising the NPV and payback period of a design should reveal the optimum solar fraction of a design. For this project, the example chosen was the preheating of boiler make-up water.

5.3 ECONOMIC ANALYSIS: LIFECYCLE COST ANAYLSIS AND GREENHOUSE GAS EMISSIONS

This section discusses the theory used in the economic analysis of the SHSs. From this analysis, one should be able to judge how long it takes for a solar heating design typical of the FB&I to pay itself off. The GHG emissions analysis has been included under the title of economics because GHG emissions savings may be a source of income. The section will highlight the underlying theory used by the stationary combustion tool developed by the World Resources Institute, which is used to calculate the GHG emissions from the factories in the F&BI.

5.3.1 LIFECYCLE COST ANALYSIS

The underlying principle of the LCA is that a sum of money today is not worth the same as it will be in the future. Money today is worth more to us than money in the future, because we could invest the money today and start earning interest. Therefore, we need to know what sum of money to invest in today's terms for a design that will incur future earnings and expenses. In the case of a SHS, earnings equate to energy cost savings and expenses to operational and maintenance costs. The present value of a cash flow, F, in the future depends on how much we discount that cash flow over time. The basic formula for the present value of a cash flow is:

$$\frac{\quad}{\quad} \qquad (5.11)$$

Where d is the discount rate (%) and n the number of years. Therefore, if we know all the costs that are incurred in the implementation of the solar design during its useful lifespan, we can calculate the NPV of the design. The cost of powering a conventional heating system is given by the following (Kalogirou 2004),

$$(5.12)$$

Where Q_{load} is the amount of energy used in kWh (electricity) or GJ (coal or HFO) and C_{energy} is the cost of the energy. The formula states that the summation of the load over a period of time, multiplied by the price for each unit of energy, gives us the total cost for the energy. When a solar system is augmented with a conventional heating system, the cost of supplying the auxiliary heat is given by the formula (Equation 5.12).

The cost of the solar design can be paid for either out of existing capital or through finance (in other words, a loan). If the design is paid by a loan, there will be an annual capital repayment amount, which needs to be considered in the LCA. There are also other costs one would have to factor in, such as the operating and maintenance costs (O&MC) and parasitic costs (PC). Parasitic costs occur because of a specific design, i.e. additional power for pumps, controllers etc (Kalogirou 2004). The overall cost savings on a yearly basis are given by the following (Kalogirou 2004):

(5.13)

A positive value indicates a saving, and a negative outcome a debt. The terms in the brackets represent costs whereas the avoided fuel costs are savings. The annual capital repayment must service both the capital borrowed and the interest charges on the loan. Inflation is taken to be zero, so that the capital is returned in equal instalments over the period. To estimate the size of the annual instalment, one needs to divide the amount of capital by the capital repayment factor (CRF). The CRF is given by:

$$ - \qquad \overline{\quad} \qquad (5.14) $$

Once the solar savings have been tallied for a given year, the present value of each annual solar saving is summated to give the overall lifecycle cost of the project. This is given as follows (Kalogirou 2004);

$$ \overline{\qquad\qquad} \qquad (6.15) $$

And finally, the time that a design takes to pay itself off can be calculated from the LCA. One can also compare the value of the project with alternative investments to determine which one would give the company the best return on investment. There are many assumptions used in the LCA, and these need to be made transparent, so that the underlying parameters can be scrutinised and compared to other studies, or so that the analysis can be adjusted to updated market parameters.

5.3.2 GHG ANALYSIS: STATIONARY COMBUSTION TOOL

The World Resource Institute's stationary combustion tool has been used to carry out the GHG analysis in this project (World Resources Institute 2008). The three main gases emitted by the combustion of fossil fuels within boilers are carbon dioxide, nitrous oxide and methane. For the purpose of this project, the emission of methane is considered as a fugitive emission associated with the coal mining process (see Chapter 6.4.1). CO_2 emissions account for over 99% of emissions from stationary combustion. The quantity of the other two gases emitted is far less than that of CO_2, but is still sufficiently significant, and therefore has been included for completeness.

All the calculations have been done using emissions factors on an energy content basis i.e. kg/GJ. This is especially important for CO_2 emissions, as there is less variability in the carbon content of a fuel when using emissions factors based on such an energy content basis. There is a close correlation between the energy content of a fuel and its carbon content (World Resources Institute 2008). The gross calorific value (GCV) has thus been used, as this has a more direct relationship with carbon content (World Resources Institute 2008), unlike the net calorific value (NCV), which is a stronger function of moisture content.

The CO_2 emissions from a given fuel are then given by the following (World Resources Institute 2008):

$$— \qquad (5.16)$$

where the emissions, in metric tonnes, are a product of energy content of the fuel A_{fh} (e.g. in GJ), F_{ch} is the carbon emissions factor based on the fuel's energy content (e.g. kg C/MJ), F_{ox} is the oxidation factor that accounts for the amount of carbon emitted as particulate matter or ash, and 44/12 is the ratio of the molecular weight s of CO_2 and carbon respectively.

The energy content of the fuel is calculated by multiplying the GCV of the fuel (on a mass basis) and the mass of fuel used[51]. On a mass basis, the simple formula is as follows:

(5.17)

The oxidation factor for fuels can vary, but in most cases, almost all of the carbon is burnt, i.e. 100%. Within days of combustion, the carbon remaining in the form of CH_4, CO and the other by-products of combustion will be oxidised to form CO_2 in the atmosphere. The only carbon not in the form of CO_2 is that, which escapes in the form of soot or ash. The IPCC default oxidation factors for coal and oil products are 99% and 98% respectively.

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[51] The calculation can be performed just as easily if the consumption of fuel is on a volume basis.

The emission of NO_2 is directly linked to the fuel-air ratio and the combustion temperature that is present in the combustion chamber (World Resources Institute 2008). In respect of the combustion of NO_2, the following equation can be used to calculate the amount emitted (World Resources Institute 2008):

—— (5.18)

where the units for emissions are measured in metric tonnes. A_{fh} is the energy content of the fuel (e.g. GJ), EF is the emissions factor based on the energy content of the fuel (e.g. kg/GJ) and the impact of emissions control equipment (1-C/100). In most instances, there is no emissions control equipment installed in companies to abate GHG emissions.

6. RESEARCH METHODS

This section explains which economic indicators and other variables were used in the calculations of the project, as it is important to know what values and units were used to derive these values. Justifications for and definitions of the principles used in the analysis are discussed too.

6.1 INFORMATION GATHERING AND DATA GATHERING

This section briefly outlines the process that was adopted when contacting members of the F&BI, and it explains exactly what information was requested from these companies. A list of questions asked has also been included.

6.1.1 CONTACTING INDUSTRIAL COMPANIES

The data collected during the course of this research comes from a selection of food and beverage manufacturers in the Western Cape. Emails were sent out at random to food and beverage manufacturers who are known to have plants in the Western Cape. A diverse range of companies within the sector was contacted to ensure that the sample was representative of the many different manufacturing processes within the industry. A copy of the research proposal sent out to the various companies is included in the appendices.

The response rate from manufacturers was generally low. Experience has shown that a response rate of around 2% is common (AIGUASOL Enginyeria 2001). Fortunately, there seemed to be a slightly higher response rate for this project. In most cases, the email responses were followed up by telephone calls, to confirm whether the email had in fact been received by the intended recipient. Emails were sent out from March 2010 onwards.

6.1.2 THE DATA COLLECTION PROCESS

In the POSHIP study, researchers sent out a questionnaire to various industries (AIGUASOL Enginyeria 2001). The response rate to the questionnaires was extremely low, as mentioned above. The main problem in that study was that the questionnaire was very long. A different approach was thus used in this study.

Initially, a research proposal was sent out on an official department letterhead, simply explaining the purpose of the research. This was followed up by a phone call, as mentioned previously. In the cases where the companies accepted the proposal, a site visit was made. Only at this stage was a detailed questionnaire given to the company to complete.

The site visit was deemed necessary, as it put a face to the email and telephonic conversations. It was also more efficient to explain the exact scope of the project during face-to-face discussions. Lastly, the site visits also gave the researcher a better understanding of the processes taking place at a facility. This made it easier to identify the processes that would be directly applicable to the study, which makes it easier and quicker to obtain the information needed from the plant engineer. It furthermore eliminated a substantial amount of unnecessary back-and-forth discussion.

In all cases, the plant managers and engineers were extremely busy with keeping the plant running. Most F&BI factories run continuously throughout the year and downtimes equate to a direct loss in income, therefore any time given to extras – such as research – is a luxury. Consequently, a high degree of flexibility was necessary on the part of the researcher.

6.1.3 ENERGY CONSUMPTION DATA AND THE ENERGY AUDIT PROCESS

Consumption data in respect of fossil fuels such a coal[52] and heavy fuel oil is (HFO) always only available in aggregated form for entire plants , and thus the direct consumption of primary fuel for a specific process is not known. A bottom-up approach[53] is used to establish how much primary energy a specific process consumes. This means working backwards from the amount of product processed, a figure that is known to plant managers and engineers.

There are two transformation stages in the energy supply chain from primary fuel to useful process heat. The primary fuel is burnt in a boiler at its rated efficiency[54], and the output from the boiler is the useful supply energy, which is in the form of steam, pressurised hot water or hot water. The steam or pressurised hot water is then transported to the process at high temperature and pressure. In the case of steam, it is passed through a pressure reducing valve, where it is stepped down to the processes' desired temperature and pressure. The conversion efficiency in this step has been chosen as 85% for this project, meaning that 15% of the water/steam's energy is lost along the supply system in the form of condensate. The three mechanism of energy loss that contribute to this 15% loss in energy are: It is assumed that dry steam is supplied to a process devoid of condensate so as to increase the efficiency of the heat transfer in the heat exchanger (wet steam lowers the efficiency of heat transfer across a heat exchanger), but this condensate is

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[52] The typical coal used in the Western Cape F&BI has a calorific value of 27 MJ/kg and is bituminous coal. This is a much higher grade coal than that typical of the power generation industry (Lloyd 2010).

[53] The bottom-up approach is a technique used in the broader field of modelling in terms of which a system is constructed based on knowledge of the base elements of the system.

[54] The boiled efficiency is dependent on the design of the boiler and varies according to manufacturer.

at a high temperature, which therefore represents a loss of energy to the system when it is removed. Also steam headers often span large distances in factories and therefore heat is lost even with insulated piping, it is impossible to provide perfect insulation to pipes. Lastly, the steam in a header pipe is reduced in quality (temperature and pressure) to suit that demanded by the local process. In this step down process, heat is again lost in the form of condensate. It is not untypical to lose 15% of one's primary energy supply in the steam reticulation system of a large factory.

As a side note, SHSs that supply heat directly to a process and not to the reticulation system, actually avoid many of these losses as the heat is generated to suit the local process demand and not the requirements of the steam reticulation system, which always has to be at higher temperature and pressures than the local processes (steam flows from areas of high pressure to areas of low pressure).

The energy supplied to a process after this transformation step is known as the useful process heat, and it is the amount of heat available to a process after all the losses and transformations have occurred.

Once these two efficiency figures are known, it is possible to work backwards using a bottom-up approach to approximate the amount of primary fuel used in a process.

In the case of electrical systems[55], the consumption can also be calculated by means of a bottom-up approach, if the conversion efficiencies of the systems are known. For this project, the author also has access to three-phase power meters. These devices record the voltage and current drawn by industrial machinery and store it in their internal memory in a format that can easily be downloaded onto a computer. These units can be installed on site without shutting down the power supply to a unit, and they will give a very accurate measurement of the energy used by that piece of equipment.

The power meters are *Elster A1700* three-phase meters. They record the real and apparent power simultaneously, and the data can be converted into Microsoft Excel spreadsheet format for easy analysis.

In the case of electricity metering, caution has to be exercised, as one has to be certain that the period of recording is typical of the average working conditions of the system being metered. For instance, a heating system's peak demand would coincide with winter, which means that any metering done during summer would exclude this peak, thus giving a false impression of the maximum demand. The converse is true with cooling systems where the peak demand occurs in summer. Therefore, the results must be analysed with caution.

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[55] Electric boiler, calorifiers and other resistance heaters.

Another factor to consider when metering electricity consumption is that not all manufacturing occurs constantly throughout the year. Again, if the recording period does not occur during the peak production period, the analyst will need to adjust the results to reflect this maximum demand.

Therefore, the analyst has to account for these factors to obtain an accurate picture of the energy consumed by an electrical system.

6.1.4 SOLAR SYSTEM INFORMATION AND ENERGY AUDIT QUESTIONARE

Below is a list of questions sent to the F&BI manufacturers after the initial interview and site visit:

Solar System Space and Orientation:

i. Available roof or ground area (m^2)

ii. Inclination of the roof space with respect to North

iii. Fuel consumption

iv. HFO and coal calorific values

v. Price of HFO and coal

vi. Boiler efficiency or mass of steam produced per mass of fuel

Heating Processes (for each process):

vii. Process type, i.e. CIP or boiler make-up water

viii. Temperature of the process (°C)

ix. Mass/flow rate of process (kg/h) or quantity of process/product heated up in a given period, i.e. 20 000 litres of water every 6 hours for cleaning.

x. Hours of operation per day

xi. Days of operation per year (or days per week and weeks per year)

xii. Is there any storage for the process (m^3)?

xiii. Is the boiler make-up water simply ambient temperature, i.e. the same temperature as the municipal supply?

Cooling Processes:

xiv. Cooling load desired (kW)

xv. Refrigerant used

xvi. Cooling temperature desired

xvii. COP of plant (if possible), i.e. the conversion efficiency of the plant

xviii. How much of the year does the cooling plant run, out of a possible 8760 hours (same as Questions ix and x)

6.2 CRITERIA FOR EVALUATING THE POTENTIAL FOR SOLAR HEAT

One of the main focuses of this project is to establish what percentage of the energy consumed in the Western Cape F&BI could be supplemented with solar energy, thus resulting in a direct saving in conventional primary energy sources. The use of solar energy would also have a positive impact on the environment, as it would reduce GHG emissions. The following chapter discusses what criteria can be used to judge this potential based on the information received from industrial players / from industry.

6.2.1 TECHNICAL POTENTIAL: SOLAR FRACTION AND ROOF SPACE

The technical potential of a technology is simply a measure of the quantity of a technology that can be implemented with current knowledge. There is no regard for economic constraints (Nadel, Shipley and Elliot 2004), and it assumes that all available opportunity is exploited.

The technical potential for a process with a constant demand throughout the year is defined by a solar fraction of 60%; this is a similar methodology to that used in the POSHIP study (AIGUASOL Enginyeria 2001). Another limiting factor will be the available roof and ground space of the plant.

The reason why 60% was chosen as the ceiling for the technical potential is that solar fractions above this require increasingly large amounts of thermal storage. This invokes the law of diminishing returns. It makes economic sense to have a small amount of storage available for load fluctuations and for weekend shutdowns. But in order to supply a large solar fraction (>60%), the amount of storage requirement becomes increasingly large, whereas the returns in the form of useful process heat diminish. Storage has only been considered in the case of Company C, i.e. 190 000 litres of storage. Storage in small amounts has been shown to be enough (AIGUASOL Enginyeria 2001) to cater for short term load fluctuations as well as for breaks in demand for one to two days (i.e. weekends or part thereof), but in the case of Company C all the heating is demanded at night and therefore more storage than 25 litre/m^2 of collector area is needed. The night time load will be catered for but at the expense of increased system costs.

Energy consumption data within the Western Cape, as stated in the literature review, is not available on a disaggregated level, therefore the most suitable definition to use will be the technical potential. This definition gives a clear indication of the overall market size that exists for solar heat. At the same time, it does not require so much work that it shifts the focus of the project away from the hypothesis, as to become a market survey of energy consumption within the Western Cape F&BI.

6.2.2 ECONOMIC POTENTIAL: COST OF ENERGY DELIVERED

The economic potential of a technology is the quantity of a technology that can be implemented, given a subset of economic criteria that have to be met. This economic potential is a more subjective term than the technical potential, and the figures it generates are directly proportional to the economic criteria chosen by the analyst. In its simplest form, the economic potential of a technology is simply the energy savings achieved by a technology, valued at a company's avoided energy costs and discount rate (Nadel, Shipley and Elliot 2004). If a given analysis uses a broader definition of economic potential that encompasses externality costs[56] avoided by society in the implementation of a new technology, then the potential would be much higher than in the simple case.

The POSHIP report uses levelised energy cost as a ceiling to the economic potential, the amount being 60€/MWh. Hence designs that had a levelised cost of 60€/MWh or more were not considered as economically viable (AIGUASOL Enginyeria 2001). Designs with a levelised cost less than 60€/MWh qualified for a subsidy of 50%, hence making them even more attractive as an investment. Levelised costs of 60€/MWh, would not be a good criterion to use in South Africa or in the Western Cape to determine whether a project is feasible or not, as there is currently no legislation in place to guarantee that companies receive revenue either in the form of a tax relief or a subsidy to fund industrial renewable energy designs.

This project instead aims to forecast at what energy price and with what technology such systems would become feasible. The project will also identify what processes are best suited for supplementation with solar heat. It must be borne in mind that investments, especially in fixed capital, that take longer than 18 months to pay back are generally not implemented by industry (DME 2002).

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[56] The externality costs could be a tax on pollution, savings to the health budget by improving air quality, carbon revenue based on GHG emissions savings, etc.

6.3 COMPARISON OF THE THREE DIFFERENT SOLAR COLLECTOR TYPES IN A TYPICAL INDUSTRIAL SCENARIO

This project will look at a particular form of process heat that is common to all industrial factories employing a boiler, viz. the preheating of make-up water. The reasons for choosing this process will be justified in this section. The analysis herein will compare the cost effectiveness of the three different solar technologies presented in Chapter 4 to supply this energy.

6.3.1 COLLECTOR TYPES AND BOILER MAKE-UP WATER SUPPLY

The process chosen for the basis of comparison with the different collector types is the heating of boiler make-up water. The primary reason for choosing this process is that it is common to all factories.

Furthermore, boiler make-up water can be a considerable part of energy consumption in some plants where a large portion of water may not be returned to the boiler for reheating. This fresh supply of water has to be heated up from an ambient temperature to the boiler operating temperature. Pre-heating this water to between 80°C and 90°C means that the boiler will consume less fuel and that it just has to top-up the heat to whatever the desired operating temperature is.

From thermodynamics, we know that in the process of heating up a body of water from 20°C to steam at 100°C and 1 bar pressure (for example), over 80% of the energy is spent in evaporating the water to form steam. Therefore, pre-heating boiler make-up water can save a considerable amount of energy, especially where the systems are pressurised to stop the water from boiling, as the heat of vapourisation can be supplied by the pre-heating system. In unpressurised systems, up to about 19% of the energy can be saved by pre-heating[57].

Solar collectors operate more efficiently when heating up water from lower temperatures. The efficiency of a solar collector is related to the temperature difference between the fluid entering the collector and the ambient temperature. Hence, a greater difference ensures that more energy is imparted to the fluid entering the collector than is lost to the surroundings (Duffie and Beckman 2006).

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[57] Pre-heating water in unpressurised systems does not save as much energy, up to 20%.When water boils, it can lead to cavitation, which may damage boiler feed pumps; in these instances, systems would be designed to avoid reaching the boiling point temperature and, hence, cavitation. The trade-off is that less energy is saved.

Table 6.1: The collector parameters used in this project

Description	***FPC***	***ETC***	***PTC***
Aperture Area Per Collector (m^2)	*2.03*	*1.39*	*28.89*
Gross Area Per Collector (m^2)	*2.15*	*2.34*	*28.89*
Cost (R/m^2) Lower Bound	*4320*	*6130*	*12450*
$F_R(\tau\alpha)_n$	*72.13*	*43.43*	*68.5*
F_RU_L	*4.325*	*1.087*	*0.4*
Temperature coefficient for FrUL	*0.0117*	*0.0043*	*0.0015*

The collector parameters used in the modelling of the SHSs are listed in Table 6.1. The costs are based on the aperture area. The area and performance data, for the FPCs, is a constructed from an average of the data from four collector manufacturers/distributors (listed in Chapter 4). The ETC data is an average of the data from the one distributor and a value from the literature (Kalogirou 2003). The PTC data is directly from the manufacturer. The assumptions and justifications behind the cost data of the collectors can be found in Chapter 4.

Figures 6.1 and 6.2 below show the process diagrams for the two systems modelled in the LCA. The first system is modelled for Company A and B and the second for Company C.

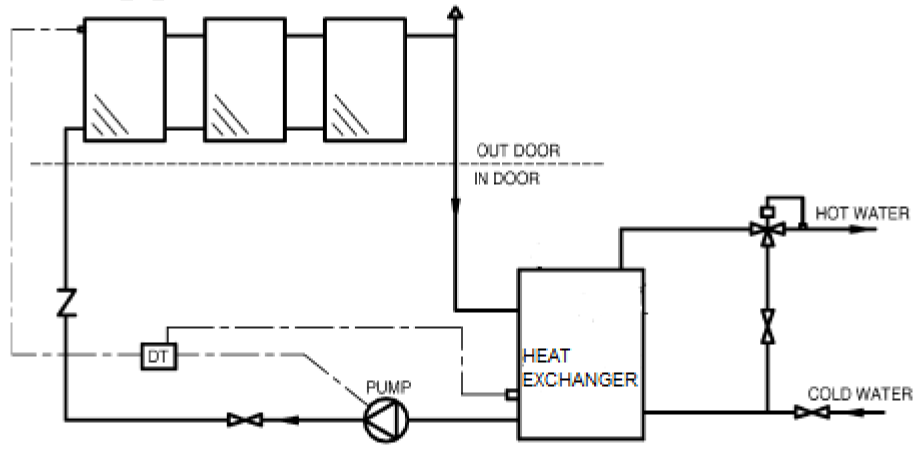

Figure 6.1: Process diagram for an indirectly fed system without storage, such as that modelled for Company A and B, adapted from (Kalogirou 2004)

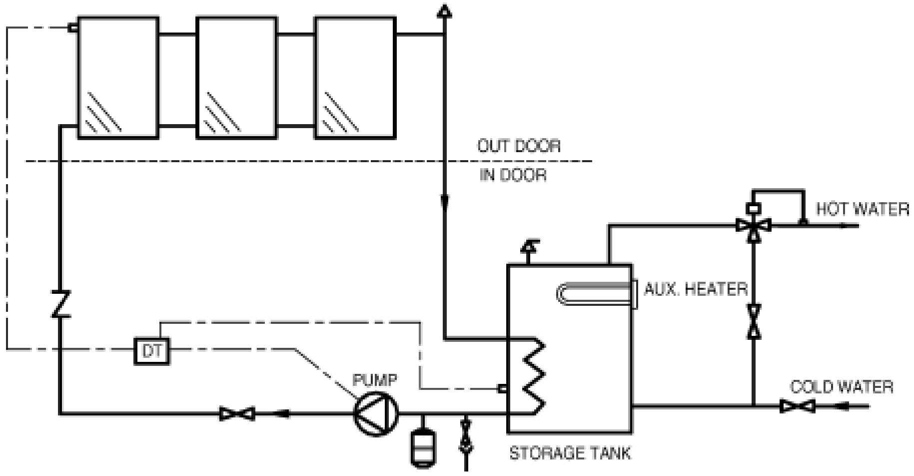

Figure 6.2: Process diagram for an indirectly fed system with storage, such as that modelled for Company C (Kalogirou 2004)

6.3.2 ECONOMIC TOOL FOR COMPARISON: NET PRESENT VALUE

The economic tool used to compare the costs of the different solar collector types in supplying the boiler make-up water is the lifecycle cost analysis (LCA), which compares the net present values of the solar systems. The net present value (NPV) analysis takes into account the time value of money, as well as the effect of discount rates. For the purpose of this study, the discount rate used will be between 4% and 11%. The discount rate reduces the future value of a cash flow so that it can be compared in today's terms, with a discount rate suitable to an investor. The NPV of the SHS can then be compared with an alternative investment of the money, e.g. in an interest bearing account at a bank, to see whether the SHS is a good investment choice or not. The LCA methodology takes into account not only the initial capital costs but also any future costs incurred in the operation and maintenance of the solar systems.

The greater the NPV of a design, the quicker the payback period will be for a given fuel cost. Hence it is desirable to find out which type of solar collector at current market costs will result in the lowest NPV for a system and hence payback in the shortest period. In the case of investing in a SHS, no actual financial gains come from the system; instead, the initial capital outlay generates a negative NPV, which represents a loss to the company. The loss however is "repaid" in the future by avoiding future energy costs since solar energy is free.

The economic indicators used in the LCA are listed in Table 6.2. It is followed by a justification for the choice of the indicators.

Table 6.2: Economic indicators used in the LCA

Interest Rate	*12.5%*
Inflation Rate	*6.2%*
Discount Rate	*4.43%*
Loan Amount	*75% of investment Cost*

The interest rate used is a compilation of three sources, namely: an average of the prime overdraft rate from the past 10 years (South African Reserve Bank 2010), an average of the First National Bank's five year forecast (Bruggemans 2010), and an average of the Nedbank Group's economic forecast for the month of July 2010 (Nedbank Group 2010).

The inflation rate is an average of the CPI over the last 10 years (Statistics South Africa 2010), including data for 2009 and 2010 (Statistics South Africa 2010).

The discount rate used herein may be termed as the social discount rate. The latter rate is typically lower than individual and corporate discount rates.

Discount rates hotly debated, reflecting divergent opinions as to how much benefit is yielded from allocating resources to competing economic enterprises. The recent FIFA Soccer World Cup offers a pertinent example of the questions raised by an opportunity cost analysis. In other words, could the resources used to build the stadia, have been more efficiently allocated to other large capital projects?

There is no easy answer to such questions. The Stern Review highlighted this debate. The extraordinarily low discount rate used in the economic modelling (0.1%) attracted much criticism. Academics such as William Nordhaus suggest a rate of 3% would have been more appropriate (Varian 2006). Discount rates for utilities can range between 3-15% depending on the country, and whether the utility is state owned.

Bearing the above debates in mind, I have elected to use discount rate of 4.43 %. I am sensitive to the fact that this is significantly lower than that customarily used in the corporate and industrial sectors. However, I consider the lower rate to be appropriate, to the extent that, like Stern and Norhaus' approaches, it attempts to holistically capture the frequently ignored positive benefits to the environment and to human wellbeing likely to accrue by virtue of investment in SWH systems.

The loan amount has been stipulated as 75% of the investment cost, as some capital outlay would have to be provided for by the plant applying for a loan. Renewable energy investments are relatively new in South Africa and there is no consensus amongst finance experts as to the financial parameters that should be used for these types of investments.

6.3.3 SOLAR FRACTION

The effect of varying the solar fraction of a design has significant effects on the upfront capital costs of a design. The larger the solar fraction supplied by a system, the larger the upfront capital costs will be due to increased collector area, piping, storage volumes and installation costs. But a higher solar fraction means that more heat will be generated by the system and hence energy savings will be increased. At some point, the law of diminishing returns will again come into play, at the point where the extra costs of another unit of solar fraction is just not worth the returns in terms of energy yield.

For a given solar system, the NPV and the energy savings potential of the system are not simply directly proportional to one another. Another goal of this project is to examine the effect that varying the solar fraction has on the NPV of a design and hence the payback period in terms of the LCA.

For the LCA, the systems will be sized to supply 60% of the heat needed to pre-heat the boiler make-up water. A sensitivity analysis will be performed on the results of the LCA, to see what effect changing the solar fraction to levels below 60% will have.

6.3.4 FUEL COSTS

The technology that yields the smallest payback period, i.e. that has the highest energy savings compared to initial capital outlay, will be chosen to undergo a sensitivity analysis with regard to fuel costs. By varying the cost of fuel, it is possible to predict when systems for applications in the F&BI, such as the pre-heating of boiler make-up water, will become economically feasible.

The following fuel costs have been used in the sensitivity analysis of the LCA results. The first two electricity price increases reflect the MYPD-2 increases that have been approved by NERSA (NERSA 2009). The prices in the first column are average prices currently available to the F&BI. The coal price has been increased on a Rand per tonne basis, the conversion to a price per unit of energy has been shown for comparison with the electricity price (the GCV used is 27.317 MJ/kg).

Table 6.3: Fuel prices used in the sensitivity analysis of the data

Electricity Price (R/kWh)	**0.416**[58]	0.52	0.65	0.75	0.80	0.9
Coal Price (R/tonne)	**1,100**	1,250	1,500	1,750	2,000	2,500
Coal Price (R/kWh)	**0.14**	0.165	0.2	0.23	0.26	0.33

In Chapter 5, the process for calculating the final energy consumption of a fuel was shown. In this process, there is an intermediary step to calculating the total final energy consumption from the useful heat demand, namely the useful supply heat. But in the case of boiler feed water, the energy is supplied from the solar system directly to the process by using a flat plate heat exchanger. Therefore, in calculating the final energy consumption, only the boiler efficiency has to be taken into account in order to find out how much fuel is supplemented by the SHS. Table 6.4 summarises the amount of water that would be pre-heated/heated per day by the SHSs.

Table 6.4: Heat demand and boiler efficiencies of the companies surveyed

Company	**Feed Water Demand (litres/day)**	**Water Heated In System (litres/day)**	**Boiler Efficiency**
Company A	144 000	-	75%
Company B	130 346	-	85%
Company C	-	240 000	100%[59]

Company A produces oil and margarine products, Company B is a fruit canning factory and Company C processes vegetables.

The system designs for Companies A and B are shown in Figure 6.1. This is simply an indirect feed system that continuously pre-heats boiler feed water.

In Company C, plant heating is only needed at night. Therefore, the quantity listed in Table 6.4 is the amount of water that charges the thermal storage system during the day, so that energy can be withdrawn from this system during the night. The amount of energy stored in the system is equivalent to 60% of the useful heat demand needed by this system. The design for this system is shown in Figure 6.2.

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[58] The first column of figures in bold font have been used in the Original Scenario Analysis.

[59] This is for an electrode boiler, which is a resistance heater.

6.4 GHG EMISSIONS CALCULATIONS

The following chapter briefly reveals the sources and the emissions factors used in the GHG emissions calculations. The chemical composition of fossil fuels varies by region. Therefore, it is important to cite emissions figures that are typical of the fossil fuels used. For coal especially, there is a large variability in chemical composition, and the best way to ensure accuracy is through either direct measurement or consultation with experts familiar with the fossil fuels being used in an area.

6.4.1 COAL EMISSIONS FACTORS AND HEATING VALUES

To calculate the GHG emissions from the F&BI companies, the Greenhouse Gas Protocol tool on stationary combustion was used. This tool uses default emissions factors based on the 2006 IPCC guidelines (World Resources Institute 2008) to calculate GHG emissions. As mentioned above, the emissions factors from coal are very area-specific due to the high variability in the chemical composition of the fossil fuel deposits themselves. South Africa is no exception; one has to take great care that the emissions factors used in a study are indeed accurate.

Coal used by industry in the Western Cape is of a much higher grade (bituminous) than the coal used in the power stations across the country. South African power stations are notorious for using very dirty coal, whilst the high grade product is sent to Richard's Bay to be sold on the international market. On average, the higher heat value (HHV) or gross calorific value (GCV) of this coal is 28 MJ/kg (of that used in the Western Cape). The reason why a better quality coal is used is that it makes no sense to transport coal with large ash contents hundreds of kilometres down to the Western Cape[60].

The average CO_2 emissions factor for this coal is 90-92 gCO_2/MJ (Lloyd 2010). For N_2O emissions, the International Panel for Climate Change (IPCC) default figure will be used, which is $0.001425 gN_2O/MJ$ of coal burnt.

The GHG protocol tool cites methane as an emission from stationary combustion. But methane is not a product of combustion. It is a 'fugitive' emission from the coal mining process. A very extensive study was undertaken by Lloyd and Cook to establish if the CH_4 fugitive emissions were the same for South Africa, as given by the IPCC defaults. It turns out that the IPCC values drastically over-estimated South African emissions (Lloyd and Cook 2005). The conclusion of the paper is that, due to geological conditions that existed long ago, much of the coal-bed methane associated with South African coal seams was burnt off due to igneous activity that followed the

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[60] The coal used in the Western Cape F&BI is of similar grade to that of the export coal and it comes from the same mines.

deposition of these coal seams. The result is that less than 72 000 tonnes/annum is given off by all of South Africa's coal mining activities.

In 2005, the same year as the report by Lloyd and Cook was published, the total mined coal was 306 Mt (U.S EPA 2009). By simple division, this equates to an emissions factor for methane of 0.2gCH_4/kg of coal. If one takes the GCV for the coal as stated above and multiplies this by the emissions factor, it becomes 0.0084gCH_4/MJ on an energy value basis. This is an extremely small figure, especially when dealing with the volumes of coal consumed by industrial size boilers, typically below 50 MW, i.e. 1000 tonnes equates to 8.4 kg of methane released.

6.4.2 HEAVY FUEL OIL EMISSIONS FACTORS AND HEATING VALUES

HFO, also known internationally as residual fuel oil (RFO), is a product of the crude oil refining process. It is part of the heavy fraction of the oil that is distilled. Crude oil is variable in composition, just as coal is from region to region, but variability in the HFO chemical composition is far less, as it has undergone the refinement process, which is designed to separate hydrocarbon chains of similar composition.

Hence, fraction no. 6, which is a product of the distillation process, is the HFO burnt in commercial and industrial heating applications (Gillenwater and ERT 2005). There are international standards and procedures that refineries adhere to, thereby guaranteeing that there is little variability in the fractional compositions of the distillation products. The result of this is that the 2006 IPCC defaults can be used for emissions factors of HFO. The emissions factor for CO_2 is 73.53gCO_2/MJ (World Resources Institute 2008). The emissions of the other two GHGs are listed in Table 6.5 below for HFO.

6.4.3 INDIRECT EMISSIONS FROM ELECTRICITY USE

By using a unit of electricity, one does not directly emit any GHGs. But at the source of the power generation, i.e. at the power station, there are continual GHG emissions from the flue stacks. The use of a unit of electricity cannot be tied down to one specific source of electricity, i.e. one specific power plant. The emissions from the national utility Eskom are a accumulation of many different kinds of fuel stations (although mainly dominated by coal). Nonetheless, an average emissions figure is needed for consumers to calculate the implications of either using or saving one unit of electricity.

The Eskom annual report publishes such a figure. The implications of one kilowatt-hour consumed or saved are as follows: 1.03kgCO_2/kWh and 0.0122 gN_2O/kWh (Eskom 2009). There is no figure quoted for coal-bed methane. Methane emissions figures from Lloyd and Cook will thus be used. Table 6.5 summarises all the emissions factors quoted above.

All the figures in Table 6.5 have been converted into g/MJ for consistency. The emissions factors quoted below have been entered into the GHG Protocol tool for stationary combustion (World Resources Institute 2008) and checked with the emissions analysis tool within RETScreen (Natural Resources Canada 2010).

Table 6.5: Various GHG emissions factors used in this project

Type of Emission	*Indirect Emissions: Eskom Electricity (g/MJ)*	*Direct Emissions: Bituminous Coal (g/MJ)*	*Direct Emissions: Heavy Fuel Oil (g/MJ)*
CO_2	*286*	*90-92*	*73.5*
N_2O	*0.003389*	*0.001425*	*0.00285*
CH_4	*0.0084*	*0.0084*	*0.00057*

Chapter 6 has highlighted all the procedures that were used in processing the data from the F&BI. The next chapter will present the results of the analysis.

7. RESULTS

This chapter presents the results of the project. The chapter begins with the results for the potential of solar heat within the Western Cape. The results of the lifecycle cost analysis are also presented. The chapter then discusses the findings of the sensitivity analysis as well as the GHG emissions analysis. There is also a discussion of the most important results in Section 7.3.

7.1 THE TECHNICAL POTENTIAL FOR SOLAR HEATING SYSTEMS IN THE WESTERN CAPE

This section presents the results of the potential for solar heat in the Western Cape F&BI. It discusses the reasons underlying the decisions made. The chapter starts with the issues surrounding the use of solar heat for cooling and refrigeration.

7.1.1 THE POTENTIAL FOR SOLAR HEAT TO SUPPLY COOLING IN THE WESTERN CAPE FOOD AND BEVERAGE INDUSTRY

In the introduction to this dissertation, it was stated that two criteria would be investigated in order to establish the potential for solar heat in the Western Cape F&BI, namely, the amount of opportunity in the market place available for this technology, and the potential cost of this technology.

As the project progressed, a working definition was formulated for establishing the amount of opportunity or potential, namely the technical potential. This quantity is not to be confused with the economic or achievable potential of the technology (see Chapter 6 for a definition of these terms). In Chapter 6, justifications were given as to why the technical potential was a suitable definition to be used in this project.

The scope of the terms of reference for this technical potential figure have changed. The technical potential used in this project, only consists of energy use for heating and not both heating and cooling as previously stated. This alteration was necessitated not out of choice but rather as a result of the findings of this study.

Most of the large-scale refrigeration systems used in the F&BI, demand temperatures below 5°C, this is below the operating temperature at which off-the-shelf lithium bromide chillers can function at. The alternative is to use the ammonia-water ARSs, but there are no examples of this type of refrigeration outside of academia within the country. The cost at which these systems could be built would be pure speculation. There are also only a handful of demonstration plants around the world (Napolitano and Sparber 2009).

This leaves alternatives, either abandoning this quantity from the technical potential or incorporating the lithium bromide chiller somewhere into the conventional vapour compression cycle refrigeration system. There are many different configurations of the vapour compression cycle available, but the most common ones found are ammonia based systems. In these systems ammonia is compressed and stored in a tank, from this tank an ammonia solution is circulated around the plant to the evaporator coils to provide cooling. The warm solution then passes back to the compressor for the cycle to be repeated. For this type of system, there are no known examples of cycles that incorporate ARSs to provide part of the energy requirement and would be a novel use of the systems in a hybrid configuration.

For smaller commercial and industrial systems, cooling is sometimes provided for by a secondary system where the refrigerant cools a low temperature HTF by using a heat exchanger. In these types of systems, it is possible for one to provide part of the cooling load to the low temperature HTF with an ARS.

Therefore to calculate the amount of ARSs and hence the potential for solar heat to provide energy for cooling systems in the Western Cape F&BI, one would need to know the amount of these systems currently in place as well as their capacities and operating constraints. With this knowledge, one could then predict the potential for ARSs in this niche.

Here in lies the problem: there are no published statistics in the public domain with regard to the capacities and types of refrigeration systems installed in industry, never mind the F&BI itself. The scope of this study has thus been shifted so that it does not include solar heat for cooling in the technical potential.

7.1.2 THE POTENTIAL FOR SOLAR HEAT TO SUPPLY THERMAL ENERGY IN THE WESTERN CAPE

In order to calculate the technical potential of solar heat in the Western Cape F&BI, a number of sources had to be consulted. The DME publishes aggregated fuel consumption data for the whole of South Africa (DME 2006, DME 2009); however, there are no energy balances disaggregated on a provincial level, as stated in the literature review. Therefore, researchers have had to find novel ways of calculating the energy consumption of the various subsectors within the provinces.

The two main sources used in the calculations of this project are the “White Paper on Sustainable Energy for the Western Cape” (Department of Environmental Affairs and Development Planning: Western Cape 2008) and a draft version of the “Energy Scenarios for Cape Town” (Sustainable Energy Africa, UCT's Energy Research Centre 2010). The latter is not to be confused with a previous paper with a similar title prepared for the City of Cape Town in 2003.

The technical potential for solar heat in the Western Cape F&BI is ***12 PJ***, which is equivalent to ***9%*** of the total industrial consumption in the Western Cape for the year 2007. The base year of the "Energy Scenarios for Cape Town" has been used (2007).

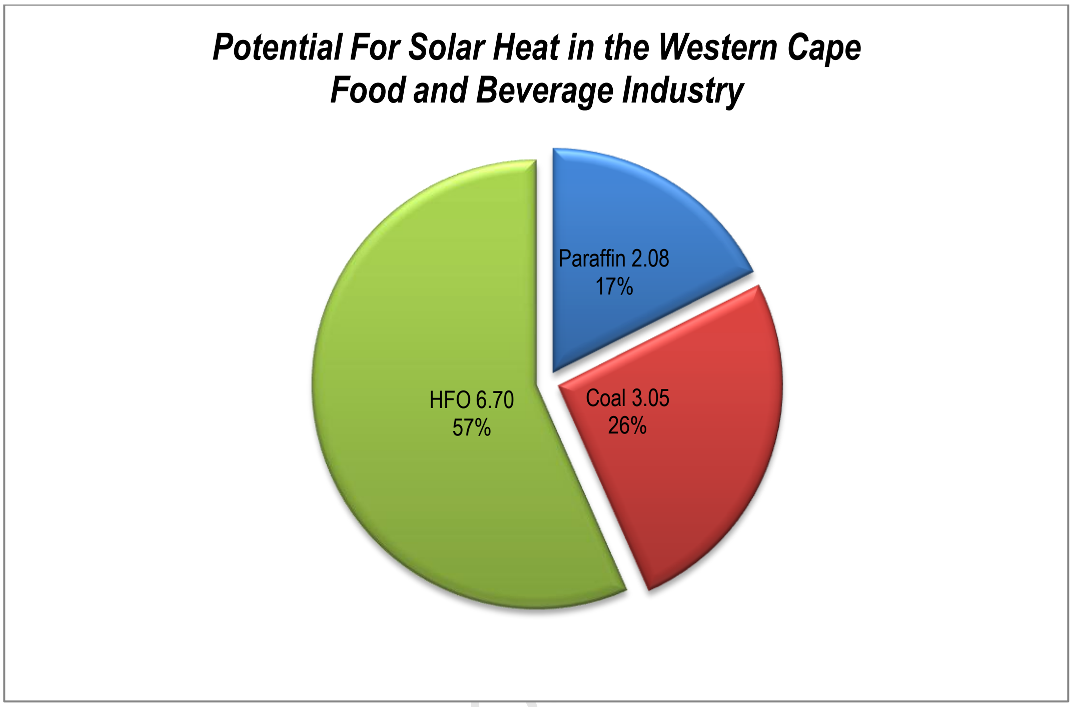

Figure 7.1: Fuel mix of the technical potential figure in PJ and the relative share of each fuel type.

Due to the lack of disaggregated energy consumption data, the main sources of data for the size of the City of Cape Town's F&BI are air quality data published by the City of Cape Town and aggregated fuel sales figures. It is strongly emphasised that the figures presented in these studies are at best *estimates* to the size of the energy consumption within the various subsectors.

Industry in the Western Cape, according to the latest figures, consumes 47% of energy within the province (Department of Environmental Affairs and Development Planning: Western Cape 2008); energy consumption was calculated as 267 PJ for the year 2007 using the 2.8% growth rate figures from the Province's White Paper on Sustainable Energy (Department of Environmental Affairs and Development Planning: Western Cape 2008, 14).

The F&BI consumed ***35 PJ*** of energy within the Western Cape for the year 2007, which is equivalent to 28% of the industrial energy consumption of the province. Figure 7.2 shows a breakdown of the energy consumption within the Western Cape's F&BI.

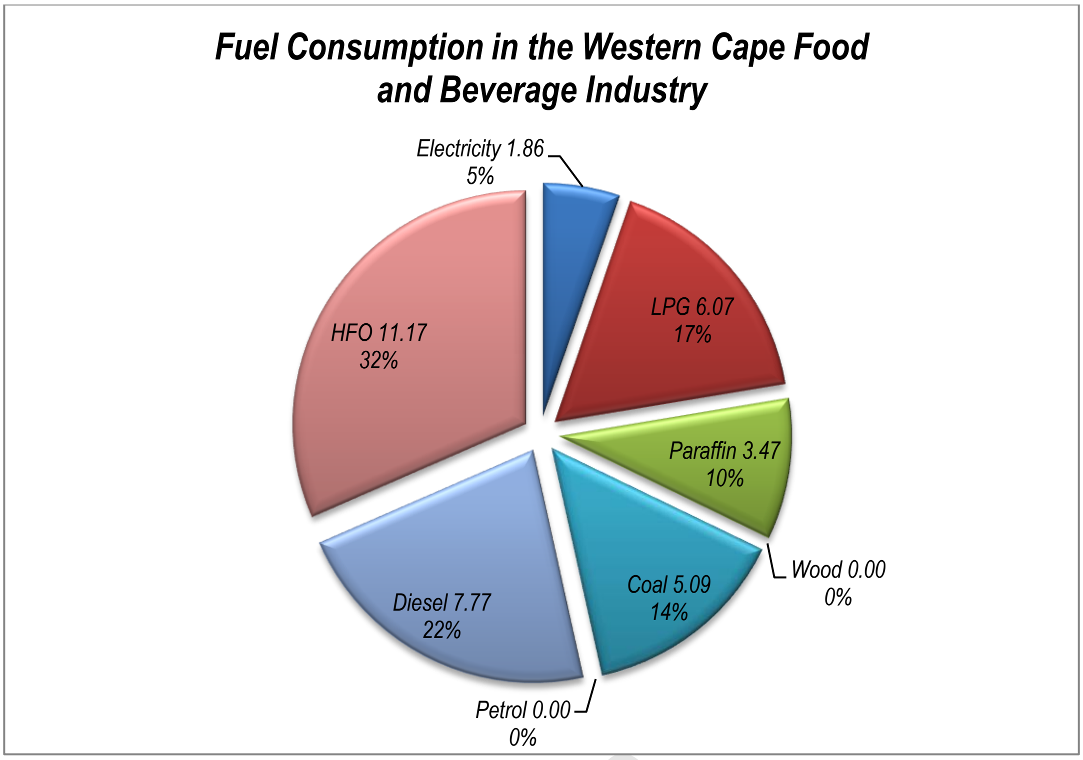

Figure 7.2: Fuel consumption in the Western Cape F&BI (PJ) and the relative share of each fuel of the total

Of the energy consumed within the Western Cape's F&BI, only coal, paraffin and HFO have been considered in calculating the technical potential. Electricity is definitely used to generate thermal heat within this industry but there is no way of calculating what proportion of the electrical consumption is used to generate thermal heat in electrode boilers and other resistance heaters. Therefore, electricity has not been considered in the calculation of this figure. The limit to the technical potential has been taken as 60% of the energy consumption of the various fuel types, for reasons discussed in Section 6.2.1.

In reality, the technical potential will also be limited by the available roof space at a plant; again, the only way of establishing this is to measure the roof space of every food and beverage facility within the province.

The relative share of each fuel type, as seen in Figure 7.2, has been calculated by projecting the figures from the City of Cape Town's study (Sustainable Energy Africa, UCT's Energy Research Centre 2010) to a provincial level. The F&BI accounted for 28% of the City's fuel consumption, and this same percentage has been used to estimate the size of the F&BI's consumption on a provincial level.

7.2 THE LIFECYCLE COST ANALYSIS OF COMMERCIALLY AVAILABLE SOLAR HEATING SYSTEMS

As mentioned in the previous chapter, the process chosen for the LCA of this project is the pre-heating of boiler make-up water[61]. In addition to this, another 6 scenarios have been modelled. In these scenarios, the prices of both coal and electricity have been varied in order to establish the effect of the fuel price on the feasibility of SHSs. As stated in the introductory chapter, the main aim of this project is *to establish whether or not there is potential for solar heat to provide energy to the food and beverage industry, using the Western Cape as the focal point of this study*, and it is therefore necessary not only to model the Original Scenarios but also potential future scenarios.

The LCA analysis demonstrated long payback periods for the SHSs under the conditions of the Original Scenario (a full list of the economic and financial parameters used in the LCA can be found in Chapter 6). The NPV of the SHSs at the end of the project life[62] was negative, in all but three of the cases modelled under the conditions of the Original Scenario. In the following chapters, the results from the various scenarios are presented. The second part of this chapter discusses the results obtained.

7.2.1 THE LIFECYCLE COST ANALYSIS RESULTS OF THE ORIGINAL SCENARIO

In the Original Scenario, the LCA analysis looked at the process of pre-heating boiler make-up water. As previously mentioned in Chapters 4 and 6, the systems modelled are indirect feed systems, where municipal-supply water in secondary loop is pre-heated by the HTF of the SHS by using an efficient flat plate heat exchanger. Two of the systems employ no storage, as this adds to the system costs and reduces the amount of useful heat delivered, as heat losses from the storage vessel are unavoidable.

However, in the case of the Company C (COMC) plant, the thermal heat generated by the SHS is only needed at night and therefore thermal storage is needed. Although this entailed modelling an extra example, the benefits are that it shows the effects of thermal storage on solar field size and annual energy output. The output temperature of the COMC solar system has been investigated at 45°C and 60 °C only, as the temperatures needed by this plant are low. The process modelled in the example of COMC is not boiler make-up water pre-heating. Instead, the system has been designed to generate 60% of the heat demand for the process itself.

The investigation into pre-heating boiler feed water has been performed over a range of temperatures to see the effect of temperature on the LCA. Likewise, the performance of the PTCs has been evaluated to see whether they function better at generating medium temperature steam

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[61] This shall now be referred to as the *Original* Scenario for ease of reading.

[62] The project life is 15 years in all cases; refer to Chapter 6 for a breakdown of the parameters used in the LCA.

(10 Bar saturated steam at 180°C) or at boiler water pre-heating. The other two types of collector do not perform as efficiently as the PTC at generating medium temperature steam (Kalogirou 2003) and therefore have not been analysed at such high temperatures.

Table 7.1 summarises the results of the LCA as well as the annual solar outputs, system sizes, and investment costs. The pre-heating of boiler make-up water is a continuous process during a production period for the companies surveyed in this project, even in the case of the plants with seasonal production periods. The length of these production periods varies by plant.

Table 7.1: Results of the LCA and RETScreen modelling for the pre-heating of boiler make-up water

Company/ Collector Type		***Output Temperature***	***Water Requirements***	***BAU Energy Requirement***	***Annual Output***	***System Aperture Area***	***Investment Cost***	***NPV (15 Years)***	***Payback Period***
		(°C)[63]	*(L/d)*	*(MWh)*[64]	*(MWh)*[65]	*(m²)*	*(1000s)*[66]	*(1000s)*	*(Years)*
COMA[67]	*FPC*	*90*	*144 000*	*4 525*	*2 694*	*1 827*	*R 8 086*	*R 705*	*14*
	ETC	*90*	*144 000*	*4 525*	*2 694*	*1 888*	*R 11 656*	*R -2 709*	*19*
	PTC	*90*	*144 000*	*4 525*	*2 730*	*1 560*	*R 19 423*	*R -10 031*	*29*
	FPC	*45*	*144 000*	*4 525*	*1 050*	*713*	*R 3 157*	*R 274*	*14*
	FPC	*60*	*144 000*	*4 525*	*1 598*	*1 082*	*R 4 797*	*R 418*	*14*
	PTC	*180*	*144 000*	*10 045*	*6 007*	*3 438*	*R 42 802*	*R -22 105*	*29*
COMB	*FPC*	*90*	*130 350*	*1 996*	*1 189*	*1 411*	*R 6 174*	*R -2 572*	*24*
	ETC	*90*	*130 350*	*1 996*	*1 189*	*1 411*	*R 8 896*	*R -5 176*	*33*
	PTC	*90*	*130 350*	*1 996*	*1 193*	*1 156*	*R 14 387*	*R -10 415*	*47*
	FPC	*45*	*130 350*	*1 996*	*448*	*524*	*R 2 324*	*R -968*	*24*
	FPC	*60*	*130 350*	*1 996*	*694*	*814*	*R 3 604*	*R -1 502*	*24*
	PTC	*180*	*130 350*	*4 485*	*2 683*	*2 600*	*R 32 371*	*R -23 877*	*47*
COMC	*FPC*	*45*	*240 000*	*1 200*	*413*	*1 027*	*R 4 551*	*R -1 570*	*22*
	FPC	*60*	*240 000*	*1 200*	*716*	*1 959*	*R 8 708*	*R -3 501*	*24*
	ETC	*60*	*240 000*	*1 200*	*716*	*1 672*	*R 10 250*	*R -4 977*	*28*

In this analysis, the business as usual (BAU) energy requirement is calculated from RETScreen, using the supply temperature demanded, water requirements (L/d) and municipal-supply

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[63] This is the output temperature from the SHS, which would be fed to the boiler.
[64] Some of these figures have been rounded off to the nearest five.
[65] This is the annual useful energy output from the solar system.
[66] Investment costs are based on aperture area of the solar field.
[67] Company A (COMA) and Company B (COMB)

temperatures, using Equation 5.1. The NPV is based on a loan amount equivalent to 75% of the investment costs. For a breakdown of the fuel costs used, please refer to Section 6.3.4.

The following general trends can be observed from Table 7.1, which summarises the results obtained from the LCA by using the financial constraints of the Original Scenario:

The LCA yielded negative NPVs for all but three of the proposed SHS systems. The payback periods are long and far exceed the maximum period at which industry deems them suitable for investment, i.e. 18 months or less (DME 2002).

The only options that lead to positive NPVs by the end of their project life are the FPC systems proposed for the COMA plant. But these values are small in comparison to those that would be obtained from investing the same amount of capital in an interest bearing account. For example, investing the R3 million in the COMA FPC 45°C option, in a bank, would yield an NPV of R8.1 million after 15 years, under similar financial constraints. Instead, the NPV of the money is R274 000 after the same period, when invested in a SHS.

Both the NPV and payback period of the options for the COMA plant are more favourable than are those of the COMB and COMC plants. This is due to the shorter seasonal production periods employed in the last two plants (four and six months long respectively). Plants that operate SHSs for less than six months of the year tend to be uneconomic, i.e. low NPVs and long payback periods. This outcome is confirmed by the POSHIP study, “Systems with only seasonal utilisation (less than 6 months operation a year) are in general not economic” (AIGUASOL Enginyeria 2001, 131). This trend is clearly highlighted in Figure 7.3 below by the four PTC options, where the first two operate for the entire year and the last two for only 6 months of the year.

The payback period of the options for the COMC plant are on average shorter than are those of the COMB plant, as this would suggest a conflict with the statements in the paragraph above. There is no conflict, however; the reason for this apparent contradiction is that the plants use different fuels to generate thermal energy. The COMC plant uses electricity, whereas the COMB plant burns coal.

The second biggest factor that affects the LCA of the SHSs, besides the length of the operating period, is the fuel type and hence price of the fuel used in the conventional heating system. Electricity is currently far more expensive[68] than coal, on an energy basis i.e. R/kWh (for a breakdown of the fuel prices used in this analysis please consult Section 6.3.4).

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[68] The price of coal, currently around R1 100/tonne, translates to 0.14 R/kWh on an energy content basis, whereas the average electricity price is 0.416 R/kWh. Even with a boiler efficiency of 75%, which would require 25% more coal to be burned, which is equivalent to consuming one unit of electricity, the price of coal is two times cheaper than electricity (the energy content of the coal being 27.317 MJ/kg).

The majority of the companies surveyed for this project used cheap fossil fuels to generate thermal energy; even taking into account the system inefficiencies of the boilers, the results above clearly show that SHSs competing with coal are uneconomic. Even in the case of COMA, where the systems would be used continually throughout the year, the price of coal is so low that the energy savings provided by a SHS are not large enough to render the project economically feasible.

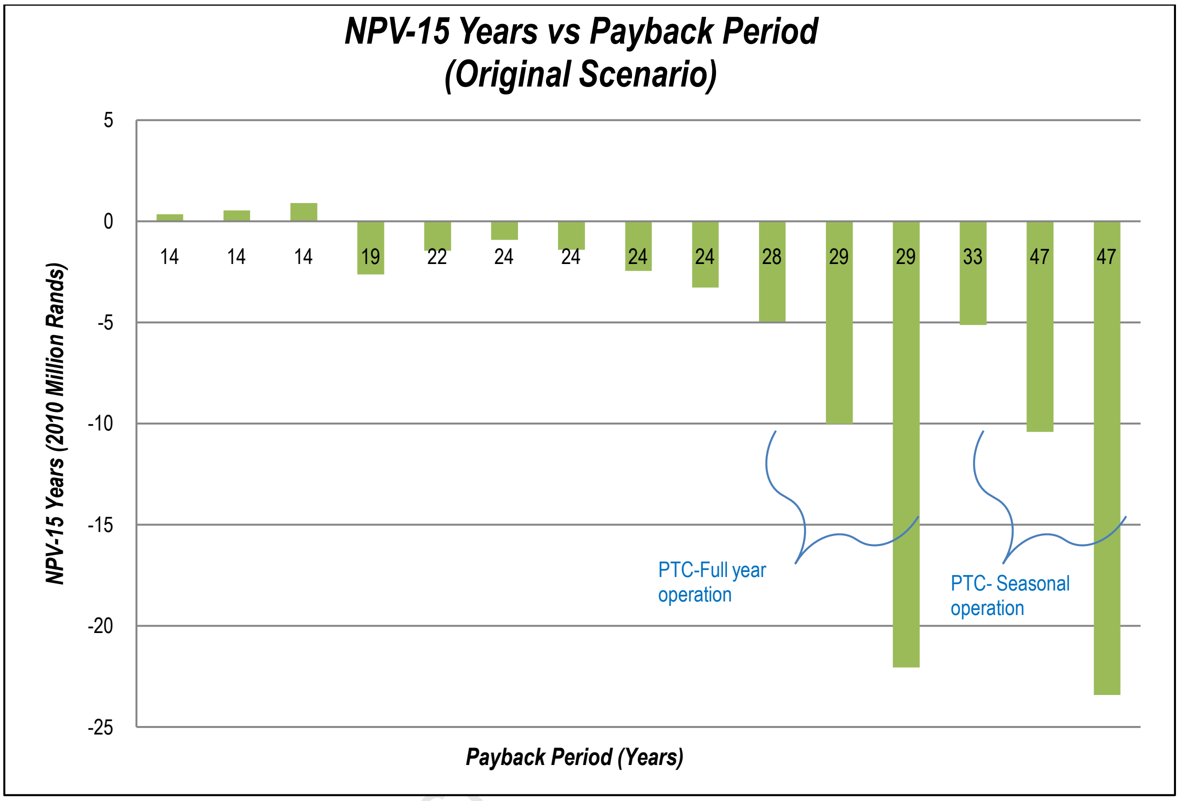

Figure 7.3: A graph of the payback period versus NPV (at 15 years) for the Original Scenario (arranged in ascending order)

With regard to collector types, the following important trends can be observed:

When pre-heating water from ambient conditions to 90°C, PTCs require 18% less aperture area than FPCs and ETCs to yield the same amount of energy. This means that the system costs will be reduced for PTCs, as a reduction in aperture area leads to a decrease in investment costs. But the upfront capital of a PTC system are much higher and therefore this 18% reduction in area does result in a large enough decrease in the investment cost to make them a favourable investment opportunity for this purpose.

ETC systems, according to the theory, are meant to yield more energy than FPC systems over a given period of time. This is not the case for the sites analysed in this study and possible reasons for this are discussed in Section 7.3. Therefore, the LCA for these collectors is not favourable when compared to the FPCs as the higher upfront capital costs have not been offset by higher annual solar gains.

Finally, the analysis seems to suggest that the payback period of the PTCs is not greatly affected by the temperature of the energy supplied, at least for temperatures between 90°C and 180°C, as modelled in this analysis. The higher temperature water/steam requires more collector area, but correspondingly the collectors save more energy; for example, providing a thousand litres of water a day at 90°C requires less energy than providing the same amount of water at 180°C. Again, the payback period is more dependent on the fuel price and annual utilisation of the heat, at least for the sites investigated in this study.

Although, the results of the systems modelled in this scenario do not yield high NPVs after 15 years, the energy costs per MWh output are shown in Table 7.1a and are compared with that of CSP and wind power. This analysis assumes that the SHSs are used for the full 12 months as is the case with electricity generating technologies.

Table 7.1a: Comparison of different energy generating technologies on MWh basis

Technology Type	*Cost (R/MWh)*
Flat plate collector	*176 (thermal energy)*
Evacuated tube collector	*251 (thermal energy)*
Parabolic trough collector	*510 (thermal energy)*
Wind Power	*1250 (electricity)*
CSP-PTC (no storage)	*3140 (electricity)*
CSP-Tower (6 hours storage)	*2310 (electricity)*

The figures quoted in Table 7.2 for wind power and CSP, come from NERSA's renewable energy feed-in tariff and are guaranteed tariffs to power producers. The figures generated for the three SWH technologies have a solar fraction of 60%. It must be noted that CSP technologies that employ storage can reach capacity factors of 60% (depending on the local solar resources of course). The contrast between the cost of SWH technologies and the other three electricity producing technologies is apparent, SWH technologies can produce thermal energy at a far cheaper rate than both wind and CSP technologies can produce electricity. This result suggests that government subsidies may be better spent on encouraging growth of industrial scale SWH systems rather than electricity producing renewable technologies.

7.2.2 INTRODUCTION TO THE FUTURE FUEL PRICE SECENARIO

Currently, the fuel prices available to industry are so low that potential energy savings from SHSs are not large enough to provide the required return on investment, which would render the projects economically feasible. But fuel price are not likely to stay low for too much longer. The price of electricity will rise 25% each year, over the next two years, as approved by NERSA (NERSA 2010). In the Future Fuel Price Scenario (FFPS), six of the options from the Original Scenario have been scrutinised to see what effects rising fuel price will have on the LCA of the solar systems.

While it may be difficult to predict the exact value of future fuel prices, this scenario acts as a sensitivity analysis, where a large range of future fuel prices has been examined. The wider the range of the sensitivity analysis is, the greater the chance of predicting the actual future conditions.

In Section 7.2.1, we established that the operating period or annual utilisation of SHSs and the fuel price are the two biggest factors affecting the financial viability of the SHSs. Therefore, the FFPS has been carried out by varying the fuel cost and annual utilization period for six of the SHSs listed in Table 7.1. There are two cases for each of the three collector types, so that the effect of rising coal and electricity prices can be examined for each collector type.

The increase in coal price is not expected to be as large as that of electricity. But to some extent, the coal price shadows the international oil price, as coal is a substitute for oil; often, the competitiveness of coal liquefaction plants depends on the oil price (The World Coal Institute 2005). The oil price is expected to rise in the next few years, with the IEA projecting that crude oil prices will average $100 per barrel (2007 dollars) over the period 2008-2015 (it is currently around US$80 per barrel) (IEA 2008). One would therefore expect the coal price to shadow this increase to some extent. The coal price has been varied at rates above inflation to simulate possible future scenarios.

If the sensitivity analysis does capture the future fuel prices within its bounds, it could then be a useful tool to help the F&BI plan future *energy* investments. The SHSs are envisaged to supplement the use of fossil fuels, thereby making their consumption under higher prices sustainable. Table 7.2 below summarises the six options modelled; see Chapter 6 for a breakdown of the fuel price increases used in the FFPS.

Table 7.2: Options chosen for investigation under the FFPS analysis

Company/ Collector Type		***Output Temperature***	***Water Requirements***	***BAU Energy Requirement***	***System Aperture Area***	***Investment Cost***	***Fuel Type***
		(°C)	***(L/d)***	***(MWh)***	***(m²)***	***(1000s)***	
COMC	*FPC*	*60*	*240 000*	*1 200*	*1 959*	*R 8 708*	*Electricity*
COMB	*FPC*	*60*	*130 350*	*1 996*	*814*	*R 3 604*	*Coal*
COMA	*ETC*	*90*	*144 000*	*4 525*	*1 888*	*R 11 656*	*Coal*
COMA	*PTC*	*180*	*144 000*	*10 045*	*3 438*	*R 42 802*	*Coal*

Company/ Collector Type		**Output Temperature**	**Water Requirements**	**BAU Energy Requirement**	**System Aperture Area**	**Investment Cost**	**Fuel Type**
		(°C)	***(L/d)***	***(MWh)***	***(m²)***	***(1000s)***	
COMC	*ETC*	*60*	*240 000*	*1 200*	*1 672*	*R 10 250*	*Electricity*
COMB	*PTC*	*180*	*130 350*	*4 485*	*2 600*	*R 32 371*	*Electricity*

The BAU energy requirements of the systems are the same as those in Section 7.2.1; the annual system output is proportional to the annual utilisation of the SHS. For each option in Table 7.2, the annual system utilisation was varied from 1 to 12 months, where one month is equal to 730 operating hours[69]. The LCA was applied to each individual operating period for each of the six options in Table 7.2, and in turn, each of these was examined under 6 different fuel prices. This is equivalent to 432 different lifecycle cost analyses and it generates a large amount of data.

Table 7.3: An example of the data inputs for one of the options (COMC FPC 60) in the FFPS analysis

Annual Utilisation	***(Hours)***	***730***	***1459***	***2189***	***2918***	***3648***	***4378***	***5107***	***5837***	***6566***	***7296***	***8026***	***8755***
BAU System Requirements	*(MWh)*	*307*	*581*	*888*	*1192*	*1518*	*1843*	*2188*	*2535*	*2868*	*3204*	*3519*	*3834*
Annual System Output	*(MWh)*	*194*	*364*	*530*	*661*	*771*	*864*	*966*	*1088*	*1228*	*1399*	*1579*	*1768*

As stated above, having a large spread of data increases the likelihood that the actual conditions present in the future will fall within the bounds of the analysis. Table 7.3 summarises the data entered into the LCA for each of the options in Table 7.2.

From Table 7.3, it can be seen that the annual plant utilisation starts in January. Data in column three and row three is therefore, the annual output of the plant for the month of January, using the RETScreen solar model. Column three, row four is the output for January & February combined, and the last row and column represent the output for a system used continuously throughout the year, i.e. 12 months. Each of the options is examined whilst varying both the fuel price and the annual utilisation. This generates 72 data points for each option. 3-D surface graphs have been used to show the relationship between the three parameters, viz. fuel price, annual utilisation and NPV (at 15 years).

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[69] It is important to note that the operating period refers to the amount of time for which the process operates; the monthly limit to the operation of the solar system is constrained by the local solar radiation limits, which in turn are affected by climatic and geographic constraints as discussed in Chapter 3.

The next section will discuss the results of the FFPS, using one out of each set of solutions for each collector type. The section ends with a brief synopsis of when and under which conditions each type of system becomes financially viable.

7.2.3 THE RESULTS FROM THE FUTURE FUEL PRICE SCENARIO LIFECYCLE COST ANALYSIS

The first example used to explain the results of the FFPS sensitivity analysis is the COMC ETC 60°C option:

The ETC system, shown in Figure 7.4, has a NPV of R-4.98 million after 15 years (and payback period of 28 years) under the Original Scenario. As stated in Section 7.2.3, the main factor affecting the viability of this investment is the annual utilisation of the plant, as it only operates for four months of the year. For comparison with the results of the Original Scenario, increasing the electricity price to 0.9 R/kWh while keeping the annual utilisation constant, only increases the NPV to R634 000 by the end of the project life. The payback in this case is 15 years, and investing the capital in the SHS provides a much lower return on investment than investing the same amount of capital in the bank (NPV of R27 million after year 15).

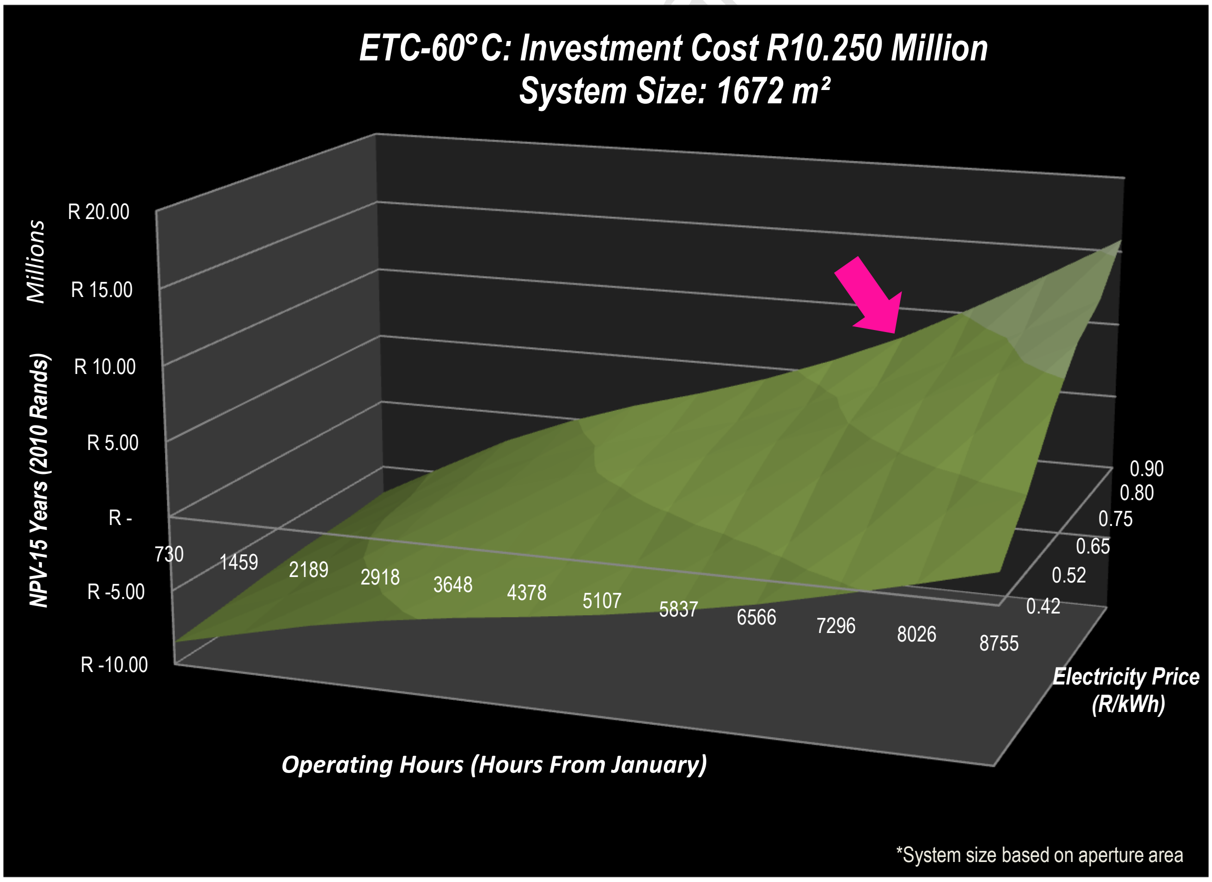

Figure 7.4: Results from the LCA for COMC ETC 60°C, where SHS supplements electricity

This option first becomes feasible when the electricity price is 0.65 R/kWh and the system is utilised for 12 months of the year. On Figure 7.4, this corresponds to the region where the NPV is above R8 million (marked by the magenta arrow on the graph) by the end of the project life.

The graph clearly shows the links between both fuel price and annual utilisation with the NPV of the system. The gradient of the surface increases in two directions, firstly as the annual utilisation increases and secondly as the fuel price increases. The closer to the top right-hand corner one gets, the more profitable the investment becomes, and this area is thus named the *region of feasibility*.

However, there is also an inverse to the region of feasibility, in other words, an area that represents the constraints under which a SHS will never be feasible, even if fuel prices reached the maximum values used in this study. In the example above, this area corresponds to everything below the level marked by the magenta arrow. On any of the 3-D surface graphs, the imaginary line that separates the region of feasibility and the area of non-feasibility can be imagined as a contour, where the contour in this analysis represents a NPV and not an altitude.

For the example above, the contour separating these two regions corresponds to a NPV of R8 million (marked by the magenta arrow). For this study, the region of feasibility includes all those investments that pay back in five years or less.

The graph below shows the results from the COMB FPC 60°C option; the energy generated by the SHS supplements coal in this case. The gradients in this graph suggest that it exhibits the same trends as in the example described for Figure 7.4 above.

In this case, the imaginary contour separating the feasible and non-feasible regions is a NPV of R3 million (indicated by the cyan arrow). The region of feasibility is much larger for this system, whilst the only major differences are the size and hence investment cost of this SHS; in this case, both are much lower. There seems to be a link between investment cost and the size of the region of feasibility, where the two major factors that influence the investment cost are collector price and system size.

The system becomes feasible at an annual utilisation of 10 months and fuel cost of 1250 R/tonne, which is the equivalent of only 0.165 R/kWh. This is only the second price rise in the series, which agrees with the finding that there is a larger feasibility region for this option. The LCA of this collector is very favourable under future price conditions and offers good returns on investment.

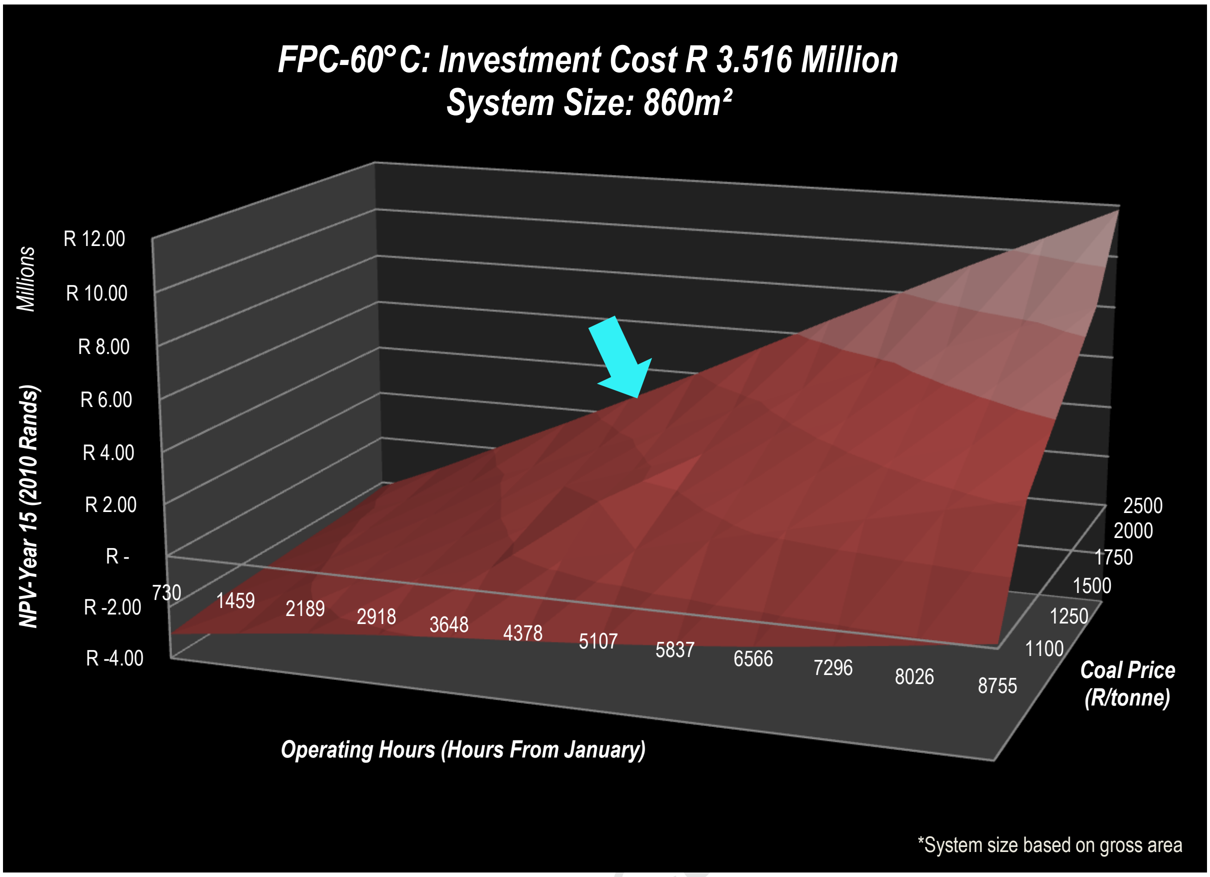

Figure 7.5: Results from the COMB FPC 60°C option.

More specifically, this option highlights an important fact, which is also evident from the Original Scenario, namely, that FPC systems with high annual utilisation are currently the most economically viable systems available. Any future energy price rises will render them the first opportunity for investment.

For the third example, the COMB PTC 180°C option has been chosen; in this scenario, however, it supplements electricity[70] and not coal as in the Original Scenario.

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[70] The supplementation of coal by a PTC has already been modelled in the COMA PTC 180°C option, therefore, for the sake of completeness, in this case the PTC is examined under electricity, to form a comparison.

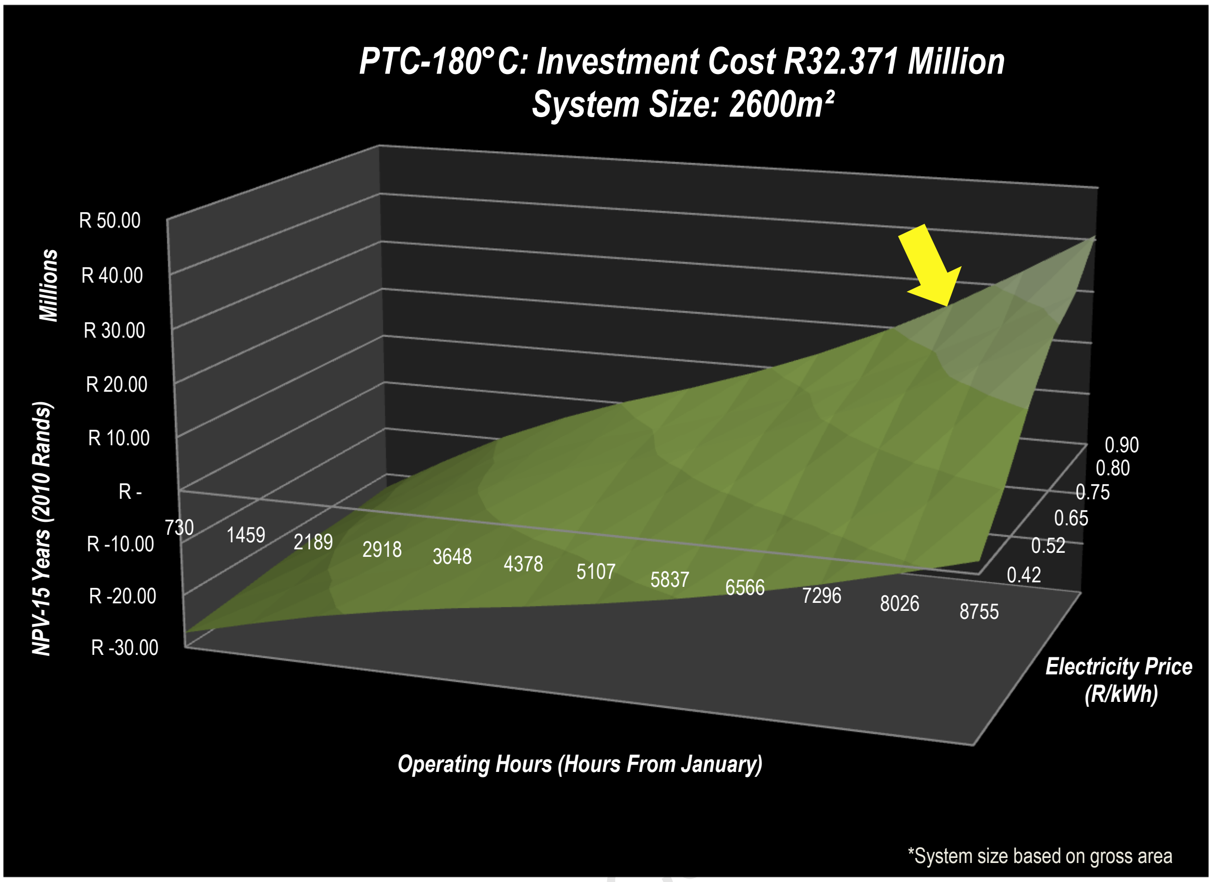

Figure 7.6: Results from the COMB PTC 180°C option

Out of the three examples cited so far, this has the smallest feasibility region (indicated by the yellow arrow). The graph seems to suggest a link between a large investment cost and a small region of feasibility, which is exactly the opposite situation to the FPC option above. The high upfront capital costs are a result of a large collector cost (Rand per square meter) and a large system size. Import duties and fees are responsible for raising the collector costs by 40% (this is not the system cost but the collector cost quoted by the manufacturer).

In the other PTC option modelled under this scenario, where coal is the fuel being supplemented, the system does not perform well in the LCA. Even at a coal price of 2500 R/tonne and an annual utilisation periods of 12 months, the system is not economic (the payback is 11 years, see Appendix B). Because of the large upfront capital costs of PTC systems, they only yield good results in cases where electricity is the fuel being substituted. The same is true of the COMA ETC 90°C option, where the price of coal is not high enough to repay the investment costs of the SHSs within the project life time of 15 years. In both cases, the majority of the surface, in the 3-D graphs, lies below the zero line and the systems never become profitable (to see the 3-D surface graphs generated in the other three cases please refer to Appendix B). Of course, the area of non-profitability is larger in the case of the PTC option than the ETC option.

The option described by Figure 7.6 becomes feasible at NPVs above R26 million (this is emphasised by the yellow arrow in Figure 7.6). The system first becomes feasible at an electricity price of 0.75 R/kWh and an annual utilisation of 12 months. This is the fourth price rise in the series, which indicates that the region of feasibility is much smaller than for the two previous examples. The NPV needed for a project to be economically viable is much higher in the case of PTCs, where the investment costs are higher.

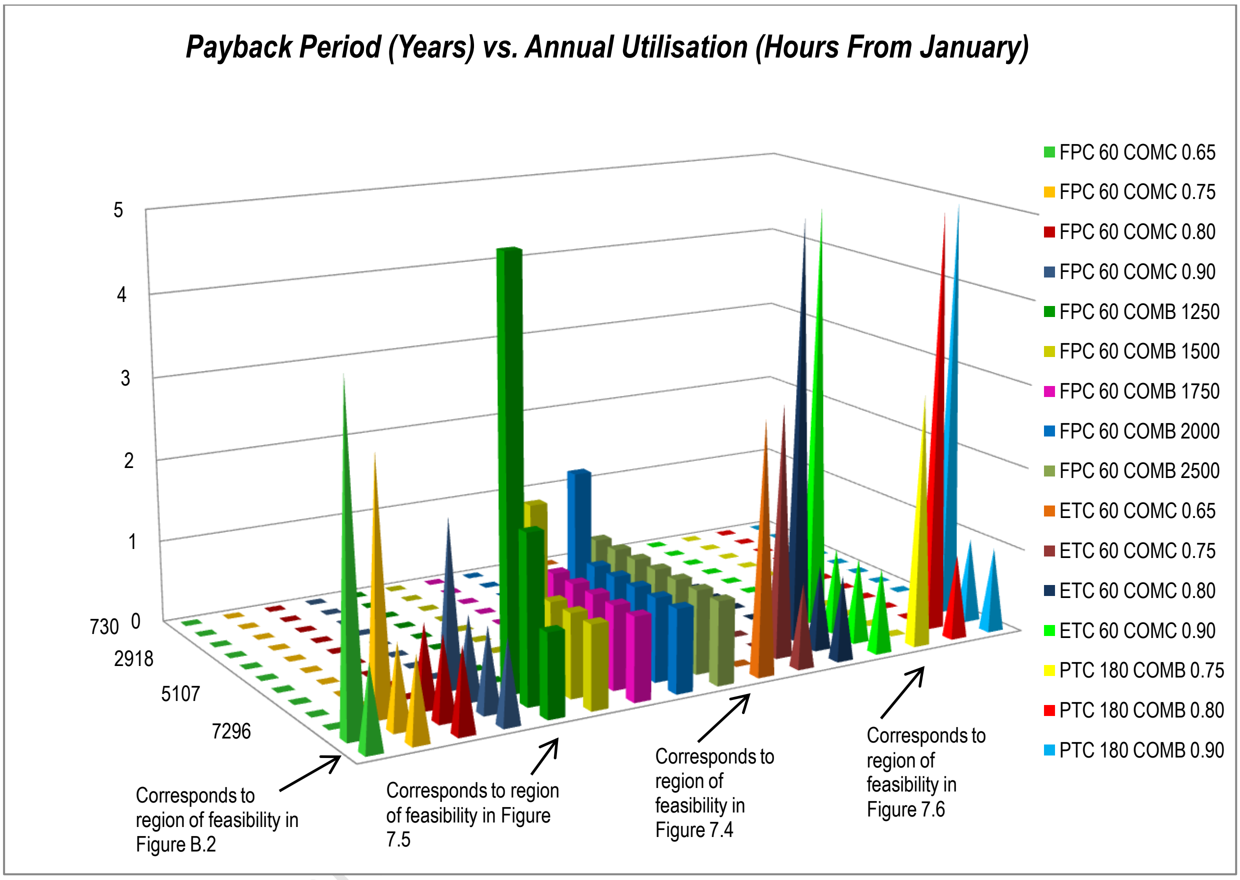

Figure 7.7: A summary of the regions of feasibility for the options that were economically viable

To summarise, out of the six options tested under the FFPS, only four of the systems offer real investment potential, whereas the other two options, namely COMA ETC 90°C and COMA PTC 180°C, never reach a point where the projects are financially viable. Even under the highest coal prices (2500 R/tonne), the systems only offer a payback of 7 and 15 years respectively. In contrast, the other four systems which supplement electricity all offered payback periods of under 5 years. Figure 7.7 summarises the payback periods for these four options. This graph is essentially a summary of the regions of feasibility for all the options that were financially feasible under future price rises. In this figure, the annual utilisation has been plotted against the payback period of the options and not the NPV.

The legend on the left-hand side indicates the name of the system and the fuel price at which the relevant case becomes feasible. For example, the first case of the COMC FPC 60°C option first becomes economically viable at an electricity price of 0.65 R/kWh and it has a corresponding payback of 3 years (the pyramids are used to indicate systems that supplement electricity whereas the bars are systems that supplement coal).

The COMB FPC 60°C option is the only one out of the three options that supplements coal, which is economically viable under future fuel prices. The prices listed in the legend for this system are in Rand per tonne.

7.3 DISCUSSION OF THE RESULTS FOR THE LIFECYCLE COST ANALYSIS OF THE SOLAR SYSTEMS

- It is evident from the analysis that a continuously fed FPC system (with high annual utilisation) that supplements electricity is by far the most economic SHS that can be designed currently. Unfortunately, none of the conditions in the plants surveyed for this project meet these conditions exactly.

  For example, under currently electricity prices (0.416 R/kWh), an indirectly fed FPC SHS, designed to pre-heat boiler make-up water continuously, with an annual utilisation of 12 months and with an investment cost of R3.5 million would currently have a payback period of just under 6 years[71] (using the same financial parameters as the Original Scenario). Therefore, under the next scheduled electricity price rise, systems operating under these constraints would be financially viable.

- The FPC systems modelled in this project become economically feasible before any of the other collector types, in terms of the price level at which they become financially viable. For a system supplementing electricity (COMC FPC 60), the payback would be under 5 years at an electricity price of 0.65 R/kWh and a coal system (COMB FPC 60) at a price of 1250 R/tonne (these two conditions are represented by the first green pyramid and first green bar in Figure 7.7 respectively). This is assuming that there is a higher annual utilisation than currently experienced in these plants.

- All the systems listed in Table 7.1 were designed to supply a solar fraction of 60%, which is the maximum theoretical limit that can be supplied for a continuously operating system, unless

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[71] This is far shorter than the payback period of a system substituting coal COMA FPC 60, 14 years currently, and a system with storage COMC FPC 60, 11 years. All systems have been compared using a 12 month annual utilisation.

thermal storage is used. Storage can only be ruled out in the case where the process is used on a continuous basis (seasonal or not) and where the hot water demand far exceeds the annual output of the solar system. In this case, one reduces the cost of the solar system by saving on storage costs. This is the case for the pre-heating of boiler feed water in all the facilities surveyed in this project, except for the COMC plant.

Simple economics dictates that, as the amount of storage needed increases, so to do the costs for that extra unit of storage. The second unaticipated consequence of having thermal storage is that it increases the size of the solar system needed when compared to a direct feed solar system. The heat losses of any given solar system increase when thermal storage is used; according to the POSHIP report, heat losses from a well designed system should not be more than 5% (AIGUASOL Enginyeria 2001). This finding is pertinent to this project, as it is one of the reasons why the COMB FPC 60 option becomes financially viable sooner than the COMC FPC 60 option, when we expect the result to be reversed, as the latter supplements electricity.

The other reason why the system needs to be larger, when storage is used, is because the temperature of the storage in the morning and when the system is in operation during the day is not as low as it would be if it were continually heating water from the municipal supply temperature, as is the case in the other two companies. In other words, the heat transfer from the solar loop through the heat exchanger is less because the difference in temperature between storage water and the water in the solar loop is less, and hence more collector area is needed to supply a similar amount of energy through the heat exchanger.

- In the analysis of the COMC FPC 60 option, the costs of storage are not taken into account; these could add anything between 10%-20% to the overall system costs, but the exact figure is uncertain. This figure is very dependent on the type of storage used and the amount of storage used. Because this study did not intend to investigate the effects of using thermal storage, it was deemed better to leave these cost assumptions out of the analysis of this option. The thermal losses and extra collector area have been accounted for in the RETScreen model and hence the annual solar output is correct.

- For comparison, an ETC system with the same specifications as the system modelled in the COMC ETC 60 option (which has a storage capacity of 114 L/m^2 of collector area), would have an oversupply of 22% if sized to supply heat in a directly fed system as opposed to a system feeding thermal storage (as in its original design).

- Removing the constraints of storage in the COMC ETC system under the same model increases the payback period by 3 years in this case, from 14 years to 11 years under current fuel prices of 0.416 R/kWh and a 12 month annual utilisation.

- The ETC and PTC systems do not become financially viable when supplementing conventional coal heating systems. The collector costs for both these systems are too high compared to the unit price of thermal energy derived from coal, even with boiler inefficiency taken into account. However, both collector types do become feasible when supplementing electricity use at 0.65 R/kWh (COMC ETC 60)[72] and 0.75 R/kWh (COMB PTC 180).

- As stated previously, the increased costs imposed by importation on PTC decreases their financial viability. Under further investigation, the payback of the COMB PTC 180 option decreases by two years if a lower collector system cost is used, viz. 10 090 R/m^2 instead of 12 450R/m^2 , with an annual utilisation period of 12 months.

- Although the costs of thermal storage and importation do increase the payback period of the systems, it is evident from the magnitude of these effects, that the annual utilisation period and fuel price are still the most crucial factors influencing the financial viability of the SHSs.

- For the output temperatures explored in this study, there seems to be less of an impact from supply temperature on the financial viability of the systems. This is somewhat contrary to the findings of the POSHIP report (AIGUASOL Enginyeria 2001), in which the temperature of the solar heat played a larger role in the financial success of the systems modelled. It is important to remember that in their study conventional heat costs are in the range of 3-4.5 cents of €/kWh (2001 Euros) for HFO and LPG (liquid petroleum gas). This is equivalent to a fuel price of between 0.38-0.57 R/kWh (2010 Rands), which is considerably higher than the current cost of coal, with the upper range being more expensive than electricity currently. This may suggest a relationship between fuel price and the temperature of the solar energy supply that becomes more apparent when the cost of the fuel being substituted is at a higher price.

- The solar output of the ETCs was in general slightly less than that of the FPC systems, except under the constraints of the COMC plant where the output of the ETCs was slightly better. However, if modelled under the same constraints as the other two plants, i.e. without storage, the output would have been slightly less than that of FPCs.

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[72] Again, the COMC FPC 60 option includes storage in the thermal analysis and hence the system is considerably larger than one that would supply the same amount of water in a continuously fed system.

- Out of the three regions, Ashton had the best solar resources, followed by Cape Town and then Prince Alfred Hamlet. This is highlighted by the energy collected per square meter of collector aperture of the three sites (FPC system output from RETScreen[73]), which are 1.58 MWh/m^2.year, 1.48 MWh/m^2.year and 1.48 MWh/m^2.year, respectively. On average, in Ashton, the three collector types generate about 7.1% more solar radiation (direct normal and diffuse combined) per year than in Cape Town and in Prince Alfred Hamlet (apart from climate data, this comparison has been made *ceteris paribus*).

- When planning to build a SHS, one needs to take into account any shading between parallel rows of collectors, as this has an effect on the output of the system and the size of the area that it takes up. The increased footprint of a system due to shading effects has no real effect on the price of the systems. But shading can lead to decreased system efficiency in the winter months when the shadows are longer due to the sun being lower in the sky.

7.4 RESULTS OF THE GREEN HOUSE GAS EMISSIONS ANALYSIS

A GHG analysis has been carried out on each of the systems modelled in the Original Scenario, the results of which are shown below in Table 7.4. The emissions savings listed in this table are the savings that result from substituting the conventional fuels with solar heat. The amount of fuel that is substituted is determined from the annual output of the SHSs. The analysis does take into account boiler efficiency. The emissions factors differ, though, according to the fuel supplemented, and a list of the emissions factors used in this study can be found in Chapter 6.

Table 7.4: GHG emissions savings, for CO_2, CH_4, N_20 and CO_2e in tonnes and kilograms

Company	***Collector Type / Operating Temperature(°C)***	***Emissions Savings (CO_2) (tonnes)***	***Emissions Savings (CH_4) (kg)***	***Emissions Savings (N_20) (kg)***	***All Emissions Savings (CO_2e) (tonnes)***
COMA	*FPC 90*	*1192*	*109*	*18*	*1200*
	ETC 90	*1189*	*109*	*18*	*1197*
	PTC 90	*1208*	*110*	*19*	*1216*
	FPC 45	*465*	*42*	*7*	*468*
	FPC 60	*705*	*64*	*11*	*710*
	PTC 180	*2661*	*243*	*41*	*2679*
COMB	*FPC 90*	*476*	*43*	*7*	*479*

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[73] The hot water temperature model used by RETScreen is worked out from the climate data. To see the climate and solar radiation data for each site, please consult Appendix A. The result is confirmed by the other two collector types, where again Ashton produces the largest solar yields, followed by Cape Town and Prince Alfred Hamlet.

Company	**Collector Type / Operating Temperature(°C)**	**Emissions Savings (CO_2) (tonnes)**	**Emissions Savings (CH_4) (kg)**	**Emissions Savings (N_20) (kg)**	**All Emissions Savings (CO_2e) (tonnes)**
COMC	*ETC 90*	*469*	*43*	*7*	*473*
	PTC 90	*472*	*43*	*7*	*475*
	FPC 45	*274*	*25*	*4*	*276*
	FPC 60	*177*	*16*	*3*	*178*
	PTC 180	*1063*	*97*	*16*	*1070*
	FPC 45	*426*	*13*	*5*	*428*
	FPC 60	*737*	*22*	*9*	*740*
	ETC 60	*741*	*22*	*9*	*744*

The last column lists the GHG emissions of the three substances totalled together, expressed as an equivalent of carbon dioxide emissions. Methane and nitrous oxide both contribute to the greenhouse effect, but their global warming potentials[74] are not equal to that of carbon dioxide, hence relatively small amounts of these gases lead to a far larger effect in terms of carbon dioxide equivalent (over a given time horizon).

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[74] Over a 100 year time horizon, methane has global warming potential 21 times that of carbon dioxide over the same period, whereas nitrous oxide has a global warming potential 310 times that of carbon dioxide, again over the same 100 year time horizon (Forster, et al. 2007, 212).

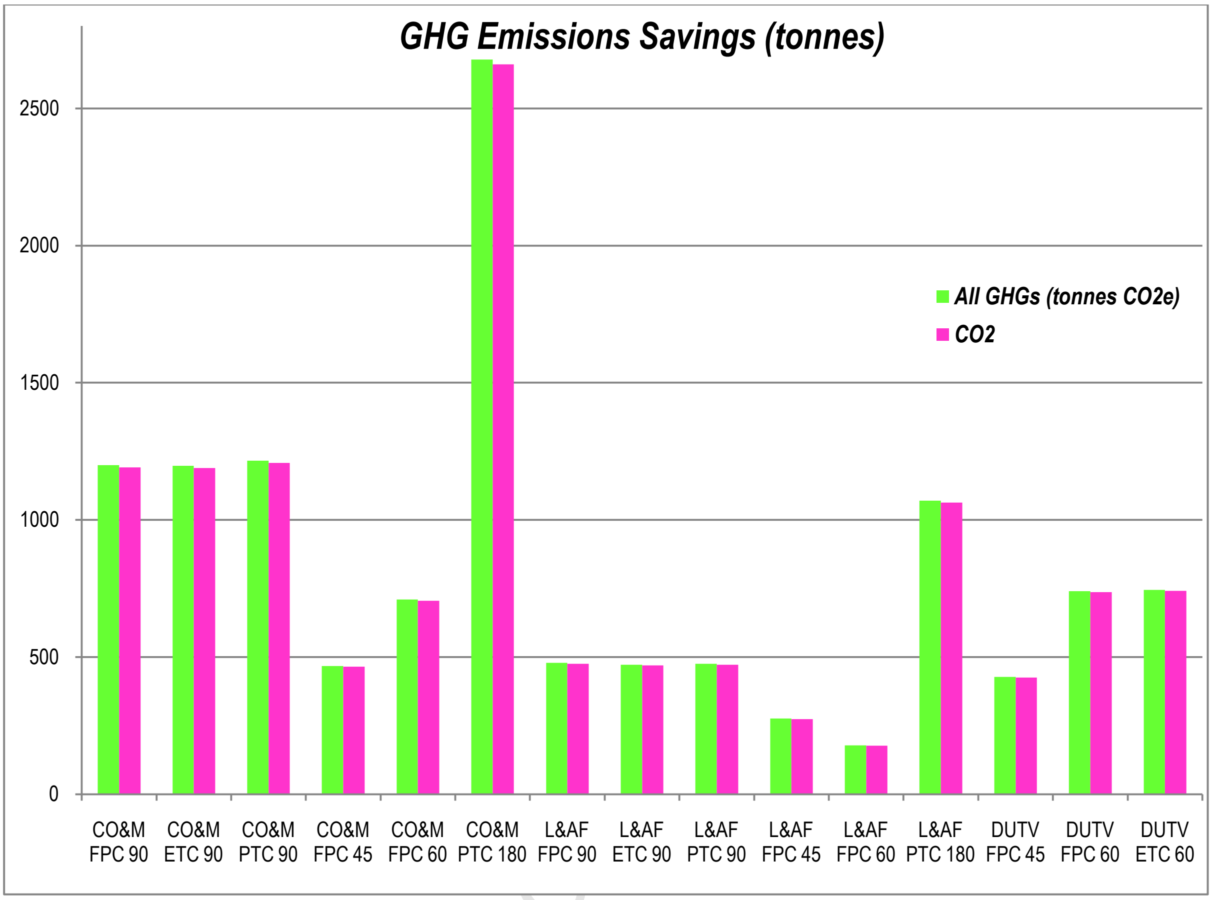

Figure 7.8: GHG emissions savings in tonnes for CO_2 and CO_2e

Figure 7.8 shows the results of the GHG analysis in graphical form, using Table 7.4 [?], and it highlights the relative importance of carbon dioxide emissions in comparison to the overall GHG emissions. Even though the global warming potential of carbon dioxide is far less than that of the other two gasses, a far larger quantity of it is emitted and therefore it has a greater impact on global warming.

The columns in Figure 7.8 are the same height for some of the entries; this is because some of the systems were designed to supply the same amount of energy, i.e. supplying 60% of the energy needed to pre-heat the boiler feed water to the specified temperature.

The quantity of the GHG emissions savings is directly proportional to the size of the annual solar output of the SHS system. Therefore, PTCs, for a given area, have a greater GHG emissions savings potential than either FPCs or ETCs. The GHG savings from the FPC and ETC are very similar in magnitude.

8. CONCLUSIONS AND RECOMMENDATIONS

The main hypothesis of this thesis was: *to establish whether or not there is potential for solar heat to provide energy to the food and beverage industry, using the Western Cape as the focal point of this study*.

In order to answer this hypothesis, two separate tasks needed to be carried out; firstly, a figure for the potential of the technology within the Western Cape F&BI needed to be established, and secondly, a price or benchmark at which the technology becomes financially viable needed to be predicted.
The following sections establish whether the hypothesis has been adequately proved or disproved.

8.1 CONCLUSIONS AND RECOMMENDATIONS: POTENTIAL FOR SOLAR HEAT IN THE WESTERN CAPE FOOD AND BEVERAGE INDUSTRY

As stated, in order to prove or disprove this hypothesis, the size of the potential for solar heat within the F&BI needed to be established. It was shown in Section 7.1.2, that the size of this potential, for fuel consumed in 2007, was 12 PJ, which is 9% of the Western Cape's total primary energy consumption. This means that there is the potential for solar heat to displace at least 12 PJ of primary energy consumption within the F&BI of the Western Cape. To put this into terms of other primary energy supplies, this is equivalent to 440 000 tonnes of coal a year (using a GCV of 27 MJ/kg) or 290 000 tonnes of oil equivalent[75]. Using the average energy collected by a square meter of FPC in Cape Town, one would need 2.3 million square meters of FPC[76] to generate 12 PJ of energy a year. This is a very large amount of collectors and is approximately comparable to the Government's plan to roll out one million solar collectors within the residential sector, for the whole of South Africa by 2014.

The three main fuels that would be displaced in this case are HFO, coal and paraffin. The emissions savings potential of such measures would be vast. It is recommended that the Western Cape provincial government seriously investigate the large scale roll-out of SWH in the F&BI. The F&BI is one of the largest energy consumers within the Western Cape, with a very high portion of energy used for thermal measures. The cost of implementing SWH is far cheaper than CSP and Wind Power, see Figure 7.1a. The devices can be readily installed onto existing factory roofs, thus avoiding the need for costly and lengthy environmental impact assessments. Within the next two years and under certain conditions, the technologies will become financially viable on a purely economic basis alone without the aid of subsidisations.

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[75] Where one TJ is equivalent to 2.388×10^{-5} Million tonnes of oil equivalent (Mtoe).

[76] This is using the annual output of the FPCs modelled in RETScreen for this project. The average energy collected by a FPC in Cape Town was 1.439 MWh/m^2 per year.

Until now, SWH has only been considered for the residential and commercial sectors, but it is recommended that future renewable energy subsidies also include SWH systems for the industrial sectors. The scale of industrial sized SHSs means that factories producing collectors for these size orders would benefit from large economies of scale. This would then help to drive down the future price of the collectors.

It is clear from the literature and this project, that there is a lack of information in South Africa with regard to the potential of SWH. There are currently no studies describing the potential for solar thermal heat in local industry. It is also hard to find references on the prices for large SWH installations. The lack of information surrounding the SWH industry is definitely one of the barriers to large-scale implementation of the technology. There is certainly scope for more research into the potential use of SWH in other industries.

It is also recommended that local municipalities within the Western Cape collect more disaggregated energy consumption statistics to make calculating the potential for new technologies more efficient.

With regard to using solar heat for cooling, it is recommended that more statistics be gathered to establish the types, capacity and operating characteristics of the installed refrigeration systems within the province, as this is another potential area for the use of solar heat.

Also, the augmentation of an ARS within the cycle of an ammonia vapour compression cycle system is definitely an area of research that could be pursued to see whether these two systems could be amalgamated. The benefit is that one could operate at low temperatures whilst saving on electricity. As the lithium bromide-water chiller is far cheaper to run at temperatures above 5°C, the idea is analogous to a hybrid car that uses both a petrol and electric engine to save on overall fuel efficiency.

8.2 CONCLUSIONS AND RECOMMENDATIONS: LIFECYCLE COST ANALYSIS OF COMMERCIALLY AVAILABLE SOLAR HEATING SYSTEMS

The main aim of this part of the project was to investigate the commercially available products and to see whether these were capable of supplying the quantities of thermal heat needed. Secondly, the current economic implications of the systems needed to be established to see why this technology has not been implemented in the F&BI thus far. And finally, the project aimed to go one step further and to establish when the technology would become financially viable.

It was deemed that the best way of fulfilling these tasks was through engagement with players within this industry. This ensures that the examples used are relevant and that the results of the research are not lost in a library corner of some academic institution.

There is no doubt that SHSs can be integrated into an existing factory to supplement the utilisation of conventional energy supplies. There are over 90 systems worldwide, which operate SHSs in parallel to conventional heating systems (Vannoni, Battisti and Drigo 2008). There is much published in the literature detailing how to integrate SHSs into existing factories and what quantities of energy can be supplied (Benz, Gut, et al. 1999, Schweiger, et al. 2000, AIGUASOL Enginyeria 2001, Kalogirou 2003, Kalogirou 2004, Weiss and Rommel 2008, Desideri, Stefania and Sdringola 2009).

The results, presented in Chapter 7, clearly show that, for all three facilities surveyed, any of the three collector types could be incorporated into the existing factories. The only physical factor that limits the size of the systems that can be implemented is the amount of available roof space, but Section 7.1.2 clearly shows that there is adequate roof space to install a considerable amount of solar heating in all the plants studied herein.

The limiting factor to the implementation of these systems is therefore their economic viability. In the Original Scenario, it was established that under current fuel prices none of the systems were economically viable. The tool used to establish this was the LCA, which revealed that only the three FPC systems utilised for 12 months of the year were capable of generating positive NPVs after 15 years. However, these values were far lower than could be obtained from investing the same amounts of capital in the bank.

Under the current operating constraints of the three facilities, the pre-heating of boiler make-up water in the case of COMA and COMB and the heating of water for thermal storage and use at night in the case of COMC would become feasible at the following energy prices:

For COMA, based on the current annual utilisation at the plant, the most economic option will be to install a FPC, when the price of coal reaches 1250 R/tonne, or when there are financial incentives that will have the effect of reducing the gap between this figure and the current coal price of R1100 R/tonne.

The COMB plant, which currently has an annual utilisation of 6 months, would only be able to install a viable FPC system when coal prices reach 2500 R/tonne. If the plant were able to make use of the system for 10 months of the year, financial viability could be reached at a coal price of 1250 R/tonne.

For the COMC plant, with an annual utilisation of 4 months, a FPC will not become financially viable, even at a price of 0.90 R/kWh. If the plant could find an alternative use for the heat for an additional 6 months of the year (i.e. annual utilisation of 10 months), the FPC system would be financially viable at an electricity price of 0.65 R/kWh.

In general, the following is recommended with regard to PTCs and ETCs: these types of system should not be considered if the existing plant operates on coal or with a fuel similar in price to coal. They should only be considered when the plant generates thermal energy by using electricity, the price of which reaches 0.75 R/kWh (12 months annual utilisation) in the case of PTC systems and 0.65 R/kWh (12 months annual utilisation) for ETC systems.

Unfortunately, none of the factories presented a case where a FPC system substituted electricity, without any extra system size, as in the case of the COMC plant (this system operates at night and therefore uses thermal storage, which needs extra collector area to make up for additional heat losses). It is a recommendation of this report that facilities, which have low temperature (<80°C) processes supplied by electrical resistance heaters, should seriously consider implementing FPC systems to cover part of this load. At an electricity price of R/kWh 0.52, which will be the average tariff after the next Eskom price increase, systems operating for 12 months of the year will have an NPV of R3.88 million by the end of their project life.

This study did not find a very strong correlation between the output temperature of the collector heat supply and the economic viability of the solar system. This could be because the water coming into the collector is always at ambient temperature or close to it, and therefore the collectors operate at a high efficiency. Therefore, no recommendations can be made as to the best operating temperatures for the three collector types apart from what is cited in the literature. On this basis, it is recommended that: FPCs be operated at 60°C-80°C ((AIGUASOL Enginyeria 2001, Kalogirou 2003), ETCs between 80°C and 120°C (AIGUASOL Enginyeria 2001) and PTCs from 120°C to 250°C (AIGUASOL Enginyeria 2001, Kalogirou 2003, Minder, Solar Thermal Research 2010).

In this report it has been shown that SHSs can be incorporated into existing plants in the F&BI, and that these systems are capable of supplying large amounts of energy, especially at temperatures under 200°C. In the previous chapter, forecasts were made as to when the systems might become feasible. However, not all institutions will use the same financial constraints to deem whether an investment is profitable or not. Nonetheless, the results of this dissertation are such that one could use the 3-D surface graphs and tables, found in the results chapter and appendices, to find a point at which these systems would become profitable to an organisation, given their own set of economic constraints.

As far as this study is concerned, SHSs have definitely fulfilled the requirements of the hypothesis set out in the first chapter. There is definitely a large potential for solar heat in the Western Cape F&BI. Within the next two years, as electricity prices increase, SWH systems that supplement electrical heating systems with a high annual utilisation will be economically feasible. Systems supplementing coal will be feasible within the next five years, especially if one believes that the oil price is due to increase to above US$ 100 per barrel as stated by the IEA (IEA 2008).

Apart from the economic benefits of fuel savings, SWH systems offer a more risk averse investment of capital, considering the possible implementation of carbon costs. If one believes that civilization is heading towards being a carbon constrained society, investment in SWH also offers an advantage of the BAU scenario.

Finally, security of supply has been an issue over the last few years, as electricity supply has lagged behind economic growth. One way in which companies can contribute to ensuring security of supply is by decreasing their electricity demand. SWH systems can decrease demand during the peak periods and therefore can contribute towards a more secure supply until the lagging power infrastructure catches up to economic growth.

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APPENDIX A

SOLAR RADIATION DATA

A1. SOLAR RADIATION DATA FOR CAPE TOWN

The solar radiation and climate data used for Cape Town is given below, the solar data is for a horizontal surface. RETScreen adjusts the radiation data accordingly for inclined surfaces and tracking systems. This data has not been shown.

Table A1: Climate data for Cape Town (Airport), adapted from (Natural Resources Canada 2010)

	Unit	**Climate data location**	**Project location**						
Latitude	˚N	-34.0	**-34.0**						
Longitude	˚E	18.6	**18.6**						
Elevation	m	42	42						
Heating design temperature	°C	5.0							
Cooling design temperature	°C	29.0							
Earth temperature amplitude	°C	15.2							
Month		**Air temperature**	**Relative humidity**	**Daily solar radiation - horizontal**	**Atmospheric pressure**	**Wind speed**	**Earth temperature**	**Heating degree-days**	**Cooling degree-days**
		°C	%	kWh/m^2/d	kPa	m/s	°C	°C-d	°C-d
January		20.4	71.0%	7.72	101.1	6.6	25.9	0	322
February		20.4	72.0%	7.06	101.0	6.5	25.5	0	291
March		19.2	74.0%	5.86	101.2	5.4	23.4	0	285
April		16.9	78.0%	4.17	101.3	4.4	19.8	33	207
May		14.4	81.0%	2.97	101.5	3.8	16.3	112	136
June		12.5	81.0%	2.44	101.8	4.0	13.1	165	75
July		11.9	81.0%	2.64	101.8	4.2	12.4	189	59
August		12.4	80.0%	3.39	101.8	4.4	13.6	174	74
September		13.7	77.0%	4.72	101.6	4.9	16.1	129	111
October		15.6	74.0%	6.08	101.5	5.6	19.6	74	174
November		17.9	71.0%	7.47	101.3	6.2	22.7	3	237
December		19.5	71.0%	7.89	101.1	6.1	24.8	0	295
Annual		16.2	75.9%	5.19	101.4	5.2	19.4	879	2,267
Measured at	m					10.0	0.0		

A2. SOLAR RADIATION DATA FOR ASHTON

Table A2 gives the climate data for Ashton, the data in this case has been copied into the RETScreen template from NASA's *Surface meteorology and Solar Energy* website (NASA 2009). Out of the three sites Ashton has the best solar radiation resources.

Table A2: Climate data for Ashton, adapted from (NASA 2009)

	Unit	**Climate data location**	**Project location**						
Latitude	˚N	-33.5	**-33.5**						
Longitude	˚E	20.3	**20.3**						
Elevation	m	776	**776**						
Heating design temperature	°C	5.0							
Cooling design temperature	°C	28.6							
Earth temperature amplitude	°C	18.5							
Month		**Air temperature**	**Relative humidity**	**Daily solar radiation - horizontal**	**Atmospheric pressure**	**Wind speed**	**Earth temperature**	**Heating degree-days**	**Cooling degree-days**
		°C	%	kWh/m²/d	kPa	m/s	°C	°C-d	°C-d
January		21.7	50.0%	8.26	94.8	4.4	26.9	2	369
February		21.8	53.5%	7.30	94.9	4.5	25.7	2	341
March		20.3	55.5%	5.88	95.0	4.5	23.3	10	329
April		17.7	55.8%	4.36	95.1	4.4	19.3	44	244
May		14.8	55.4%	3.30	95.2	4.7	15.2	98	165
June		11.7	58.5%	2.72	95.4	4.9	11.3	177	73
July		11.1	58.2%	3.03	95.5	5.0	10.8	204	62
August		12.1	56.4%	3.92	95.4	4.7	12.8	170	90
September		14.1	54.1%	5.15	95.2	4.5	16.0	114	139
October		16.6	51.5%	6.47	95.2	4.6	20.0	67	210
November		18.7	49.8%	7.68	95.0	4.4	23.5	29	265
December		20.4	50.9%	8.18	94.9	4.4	25.8	7	328
Annual		16.7	54.1%	5.51	95.1	4.6	19.2	924	2,615
Measured at	m					10.0	0.0		

A3. SOLAR RADIATION DATA FOR PRINCE ALFRED HAMLET

Table A3, gives climate data for Prince Alfred Hamlet, again this is from the NASA website (NASA 2009).

Table A3: Climate data for Prince Alfred Hamlet, adapted from (NASA 2009)

	Unit	Climate data location	Project location
Latitude	˚N	-33.3	**-33.3**
Longitude	˚E	19.3	**19.3**
Elevation	m	754	**754**
Heating design temperature	°C	5.4	
Cooling design temperature	°C	28.7	
Earth temperature amplitude	°C	18.2	

Month		**Air temperature**	**Relative humidity**	**Daily solar radiation - horizontal**	**Atmospheric pressure**	**Wind speed**	**Earth temperature**	**Heating degree-days**	**Cooling degree-days**
		°C	%	kWh/m²/d	kPa	m/s	°C	°C-d	°C-d
January		21.9	49.8%	7.82	96.2	4.6	27.0	1	375
February		22.2	5.6%	7.09	96.2	4.7	26.0	1	351
March		20.7	55.3%	5.74	96.3	4.6	23.6	7	340
April		18.0	57.2%	4.18	96.5	4.5	19.6	38	251
May		15.1	58.6%	3.07	96.7	4.7	15.5	92	173
June		12.0	62.3%	2.55	96.8	5.0	11.6	167	80
July		11.3	62.5%	2.77	96.9	5.1	11.0	196	65
August		12.2	60.2%	3.57	96.8	4.9	12.8	167	91
September		14.2	57.2%	4.73	96.7	4.7	15.9	111	140
October		16.9	52.3%	6.09	96.6	4.9	20.1	60	215
November		18.9	50.0%	7.22	96.4	4.6	23.7	24	271
December		20.7	51.0%	7.67	96.3	4.6	26.0	5	334
Annual		17.0	52.2%	5.20	96.5	4.7	19.4	869	2,686
Measured at	m					10.0	0.0		

APPENDIX B

RESULTS: 3-D SURFACE GRAPHS

B1. 3-D SURFACE GRAPHS FOR THE OTHER THREE OPTIONS IN THE FUTURE FUEL PRICE SCENARIO

Figure B.1 shows the economic modelling results of the COMA PTC 180°C option, in this case coal is the fuel being substituted. It is clear to see from Figure B.1 that the investment in the PTC system is not a good investment in this case. The returns do become positive after 15 years, but only at very high coal prices. But even when positive the graph indicates that the return on a R42 million investment is only R5 million at coal prices of 2500 R/tonne. This is a very small value when compared to investing the same amount of capital in a bank, which would yield R116 million.

The results therefore seem to suggest that if the unit price of energy is very low investing in a relatively expensive concentrating solar collector to supplement one's conventional energy use is not economical on a purely financial basis alone. The results displayed on this graph are consistent with the other findings in this dissertation in that fuel price is a very big factor to consider when investing in a SHS. Even under high annual utilisation and high coal prices the PTC system in Figure B.1 never becomes competitive.

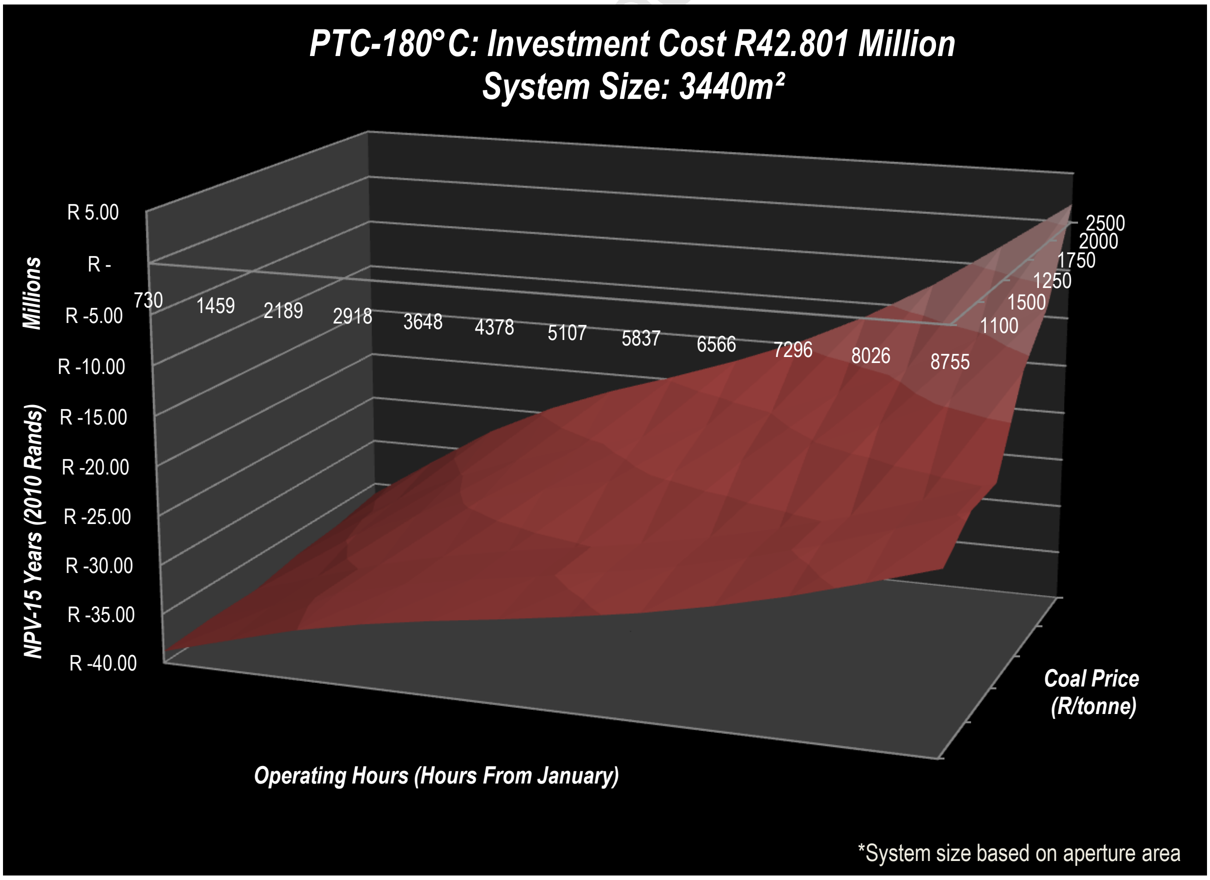

Figure B.1: Results from the COMA PTC 180°C option

Figure B.2 shows the results of the COMC FPC 60°C option, this case represents the most economically competitive scenario for SHSs. When the unit price of electricity is 0.65 R/kWh and the annual utilisation is 11 months the system becomes economically viable. This is indicated by the green arrow on Figure B.2. When comparing the results of this option to that of the COMB FPC 60°C, it may seem as if the COMB system is more competitive even though the fuel being substituted in that case is coal, it seems as if there is a contradiction in the results. In fact there is untrue, the system modelled below is designed for a system making use of thermal storage as the heating is needed at night. This means that the collector field needs to be larger to account for increased thermal losses.

A FPC system with a high annual utilisation that substitutes electricity, where no thermal storage is needed, will be the most economically competitive scenario for SHSs. This is a so called “win-win” case. See Chapter 8 for recommendations for systems that could potentially operate under these conditions.

In Figure B.2, the region of feasibility is above NPVs of R7 million. Comparatively, an investment of R8.4 million in the bank would yield a NPV of R22 million after 15 years.

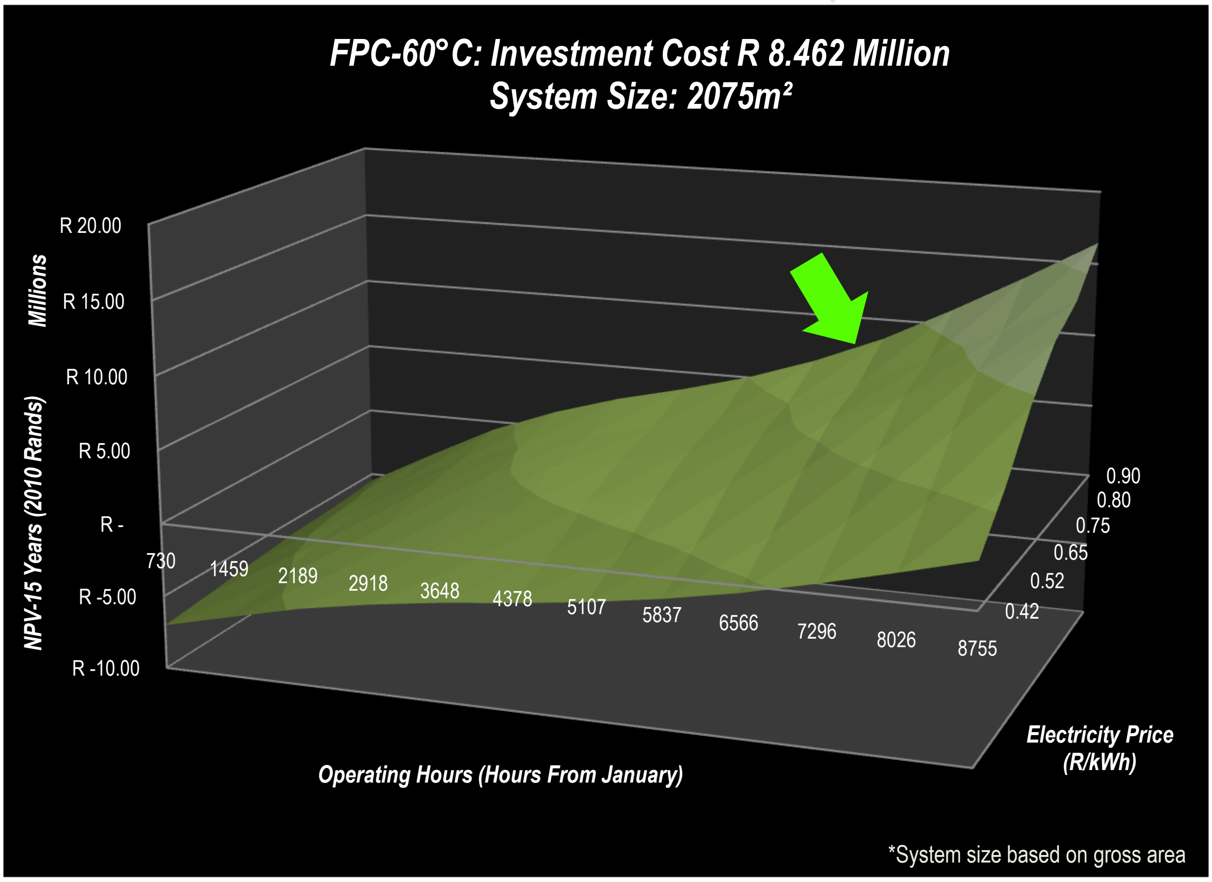

Figure B.2: Results from the COMC FPC 60°C option

Figure B.3 shows the results for the COMA ETC 90°C option, the project in this case does not reach a stage where it becomes financially viable. The system here again is too expensive compared to the small unit price of coal to reach a point where the payback of the system is below 5 years.

Investing the R11.5 million in a bank would yield a return of R31 million after 5 years. It must be stated at this point, the return on investment from a bank has been shown for a comparison. The systems will struggle to yield returns as high as that of a bank, under current economic conditions and those over the next five years, but investing in the SHS does provide the companies with a means to reduce operating costs compared to the BAU scenario, whilst at the same time getting some return on investment albeit a smaller one.

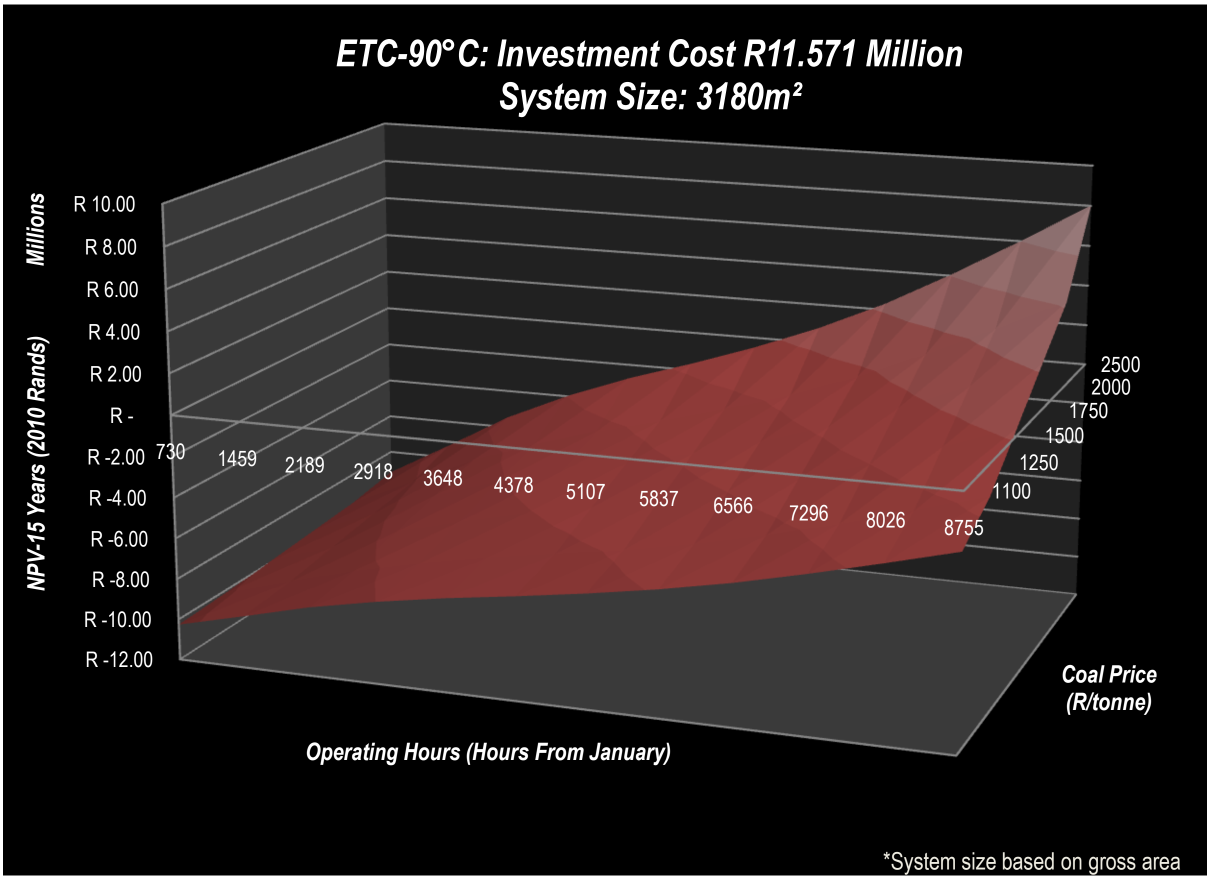

Figure B.3: Results from the COMA ETC 90°C option

APPENDIX C

PTC IMPORT COST BREAKDOWN AND EXCHANGE RATES

C1. PTC IMPORT COST BREAKDOWN

Table C.1 lists the fees and duties incurred when importing solar collectors into South Africa (Cronje 2010). The collectors are delivered CIF to a South African port.

Table C.1: Import duties and fees for the PTCs

Import Duty	*15.00%*
Upliftment Fee	*10.00%*
VAT	*14.00%*
Clearance Agent Fees	*8.00%*

The upliftment fee, is not paid it is added onto the sub-total of the goods' value to inflate the VAT paid on the items being imported. The fees are added on top of one another in the order listed in Table C.1. Table C.2 shows the results of applying these fees to the collector quote (CIF) supplied by the manufacturer.

Table C.2: Costs for PTCs, 516$m^2$of collector aperture area

Import Costs	
Collector, Receiver & Structure Cost (2010 AUS $)	*$292,000.00*
Cost (2010 Rands)	*R 1,959,806.61*
Cost with Import Duty	*R 2,253,777.60*
Cost with VAT	*R 2,600,859.35*
Cost with Clearance Agent Fees	*R 2,757,643.87*
Total Cost (2010 Rands)	***R 2,757,643.87***

Table C.3, below, gives a breakdown of the exchange rates used. The exchange rates are for 2010 US Dollars. The reason for converting Australian Dollars to US Dollars then to South African Rand is that the US Federal Reserve regularly publishes long term exchange rate data that is freely available and consistent (US Federal Reserve 2010). The exchange rate for the first six months of the year has been used in this case.

The net effect of all the duties and taxes is that the price of the collectors has been increased by 40.71% to AUS$ 410 873. Clearly, it would be advantageous to eliminate this increase by locally manufacturing the collectors.

Table C.3: Exchange rates, Australian Dollars and South African Rand

Exchange Rate (2010 US $)	AUS ($)	ZAR (RAND)
January	0.9127	0.134
February	0.8857	0.1304
March	0.9123	0.135
April	0.9262	0.1362
May	0.8713	0.1307
June	0.8363	0.13
Average	**0.890**	**0.132**

APPENDIX D

SOLAR COLLECTOR MANUFACTURER'S DETAILS

D1. SOLAR COLLECTOR MANUFACTURER'S DETAILS

The following list is compiled of the contact details of the solar manufacturer's that were consulted for this project. More companies were contacted than listed, many companies did not reply to the request for information. This study was not intended to be a comprehensive market study of the available collectors within South Africa. The companies are listed by collector type and in alphabetical order.

Evacuated Tube Collectors

- **EFA Solar**

  Email: info@efasolar.co.za

  Phone: 021 691 6721

  Fax: 021 691 7161

  Physical Address: 9 Induland Ave, Lansdowne, Cape Town, 7780

  Postal Address: P.O. Box 24542, Lansdowne, 7779

Flat Plate Collectors

- **Atlantic Solar**

  E-mail: capetown@atlanticsolar.co.za

  Phone: 021 905 7801

  Fax: 086 619 4881

  Factory Address: Unit C1, Wijnlandpark, Chardonnay Street, Saxenburg 1

  Postal Address: P.O. Box 294, Blackheath, 7581

- **Solar Heat Exchangers**

  E-Mail: info@solarheat.co.za

  Phone: +27 (0)11 462 0024

  Fax: +27 (0)11 704 6570

Office Address: No 40 Avant-Garde Avenue, Northlands Deco Park, Newmarket Road, North Riding, Johannesburg

- **Solar Zone**

  E-mail: info@solarzone.co.za

  Phone: +27 (0) 21 845 4440

  Fax: +27 (0) 86 667 3629

  Street Address: 34 Chilwan Crescent, Helderberg Industrial Park, Strand, 7140

  Postal Address: P.O. Box 3436, Somerset West, 7129

- **Sonnenkraft**

  Email: info@sonnenkraft.co.za

  Phone: +2711 781 6104

  Fax: +2711 326 2344

  Office Address: Sonnenkraft SA (Pty) Ltd, 168 Bram Fischer Drive, Randburg, 2194

Parabolic Trough Concentrators

- **NEP SOLAR / NEP EUROPE GmbH**

  Phone: +41 44 445 1695

  Fax: +41 43 411 9008

  Office Address: Technoparkstrasse 1, 8005 Zürich, Switzerland