Energy savings potential of CO_2 heat pumps in the South African industrial sector

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Abstract

TITLE: Energy savings potential of CO_2 heat pumps in the South African industrial sector

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KEYWORDS: CO_2 Heat pump; Industrial sector; Chicken abattoir.

The South African industrial sector is the largest energy user, accounting for more than a third of the country's energy usage and 80% of the heat demand. Heat pumps (HP) have the potential of reducing the industrial energy heat demand. However, a commercial HP typically have a low operating temperature of 65 °C.

An alternative to commercial HPs is the introduction of CO_2 as a natural refrigerant. CO_2 holds several advantages for the industrial heat pumps market. Not only can multi-function CO_2 HPs deliver water at discharge temperatures of 65 °C and 90 °C, but also chilled water as low as -9 °C. The wider operating temperatures can thus open a broader market of application for HPs in the industrial sector.

This study firstly aimed to determine which divisions in the industrial sector are the most suited for the implementation of industrial heat pumps (IHPs). From the literature it became evident that the food, beverage, and tobacco division has the highest potential for energy savings.

To determine the most suitable South African industrial division, the author estimated and analysed the heat demand for 12 divisions with a maximum temperature of 100 °C. The analysis showed that the food, beverage, and tobacco division was the most suitable division, with the poultry abattoirs being the most suited for the integration of CO_2 HPs.

To show the energy savings potential in the identified poultry sector, a techno-economic and environmental evaluation was done of the integration of CO_2 HPs for a case study poultry abattoir. For the evaluation, a mathematical model was developed to compare CO_2 HPs against four alternative heating sources, namely coal, paraffin, liquid petroleum gas, and electrical resistance. The model evaluated the CO_2 HPs for various climatic zones of South Africa. The results showed that, on average, CO_2 HPs use 4.5 times less energy than coal when combined with an ammonia chiller but cost 2.2 times more to operate than a coal boiler.

A barrier to the implementation of CO_2 HPs in the industrial sector is the uncertainties concerning inflation, capital layout cost, and energy cost. Consequently, a sensitivity analysis was done. The investigation showed that the capital cost has the largest impact on economic indices investigated and influences the indices investigated positively.

Finally, the impact of CO_2 HPs on the greenhouse emissions of South Africa was investigated. This covered 17 high-throughput abattoirs, which represent approximately 75% of the country's poultry throughput. The results showed that if all the abattoirs changed over to HPs, the greenhouse emissions could be reduced by at least 45%.

Although CO_2 HPs do not currently make sense financially when compared with coal boilers, they have a large environmental impact in the industry. CO_2 HPs thus have the potential to reduce industrial sector greenhouse gases, a zero-ozone depletion value, very low greenhouse warming potential, and are non-toxic and non-flammable. CO_2 HPs thus have the potential to make a significant environmental impact.

Articles published

The following articles have been published in international and accredited conferences:

Kaiser, W.H. van Eldik, M. 2015. The potential for CO_2 heat pumps in the South African industrial sector. Industrial and commercial use of energy. Cape Town South Africa. p70-75

Kaiser, W.H. van Eldik, M. 2019. Estimating the South African industrial heat demand potential for CO_2 heat pumps. Industrial and commercial use of energy. Cape Town South Africa. p 128 -136

Declaration

I, Werner Heinrich Kaiser, hereby declare that, except where specific reference is made to the work of others, the contents of this thesis are original and have not been submitted in whole or in part for consideration for any other degree or qualification in this or any other university. This thesis is the result of my own work and includes nothing that is the outcome of work done in collaboration, except where specifically indicated in the text.

Werner H Kaiser

Promoter: Prof. M van Eldik

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Nomenclature

Glossary

Term	Description
Heat pump	Heat pumps are mechanical devices that extract low-grade heat from one source and transfer the heat to another. However, a heat pump requires an external mechanical energy source. The advantage of a heat pump is that it upgrades the heat to a higher temperature than the source from which the heat was extracted. Heat pumps are used in a wide number of applications ranging from residential to commercial to industrial applications.
Industrial heat pump	A heat pump that is only used in an industrial environment.
CO_2 heat pump	A heat pump that uses CO_2 as a refrigerant. The heat pump can be used in residential, commercial, and industrial applications. The focus of this thesis is on industrial applications.

Acronym and abbreviations

Acronym	**Meaning**
AGEB	"Arbeitsgemeinschaft Energiebilanzen"
AWW	Air-water-water
COC	Certificate of compliance
COP	Coefficient of performance
CW	Chilled water
DAFF	Department of Agriculture, Forestry and Fisheries
DoE SA	Department of energy South Africa
DSM	Demand-side management
ECPC	Economic classification policy committee
EIA	Energy information administration
GDP	Gross domestic product
GHG	Greenhouse gas
GVA	Gross value added

Acronym	Meaning
GWP	Global warming potential
HCFCs	Hydrochlorofluorocarbons
HFC	Hydrofluorocarbons
HP	Heat pump
IHP	Industrial heat pumps
HPD	Heat pump drying
HPTCJ	Heat Pump and Thermal Storage Technology Centre of Japan
HX	Heat exchanger
HT	High-throughput
IDM	Integrated demand management
IEA	International Energy Agency
IEP	Integrated energy plan
IHP	Industrial heat pumps
IOPSA	Institute of Plumbing South Africa
IRR	Internal rate of return
ISIC	International Standard Industrial Classification of all Economic Activities
JSE	Johannesburg Stock Exchange
LPG	Liquid petroleum gas
LT	Low-throughput
MECS	Manufacturing Energy Consumption Survey
Mfg	Manufacturing
MIT	Massachusetts Institute of Technology
n.e.c.	Nowhere else classified
NACE	European Classification of Economic Activities
NAI	Notifiable avian influenza
NAICS	North American Industry Classification System
NATSURV	National Industrial Water and Wastewater Survey
NERSA	National Energy Regulator of South Africa
NPV	Net present value
ODP	Ozone depletion potential
PH	Processing heat
PIRB	Plumbing Industry Registration Board
PPP	Power purchasing parity
Prcng	Processing

Acronym	**Meaning**
Prsvng	Preserving
R&D	Research and development
ROI	Return of investment
RT	Rural throughput
SA	South Africa
SAPA	South Africa Poultry Association
SATIM	South African TIMES model
SBC	Small business corporations
SETA	Sector Education and Training Authority
SF	Sensitivity factor
SH	Space heating
SIC	Standard Industrial Classification of all Economic Activities
SP	Straight payback
TIMES	The integrated MARKAL-EFOM system
TPES	Total primary energy supply
US	United states
UNSTAT	United Nations Statistical Commission
VAT	Value added tax
WRC	Water Research Council
WW	Warm water
WWF	World Wide Fund for Nature
WZ	'Wirtschafts Zweige'

List of symbols

Δt: time step [min] 137

$\Delta T65°C$: The temperature difference between the hot water temperature at 65 °C and the inlet [K] 130

$\Delta T90°C$: Temperature difference between the hot water temperature at 90 °C and the inlet [K] 130

ΔT_{HW}: Temperature difference between the outlet and inlet hot water [K] 130

$\sum P_{tot/day}$: Total energy use of the CO_2 HP for the day[kWh/day] 136

C: Carbon dioxide emissions of a fuel type determined [kg CO_2/TJ] 141

CO_2Tax/tonne: Tax amount payable per tonne [R/tonne] 141

CO_2Tax: Total tax amount payable [R] 141

COP: Coefficient of performance of the CO_2 HP [-] 129

COP_c: Coefficient of performance of the chiller [-] 126

CV: Default calorific value [TJ / tonne] 141

CV_{fuel}: Calorific value of the fuel [kJ/kg] 109

E: Energy use [PJ] 48

E_{EHD}: Total electric head demand [PJ]. 49

$E_{THD,PH100°C}$:Total head demand for process heat with a temperature below 100 °C [PJ] 49

E_{THD}: Total thermal head demand [PJ] 49

Ɛ: the effectiveness of the heat exchanger [-] 107

f_1: Equipment erection cost factor [-] 142

f_2: Piping cost factor [-] 142

f_3 : Instrumentation cost factor [-] 142

f_4: Electrical cost factor [-] 142

f_5 : Buildings cost factor [-] 142

f_6: Utilities cost factor [-] 142

f_7: Storages cost factor [-] 142

f_8: Site development cost factor [-] 142

f_9: Ancillary buildings [-]. 142

FR_{HD}: Fraction heat demand for electricity [-]. 48

g: Gravity constant [m/s^2] 103

h_0: Stagnation enthalpy [kJ/kg] 103

$h_{AIR.IN}$: Enthalpy of the inlet air [kJ/kg] 130

hr: Number of hours the CO_2 HP runs [hr] 135

$hr_{HP,TOT,SUP/day}$: Total number of hours the CO_2 HP runs per day to supply the hot water [hr] 135

L: Length of the control volume [m] 104

$\dot{m}$: Mass flow [kg/s] 103

m: Mass of fuel used [tonne] 141

M: Mass of the storage capacity [kg] 137

$\dot{m}$: Water mass flow for a single CO_2 HP [kg/s] 132

Me: Methane emissions of a fuel type [kg CH_4/TJ] 141

$\dot{m}_{fuel}$: Mass flow of fuel [kg/s] 109

N: Nitrous Oxide emissions of a fuel type [kg NO_2/TJ] 141

N_{HP}: Number of CO_2 HP [-] 135

P: Energy use of the CO_2 HP [kWh/day] 136

P: Energy use of the heat pump or chiller [kW] 109

p: Static pressure [Pa] 103

PCE: Total physical equipment cost [R] 142

$PHD_{PH100°C}$: Percentage head demand for process heat with a temperature below 100 °C [%] 49

PIC: Total plant installation cost [R] 142

P_P: Power usage of the pump [W] 110

Q_c: Cooling capacity of the chiller [kW]. 126

Q_e: Rate of energy removed from the storage tank [kW] 137

Q_i: Rate of energy delivered to the storage tank [kW] 137

Q_{tl}: Rate of energy loss from the storage tank [kW] 137

R^2 : Coefficient of determination 126

t: times [s]. 104

T_0: Stagnation temperature [K]. 104

$T_{CW,IN}$: Cold-water inlet temperature [K] 130

T_s: Storage tank temperature [K] 137

$T_{s+\Delta t}$: New storage tank temperature after time interval Δt [K] 137

V: Velocity of the fluid [m/s] 104

List of subscripts

Chapter 1. Introduction

1.1 Problem and setting

The South African (SA) industrial sector is the largest energy user, accounting for more than one-third of the country's national energy usage. According to the Department of Energy South Africa (DoE SA, 2008), the industrial sector has the potential to achieve the largest energy savings by replacing older technologies with more advanced solutions and by employing best energy management practices. Figure 1 shows that SA's industrial sector has the highest energy and thermal demand, making up 37.8% and 23.8% of the total energy demand. The sector thus accounts for 80% (780 PJ of 974 PJ) of the thermal demand of SA. The implementation of an energy-efficient technology, such as industrial heat pumps (IHPs), may potentially reduce the thermal energy heat demand of this sector.

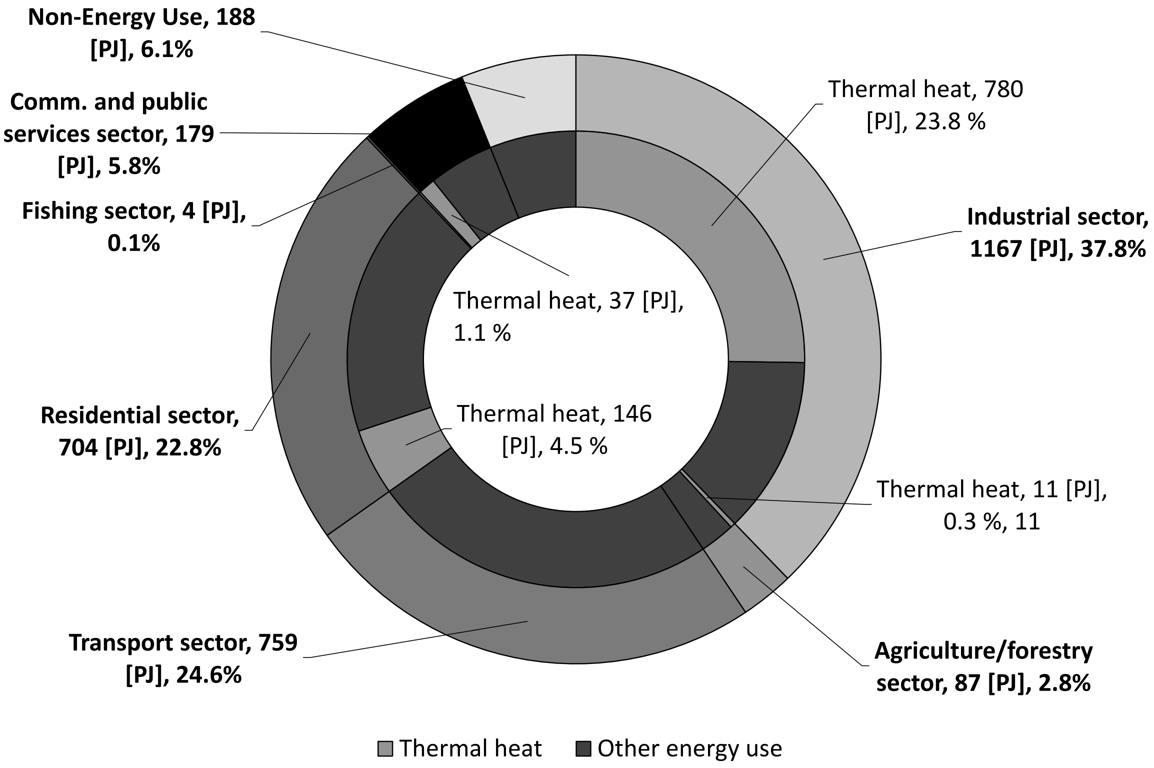

Figure 1: Pie chart indicating the percentage of energy use and heat demand for the various major sectors of SA in 2015. Source: Data from IEA (2017a)1; (DoE SA, 2016d);

According to IEA HPC Annex 35 (2014), heat pumps (HPs) play an increasingly important role in the world as a technology for improving energy efficiency and reducing CO_2 emissions. HPs can save up to

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[1] International Energy Association (IEA)

67% of the heating energy used for the residential, small business (Eskom, 2012) and the hospitality sectors (Eskom, 2015). Furthermore, HPs can typically reduce the CO_2 emissions of buildings by 50% and of the industrial sector by 5% (IEA HPC, 2008). HPs thus have the potential to reduce CO_2 by 1.8 billion metric tonnes of per year, which equates to nearly 8% of the total global CO_2 emissions (IEA HPC, 2008).

Worldwide, HPs are used mainly in residential buildings for space heating and domestic hot water, with the expectation to expand the technology to the industrial sector (IEA HPC Annex 35, 2014). Given that the industrial sector is a sizeable energy consumer, Zimny *et al.* (2015) also confirmed that the industrial sector is potentially a very important HP consumer.

However, there are various barriers to the implementation of IHPs; these include:

1. Lack of information

   The IEA HPC Annex 35 (2014) indicated that several good references are needed before a customer will be convinced to invest in HPs. For the SA industrial sector, only one example could be found of an installed HP at RCL Foods' Rainbow chicken division. The chicken division installed an ammonia HP at its Hammersdale operation in KwaZulu-Natal (de Bruyn, 2012). The HP, which replaced an electrode boiler that was used for site ablutions and washing, heats water to 55 °C. The company reported a saving of 300 kW based on the average water consumption with a straight payback of less than two years (de Bruyn, 2012).

2. Long payback periods

   When compared to gas and oil boilers, HPs have relatively high investment costs (IEA HPC Annex 35, 2014). For example, IHP cost between 450-500 €/kW and conventional steam boiler cost between 200 – 300 €/kW (Thermea, 2008). At the same time, companies expect low payback periods of less than two to three years for implementing a new technology (IEA HPC Annex 35, 2014).

3. Uncertainty of future energy prices

   Cagno *et al.* (2013) indicated a study by Velthuijsen (1995) which suggested that the uncertainties regarding future energy prices pose a barrier to investment. With an increase in boiler energy cost, the payback period of the HP reduces, which in turn increases the rate of the return on investment (ROI).

4. Profitability (low returns)

Trianni and Cagno (2012) found low returns on energy efficiency investments to be a barrier. They reasoned that low returns relate to uncertainty and risk. Greater uncertainties on the effective performance of the equipment might affect the profitability of an energy-efficient investment.

5. Lack of skilled installers and poor equipment quality

According to Goetzler *et al.* (2009), the French and Austrian HP market developed during the oil crisis from 1975 to 1985. However, after the boom, the market virtually disappeared due to a lack of skilled installers and poor equipment quality. The deficient performance and reliability of HPs were mainly a result of less experienced companies that began to enter the market during the oil crisis. The IEA HPC Annex 35 (2014) also indicated that, historically, technical barriers were mainly related to the availability of reliable HP components.

6. Low awareness of heat consumption

According to the IEA HPC Annex 35 (2014), the knowledge that most companies possess about their heating and cooling demands is limited. This lack of knowledge results in them using expensive and time-consuming metering to identify HP integration opportunities.

7. Lack of knowledge

The integration of HPs with industrial applications requires detailed knowledge of the process itself as well as the technology to be implemented. A limited number of installers and decision-makers have this combined knowledge to enable them to integrate an HP effectively (IEA HPC Annex 35, 2014).

8. Low operating temperature of HPs

According to IEA HPC Annex 35 (2014), a market barrier for IHPs in the industrial sector is the temperature limit of conventional HPs. Most HPs can deliver hot water temperatures of up to 60 °C (ASHRAE, 2015). This temperature is more in line with the requirements of the residential and commercial sectors. The IEA HPC Annex 35 (2014) indicated that the theoretical potential for HP increases significantly by developing energy-efficient HPs with heat sink temperatures of up to 100 °C.

A possible solution to the low operating temperature of HPs is the implementation of CO_2 HPs. CO_2, also referred to as R744, can deliver hot water up to a temperature between 90 °C(Mayekawa, 2013a) and 120 °C (Eikevik *et al.*, 2005; Engie, 2018). Furthermore, CO_2 HPs have various advantages over common refrigerants.

Table 1: Refrigerants for industrial vapour compression HPs. Source Arpagaus *et al.* (2016)

Type	Refrigerants	Description	Critical temperature (°C)	Critical pressure (MPa)	ODP	GWP	Toxicity	Flammability
Natural	R744	CO_2	31.1	7.38	0	1	Low	No
	R717	NH_3	132.5	11.33	0	0	Yes	Medium
	R718	Water	373.9	22.06	0	0	Low	No
Hydrocarbons	R600a	Isobutane	134.7	3.63	0	4	Low	High
	R601	Pentane	196.6	3.37	0	5	Low	High
	R1270	Propene	91.1	4.56	0	2	Low	High
	R290	Propane	96.7	4.25	0	3	Low	High
Hydrofluoro -carbons	R245fa	1, 1,2,2,3-Pentafluoropropane	154.0	3.65	0	950	Yes	No
	R134a	1, 1, 1,2-Tetrafluoroethane	101.06	4.06	0	1300	Low	No
	R410A	R32/R125 50/50 mixture	72.6	4.90	0	2088	Low	No
Hydrofluoroolefins	R1336mzz(Z)	1, 1, 1, 4, 4, 4-Hexafluoro-2-butene	171.3	2.90	0	2	Low	No
	R1334ze(E)	trans-1,3,3,3-Tetrafluoro-1- propene	109.4	3.64	0	<1	Low	Low
Hydrochloro -fluoroolefins	R1233zd(E)	1-chloro-3,3,3-Trifluoro-propene	166.5	3.62	0.00034	1	Low	No
	R1224yd(Z)	1-chloro-2 ,3,3,3-Tetrafluoro-propene	155.5	3.33	0.00012	<1	Low	No

Table 1 shows that all the natural refrigerants, which include CO_2, ammonia (R717), water (R718) and isobutane (R600a), have an Ozone depletion potential (ODP) of zero (0) and a global warming potential (GWP) of one and less. However, CO_2 is the only known natural non-toxic and non-flammable refrigerant (Mota-Babiloni *et al.*, 2015) that have commercial heat pump available (Mayekawa, 2017). Apart from the aforementioned environmental benefits of using CO_2, it also has some excellent thermo-physical properties. These properties include high specific heat, high thermal conductivity, high vapour viscosity, low liquid viscosity, and low surface tension (Cheng *et al.*, 2006).

CO_2 heat pumps is a trans critical cycle, with a large temperature glide on the heat sink thus making them ideal for water heating (Arpagaus *et al.*, 2018). This in contrasts with the classical heat pump circuit where the condenser is replaced by a gas cooler (Maina & Huan, 2015).

The disadvantage of CO_2 is the ineffective heat transfer to ambient conditions below its critical temperature and, therefore, CO_2 HPs have a transcritical cycle with high operating pressures. One of the challenges that design engineers face is that the operating pressure, which is typically five to 10 times higher than that with conventional refrigerants (Bansal, 2012), results in the need for more specialised or custom-designed components.

Despite the disadvantages, CO_2 HPs with simultaneous heating and cooling can achieve a combined coefficient of performance (COP) of 6.8 and provide hot water as high as 90 °C and chilled water as low as −9 °C (Mayekawa, 2013a). CO_2 HPs not only have the potential to reduce the industrial sector's dependence on electric heat but can also have several environmental advantages.

1.2 Purpose of this study

The purpose of this study is to estimate the potential impact of CO_2 HPs on the SA industrial sector. The study is divided into three main parts. The first part identifies from international studies the divisions, subdivision and processes that have the highest potential for the implementation of CO_2 HPs.

The second part of the study identifies the most suited industrial division and process for the integration of a CO_2 HP. For this, the theoretical heat demand below 100 °C is determined for 12 industrial divisions in SA. Although the CO_2 HP maximum temperature is at 110 °C, a temperature level of 100 °C was chosen specifically because as it is the closest available data. It is important to note that study focus was on various IHP that can reach 100°C. These IHP refrigerant include: R134a, R245fA, R717/R718 (Arpagaus *et al.*, 2018). To determine theoretic heat demand of CO_2 IHP, one needs to estimate the market penetration of the CO_2 IHP. The market penetration is not known to the author and is thus excluded from the study.

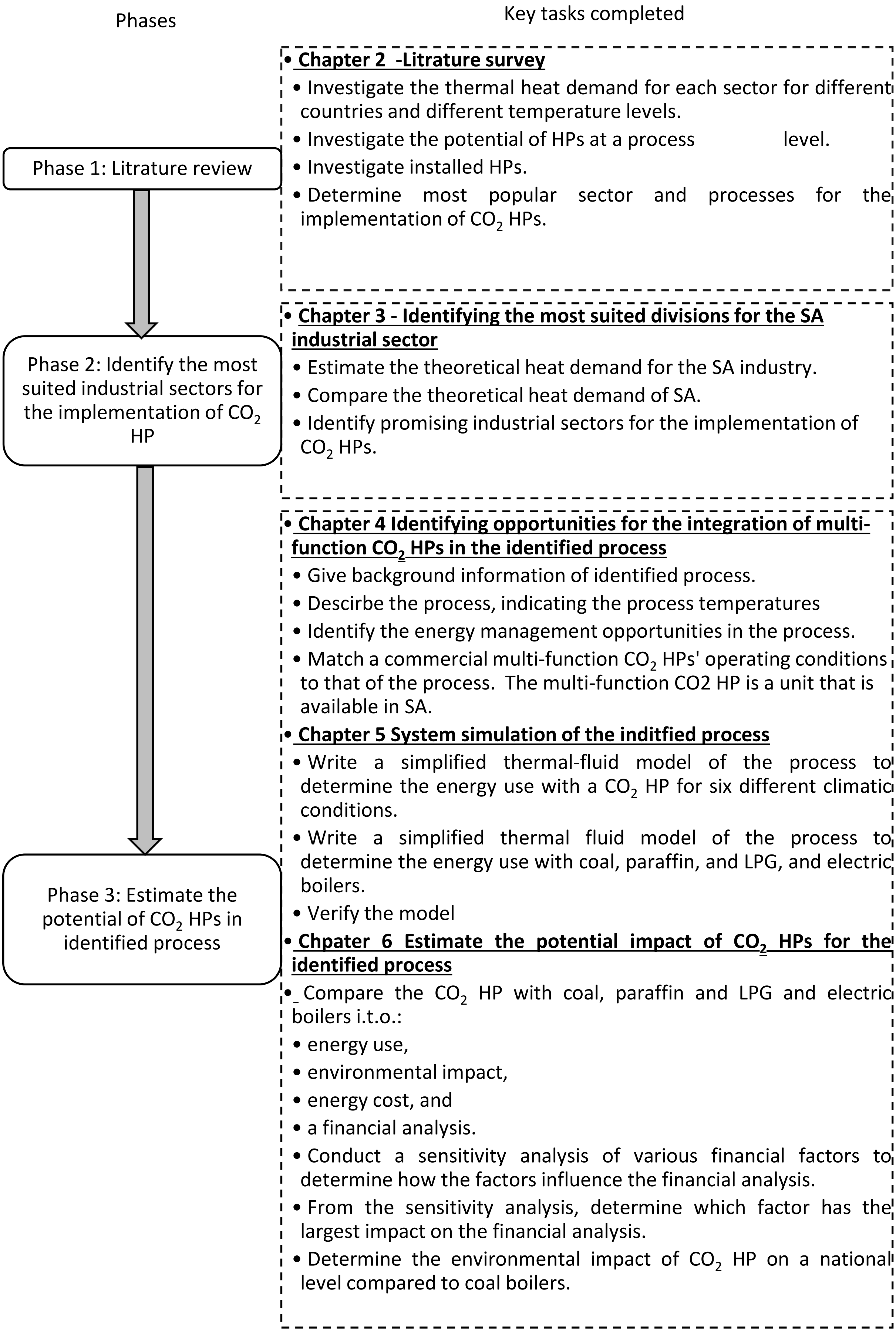
The information is then combined with the percentage gross value added (GVA) for the divisions and typical temperature ranges of various processes to determine the most promising industry. The investigation is then further refined by looking at the number of companies in the division and energy used per kilogram of a product to determine the most suitable process.

The final part of the study determines the impact of CO_2 HP for the identified process in SA. For this, a steady-state simulation is written to determine the techno-economic and environmental impact of the CO_2 HP. The CO_2 HP energy use, environmental impact, energy cost, and financial viability are compared to that of an electric and a steam boiler using coal, LPG and paraffin as fuel. For the financial analysis, the estimated total costing of the CO_2 HP will be done on the replacement of the current plant. Finally, an investigation is done to determine the potential environmental impact of CO_2 HPs if they were to be applied in an industrial process.

1.3 Method of investigation

The method of the investigation shown in

Figure 2 illustrates the composition of the distinct phases of the research approach. These are the literature review (phase 1), the identification of the most suited industrial divisions for the implementation of CO_2 HPs (phase 2), and the estimation of the potential of CO_2 HPs in the identified process.



- **Chapter 2 -Litrature survey**
- Investigate the thermal heat demand for each sector for different countries and different temperature levels.
- Investigate the potential of HPs at a process level.
- Investigate installed HPs.
- Determine most popular sector and processes for the implementation of CO$_2$ HPs.

- **Chapter 3 - Identifying the most suited divisions for the SA industrial sector**
- Estimate the theoretical heat demand for the SA industry.
- Compare the theoretical heat demand of SA.
- Identify promising industrial sectors for the implementation of CO$_2$ HPs.

- **Chapter 4 Identifying opportunities for the integration of multi-function CO$_2$ HPs in the identified process**
- Give background information of identified process.
- Descirbe the process, indicating the process temperatures
- Identify the energy management opportunities in the process.
- Match a commercial multi-function CO$_2$ HPs' operating conditions to that of the process. The multi-function CO2 HP is a unit that is available in SA.
- **Chapter 5 System simulation of the inditfied process**
- Write a simplified thermal-fluid model of the process to determine the energy use with a CO$_2$ HP for six different climatic conditions.
- Write a simplified thermal fluid model of the process to determine the energy use with coal, paraffin, and LPG, and electric boilers.
- Verify the model
- **Chpater 6 Estimate the potential impact of CO$_2$ HPs for the identified process**
- Compare the CO$_2$ HP with coal, paraffin and LPG and electric boilers i.t.o.:
- energy use,
- environmental impact,
- energy cost, and
- a financial analysis.
- Conduct a sensitivity analysis of various financial factors to determine how the factors influence the financial analysis.
- From the sensitivity analysis, determine which factor has the largest impact on the financial analysis.
- Determine the environmental impact of CO$_2$ HP on a national level compared to coal boilers.

Figure 2: Overview of the PhD research methodology

1.4 Delineation and limitations of the thesis

The following limitations apply for this thesis:

1. To determine the most industrial division and process for the integration of a CO_2 HP, the author estimated the theoretical heat demand of below 100°C. Currently, there are other IHP can also reach 100°C temperature, including R134a, R245fA, R717/R718 (Arpagaus *et al.*, 2018). The estimated values can thus be used in a wider study where the other refrigerants are also included.
2. A multi-function CO_2 HP that is available in South Africa will be matched to a single process in the SA.
3. Due to the high cost of a single CO_2 HP which exceeds R 1 million, the CO_2 HP was not implemented in a demonstration plant. The estimated savings are thus not validated against actual measurements on a plant.
4. The actual metering of the mass flow and water temperatures of the investigated is expensive and time-consuming. Thus, no actual measurement were taken on the plant and the data is only sourced from literature.
5. For the financial investigation of the CO_2 HP, it is assumed that the CO_2 HP and storage tanks replace the current installed technology. It is also assumed that all energy and equipment prices have value added tax (VAT) included.

1.5 Statement of originality

The original contributions can be summarised as follows:

1. A thorough investigation is conducted of the heat demand of various SA industrial sectors below 100°C. The investigation identifies in which divisions CO_2 HPs have the largest impact. The data is then further analysed to determine which division and process is the most suitable for the integration of a multi-function CO_2 HP.
2. This study quantifies the contribution of CO_2 HPs towards reducing the country's peak demand and electricity usage for one selected SA industrial division.

Chapter 2. Literature survey

2.1 Introduction

Kivevele and Huan (2013) are the only South African authors that published an article on the use of IHPs. They indicated that heat pump drying (HPD) is a technology by which materials can be dried at low temperatures and in an oxygen-free atmosphere. From their analysis, HPD had the highest specific moisture extraction rate when compared with hot air drying and vacuum drying. They also found that IHPs had the highest drying efficiency and that HPD uses less energy than standard drying methods. Additionally, the HPD capital cost was lower than that of vacuum drying, with the running cost also being the lowest. They gave no specific data on the economic analysis. However, according to a study by Meyer and Greyvenstein (1992) (as cited by Kivevele and Huan (2013)), the life cycle cost of an electrical heater and diesel engine were three and four times higher, respectively, than that of HPD systems.

Consequently, the literature review in this chapter investigates international sources on the application of HPs in industry. Firstly, the literature research focuses on determining the potential divisions and processes in which CO_2 HPS can be applied. Secondly, the literature research focuses on international studies to determine where CO_2HPs, as well as IHPs in general, have been implemented in industry. Only eight examples of CO_2 HPs in industry have been found. The search has thus been winded to include other instanced of IHP implementation to better understand where CO_2 HP can potentially be implemented.

The literature is divided into five main sections. The first section gives a brief overview of standard industrial codes that are used for this research. The standard industrial codes are vital, as they provide an overview of the sectors and their associated naming conventions that are used in this study.

In the literature, various authors often refer to top-down and bottom-up energy modelling. Hence, the second section presents a summary of bottom-up and top-down energy studies.

Thirdly, various international studies are summarised that show the potential heat demand of IHPs for various industrial divisions. The maximum operating temperature level is capped at 100 °C, as this is the closest available data to the operating conditions of the CO_2 HP. This information is used to determine which industrial sector has the highest potential for the integration of CO_2 HP. The fourth section provides an in-depth examination into which process has the highest potential for implementing CO_2 HP. The fifth section determines the international implementation of IHPs.

2.2 Standard industrial codes

The literature that is reviewed for this study often refers to various industrial sectors. However, the authors rarely indicate which classification system and associated classification numbering they used. Furthermore, the various classifications differ between systems and editions. In the literature, the various authors refer to five various standard industrial codes, namely:

1) The International Standard Industrial Classification of all Economic Activities (ISIC) (rev. 4),
2) South Africa's Standard Industrial Classification of all Economic Activities (SIC),
3) The European Classification of Economic Activities (NACE),
4) The German industrial classification or "Klassifikation der Wirtschafts Zweige" (WZ), and
5) The North American Industry Classification System (NAICS).

The next few paragraphs give a brief overview of each of the standards, which includes a discussion of the background and latest version of each standard.

The ISIC is the international reference classification of productive activities. Its primary purpose is to provide a set of activity categories that can be utilised for the collection and reporting of statistics according to such activities (United Nations, 2008). Since the adoption of the original version of ISIC in 1948, most countries around the world have used ISIC as their national activity classifications or have developed national classifications derived from ISIC. ISIC is therefore used to guide countries in developing national activity classifications and has become an essential tool for comparing statistical data on economic activities at an international level (United Nations, 2008).

SA uses the SIC to classify the various economic activities and is currently in its seventh edition. The SIC ver. 7 is based on the ISIC rev. 4, which was published in 2008 with several variations for local conditions (Statistics South Africa, 2012).

NACE, which is published by the European Union (2008), is the statistical classification of economic activities in the European community and is the subject of legislation at the European Union level 2. The classification system imposes the use of the classification uniformly within all the member states. The current NACE rev. 2 is the outcome of a significant revision of the integrated international system of economic classifications which took place between 2000 and 2007. NACE rev. 2 has been created based on ISIC rev. 4 and adapted for European circumstances by a working group of experts on statistical classifications from the member states, candidate countries, and European Free Trade Association countries, with the support and guidance of the classification section at Eurostat.

The German Classification of Economic Activities Statistisches Bundesamt (2008) issue 2008, or WZ 2008, was developed under the extensive participation of data users and data producers in administration, economy, research, and society. It provides a basis for consistent classification of economic activities of enterprises, local units, and other statistical units in all official statistics. It respects the requirements of the NACE rev. 2, which is based on the ISIC rev. 4 of the United Nations.

The NAICS (2017) represents an ongoing cooperative effort among Statistics Canada, Mexico's Instituto Nacional de Estadística y Geografía (INEGI), and the Economic Classification Policy Committee (ECPC) of the United States. The NAICS is unique among industry classifications in that it is constructed within a single conceptual framework. Although NAICS differs from other industry classification systems, the three countries continue to strive to create a system that does not cross two-digit boundaries of the United Nations' ISIC. The NAICS is currently in its fifth version and is revised every five years.

The ISIC rev. 4 system is henceforth used for the purposes of this study. The ISIC consists of a coherent and consistent classification structure of economic activities based on a set of internationally agreed-upon concepts, definitions, principles, and classification rules (United Nations, 2008). These economic activities are subdivided in a hierarchical, four-level structure of mutually exclusive categories. The categories at the highest level are called sections, which are coded alphabetically and intended to facilitate economic analysis. The sections subdivide the entire spectrum of productive activities into broad groupings, such as section A "Agriculture, forestry and fishing", section C "Manufacturing", and section F "Construction". The classification is then organised successively into more detailed categories, which are numerically coded according to two-digit divisions, three-digit groups, and, at the greatest level of detail, four-digit classes (United Nations, 2008).

In this thesis, the sections are referred to as to sectors, the two digits as divisions and the three- to four-digit codes as subdivisions. For example, the two-digit ISIC code 10, which is the food divisions and the ISIC code 1071, is the manufacturing of bakery products for the food subdivision.

The literature research is based on the industrial sectors as defined by the IEA (2016). According to the IEA (2016), the industrial sector is defined as mining (excluding fuels) and quarrying (ISIC code 07, 08, 99; ISIC code C), manufacturing, and construction. However, some authors extended their research to various other divisions, for example, agriculture, and forestry, and water collection, treatment, and supply. Consequently, these sectors and divisions are included in this study. Furthermore, the various authors used various standards for the naming of the sectors and divisions. These differences might make it difficult to make exact conclusions from the multiple sources for a specific sector or division. In an attempt to identify the various sectors, divisions, and subdivisions in which CO_2 HPs can be applied within the context of this study, a consistent naming convention was used, as shown in Table 2.

Table 2: Industrial sectors included in the investigation of HP. Source: United Nations (2008); IEA (2016)

ISIC code	Abbreviated description	Original ISIC rev. 4 description
A	Agriculture, forestry, and fishing sector	Agriculture, forestry, and fishing (ISIC Division 01-03)
01	Agricultural	Crop and animal production, hunting, and related service activities
02	Forestry and logging	Forestry and logging
03	Fishing and aquaculture	Fishing and aquaculture
B	Mining and quarrying sector	Mining and quarrying (ISIC Division 05-09)
05	Mining of coal and lignite	Mining of coal and lignite
06	Extraction of crude petroleum and natural gas	Extraction of crude petroleum and natural gas
07	Mining of metal ores	Mining of metal ores
08	Other mining and quarrying	Other mining and quarrying
09	Mining support service activities	Mining support service activities
C	Manufacturing sector	Manufacturing (ISIC Division 10-33)
10	Food	Manufacture of food products
11	Beverages	Manufacture of beverages
12	Tobacco products	Manufacture of tobacco products
13	Textiles	Manufacture of textiles
14	Wearing apparel	Manufacture of wearing apparel
15	Leather and related products	Manufacture of leather and related products
16	Wood and wood products	Manufacture of wood and products of wood and cork, except furniture; manufacture of articles of straw and plaiting materials
17	Paper and paper products	Manufacture of paper and paper products
18	Printing and reproduction of recorded media	Printing and reproduction of recorded media
19	Coke and refined petroleum products	Manufacture of coke and refined petroleum products
20	Chemicals and chemical products	Manufacture of chemicals and chemical products
21	Basic pharmaceutical products and preparations	Manufacture of basic pharmaceutical products and pharmaceutical preparations
22	Rubber and plastics products	Manufacture of rubber and plastics products
23	Other non-metallic mineral products	Manufacture of other non-metallic mineral products
24	Basic metals	Manufacture of basic metals

ISIC code	Abbreviated description	Original ISIC rev. 4 description
25	Fabricated metal products	Manufacture of fabricated metal products, except machinery and equipment
26	Computer, electronic, and optical products	Manufacture of computer, electronic, and optical products
27	Electrical equipment	Manufacture of electrical equipment
28	Machinery and equipment n.e.c.	Manufacture of machinery and equipment n.e.c.
29	Motor vehicles, trailers, and semi-trailers	Manufacture of motor vehicles, trailers, and semi-trailers
30	Other transport equipment	Manufacture of other transport equipment
31	Furniture	Manufacture of furniture
32	Other manufacturing	Other manufacturing
33	Repair and installation of machinery and equipment	Repair and installation of machinery and equipment
E	Water supply, sewerage, and waste management sector.	Water supply, sewerage, waste management, and remediation activities.
36	Water collection, treatment, and supply	Water collection, treatment, and supply
37	Sewerage	Sewerage
38	Waste collection, treatment, and disposal activities; materials recovery	Waste collection, treatment, and disposal activities; materials recovery
39	Remediation activities and other waste management services	Remediation activities and other waste management services
F	Construction sector	Construction
41	Construction of buildings	Construction of buildings
42	Civil engineering	Civil engineering
43	Specialised construction activities	Specialised construction activities

Finally, the various authors had different definitions for the non-specified division, also referred to as the other sector. The authors did not explicitly reference in their study what the definition was for the non-specified industrial division. The meaning of the non-specified industrial division thus depends on which sectors and divisions the authors investigated. For example, in some cases, one author would investigate the construction division specifically, while another author would categorise this sector as part of the non-specified division. For completeness, the non-specified division is included in this study, but no significant conclusions can be made from analysing the non-specified industrial division.

The next section provides an overview of top-down and bottom-up models.

2.3 Bottom-up versus top-down energy modelling

In the literature study, various authors refer to top-down and bottom-up energy modelling. In this section, a brief overview is given of the two techniques. The two methods are discussed briefly, highlighting the main differences between them. The methods are then further elaborated by giving information on the underlying approaches. Finally, the similarities between the approaches are discussed.

According to Johnston (2003), the two principal methods of forecasting energy use are top-down and bottom-up methods. The main difference between these two methods is the perspective that is adopted. Top-down methods begin with aggregate information and then the information is disaggregated as far as possible. Since top-down methods begin with aggregate data, they provide a comprehensive modelling approach. Bottom-up methods, on the other hand, begin with detailed disaggregated information and this information is aggregated as far as possible. Since bottom-up approaches only tend to model part of the whole picture, they lack the comprehensiveness of top-down approaches.

Top-down methods take a macroeconomic approach to modelling energy supply and energy demand (Johnston, 2003). Kavgic *et al.* (2010) indicated that the modelling approach works at an aggregated level, typically aimed at fitting a historical time series of national energy consumption. Top-down models focus on the interaction between the energy sector and the economy at large and can be categorised broadly as econometric and technological top-down models (Kavgic *et al.*, 2010).

The econometric top-down models express the connection between the energy sector and economic output. They are based primarily on energy use in that they are related to economic variables such as fuel prices, income, and gross domestic product (GDP) (Kavgic *et al.*, 2010). According to the Massachusetts Institute of Technology (MIT, 1997), as cited by Kavgic *et al.* (2010), econometric top-down models can also include general climatic conditions, such as population-weighted temperature, for a nation. As such, the econometric top-down models often lack details on current and future technological options, as they emphasise the macroeconomic trends and relationships observed in the past. For example, they do not focus on the individual physical factors in a steam plant that can influence energy demand.

The technological top-down models include a range of technical factors that influence energy use. These include saturation effects, technological progress, and structural change (Kavgic *et al.*, 2010). However, these factors also tend to be modelled using econometric equations rather than being described explicitly within the model (Johnston, 2003).

For top-down models, assumptions are made about the econometrically based input data, for instance GDP growth, income, and fuel price elasticities. These assumptions are subsequently translated into a change in the demand for energy within different sectors of the economy. These changes in energy demand then move down through the system, altering the mix of energy-generating technologies that are available within the model until the energy demand and supply balance. Finally, the resultant mix of energy-using technologies is used to determine the energy use and CO_2 emissions attributable to each sector of the economy (Johnston, 2003).

Top-down energy models include computational general equilibrium models, econometric models, input-output models, and system dynamics models that treat the energy system as a part of the macro-economy (Herbst *et al.*, 2012). Top-down models tend to be developed and used by economists and public administrations (Herbst *et al.*, 2012).

Bottom-up modelling methods take a disaggregated approach to modelling energy supply and energy demand (Johnston, 2003). Bottom-up models are generally constructed and used by engineers, natural scientists, and energy supply companies (Herbst *et al.*, 2012). The modelling method focuses on the energy sector alone and tends to use highly disaggregated physically-based engineering-type models to model the energy demand and supply sectors in detail (Johnston, 2003). Bottom-up methods are built up from data on a hierarchy of disaggregated components that are then combined according to some estimate for their respective individual impact on energy usage (Kavgic *et al.*, 2010). The data input required for these models consists mainly of quantitative data on physically measurable variables, such as the thermal performance of a wall or the efficiency of a space heating system (Johnston, 2003). Johnston (2003) indicated that it is vital to note that economic variables, such as income and fuel prices, are not explicitly modelled within bottom-up methods. Bottom-up methods thus need extensive databases of empirical data to support the description of each component (Shorrock & Dunster, 1997).

Although top-down and bottom-up methods represent two alternative approaches to modelling, there is a degree of similarity between them. First of all, they are capable of operating at the same level of disaggregation and, secondly, both make use of the same facts but describe and use them in different ways (Johnston, 2003).

The next section discusses the potential of IHP based on heat demand.

2.4 The potential heat demand for IHPs for various industrial divisions

2.4.1 Introduction

Only a limited number of publications illustrates the potential heat demand of IHPs on a country or regional level. In particular, the potential of IHPs was investigated by Arpagaus *et al.* (2018), Wolf (2017), Wolf *et al.* (2014), and Lambauer *et al.* (2008). The various authors specifically investigated the theoretical potential of IHP for several temperature levels and divisions for Germany, Switzerland, France, the United States, and Europe. The literature review below is grouped according to the countries and regions. The grouping was done as such because Germany was investigated by Arpagaus *et al.* (2018), Lambauer *et al.* (2008), Wolf *et al.* (2014), and Wolf (2017), and Arpagaus *et al.* (2018) summarised the potential of IHPs for Switzerland, France, the United States, and Europe. From the investigations, it is possible to determine which divisions show the largest potential for IHPs. The articles did not investigate the theoretical potential of CO_2 HPs but of IHPs in general. The investigation was therefore limited to a maximum temperature of 100 °C, given that most of the authors provided data for temperature ranges of up to 100 °C. This temperature is close to the maximum operating temperature of the CO_2 HPs. The investigation excluded space heating, as this is not in general applicable for SA.

The articles are summarised by considering the divisions, showing the largest potential for CO_2 HPs ,and the potential saving obtainable. The publications are also summarised in terms of the methodologies used and the quantified potentials. Furthermore, the most popular divisions are then identified by using a frequency analysis of the top three divisions. Finally, this section concludes by naming the existing knowledge gaps that have been identified.

2.4.2 The potential heat demand for CO_2 HPs in Germany by Wolf (2017)

Lambauer *et al.* (2008), Wolf *et al.* (2014), and Wolf (2017) investigated the potential of IHPs in Germany. To simplify the analysis, the investigation only shows the latest work by Wolf (2017). Wolf (2017) performed a mixed top-down and bottom-up approach to determine the potential of IHPs in Germany. The investigation looked at the theoretical, technical, economic, and CO_2 avoidance potential of HPs.

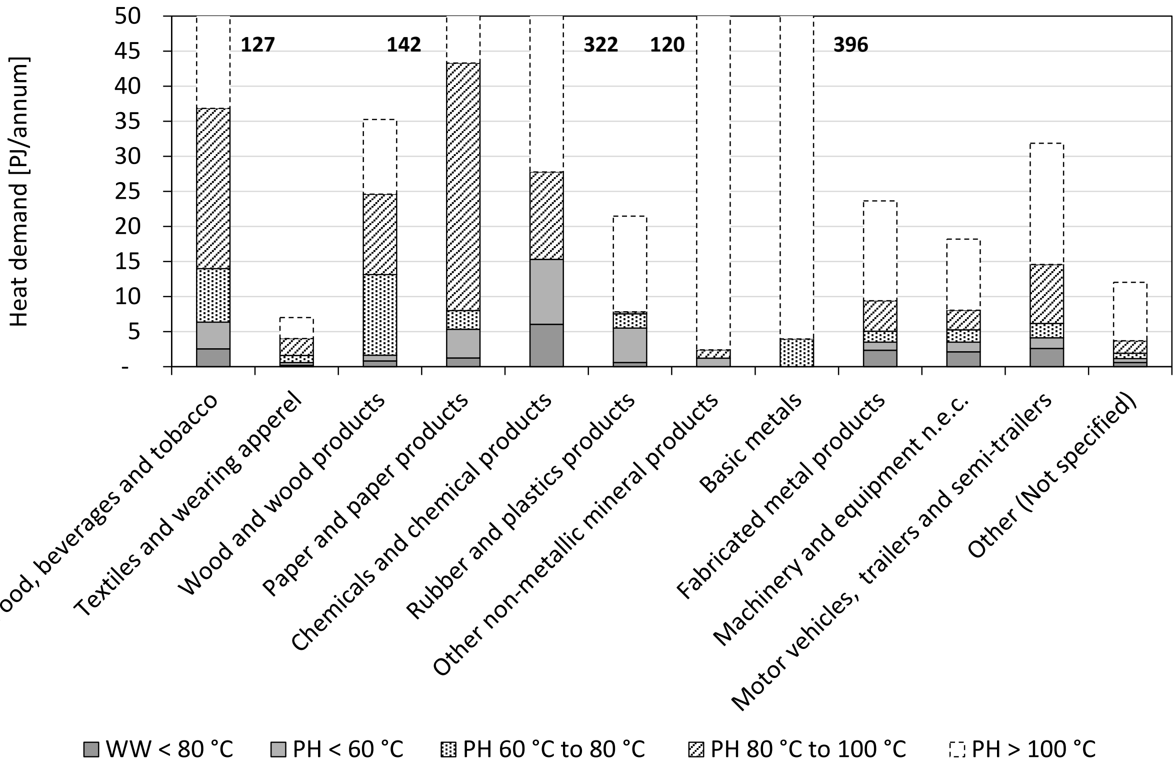


Figure 3: Potential of IHP for selected industrial divisions in Germany[2]. Source: Data from Wolf (2017);

From Figure 3 one can observe that Wolf (2017) investigated 12 industrial processes with temperatures of up to 100 °C, ranging from the food, beverage, and tobacco division to the basic metals division. From the data, the highest three potentials for temperatures below 100 °C were paper and paper products; food, beverages, and tobacco; and chemical and chemical products. For the paper and paper products division, the total heat demand of 43 PJ/annum] is available below 100 °C. The value represents 3.2% of the total industrial heat demand for Germany. The total heat demand available between 60 °C and 100 °C is 38 PJ/annum]. The value represents 88% for the available warm water (WW) and processing heat (PH).

From Figure 3, one can determine that at least a 167 PJ (14%) higher heat demand is available for the IHPs with an operating temperature of 100 °C than those of 60 °C. There is thus a modest increase in the available heat demand for IHPs. The data shown in Figure 3 excludes space heating, as this does not apply to South African conditions.

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[2] SH -Space heating

WW –Warm water

PH – Process heating

Table 3: Result summary of the potential analysis for the application of IHPs in Germany. Source: (Wolf, 2017)

Potential category	Description	Theoretical potential	Technical potential	Economic potential
Heat generation	Absolute [PJ]	658	311	45
	Relative to heat demand of the industrial sector	49.3%	23.3%	3.4%
Energy savings	Absolute [PJ]		225	37
	Relative to the energy demand of the industrial sector		8.9%	1.5%
CO_2 avoidance potential	Absolute [Mt CO_2]		8.2	2.7
	Relative to the CO_2 produced by the industrial sector		3.2%	1.1%

From Table 3, one can observe that Wolf (2017) found the economic potential for the application of IHPs relative to the industrial sector to be 3.4% for heat generation and 1.5% for energy saving. The economic CO_2 avoidance potential is 1.1%. Thus, although the percentage of economic potential seems small in terms of the heat demand of the industrial sector, the absolute economic potential is still a reasonable number.

2.4.3 The potential heat demand for IHPs in Switzerland by Arpagaus *et al.* (2018)

Arpagaus *et al.* (2018) summarised the potential of IHPs for Switzerland. In total, there were 12 industrial processes, ranging from the chemical and petrochemical to the energy and water division. For the Swiss industrial sector, the process heat demand accounts for about 54% of the total heat demand (84.9 PJ of 156 PJ in 2015). From Figure 4, one can observe that the author divided the process heat demand for the industrial sector between space heating, hot water, and process heat. According to Rieberer (2015) (as referenced by Arpagaus *et al.* (2018)), in general, process heat is supplied above 80 °C. The author gave no further detail on various temperature scales for process heat. Arpagaus *et al.* (2018) also gave a combined value for space heating and hot water. The space heating could not be separated from the hot water, and these values were consequently ignored for the investigation.

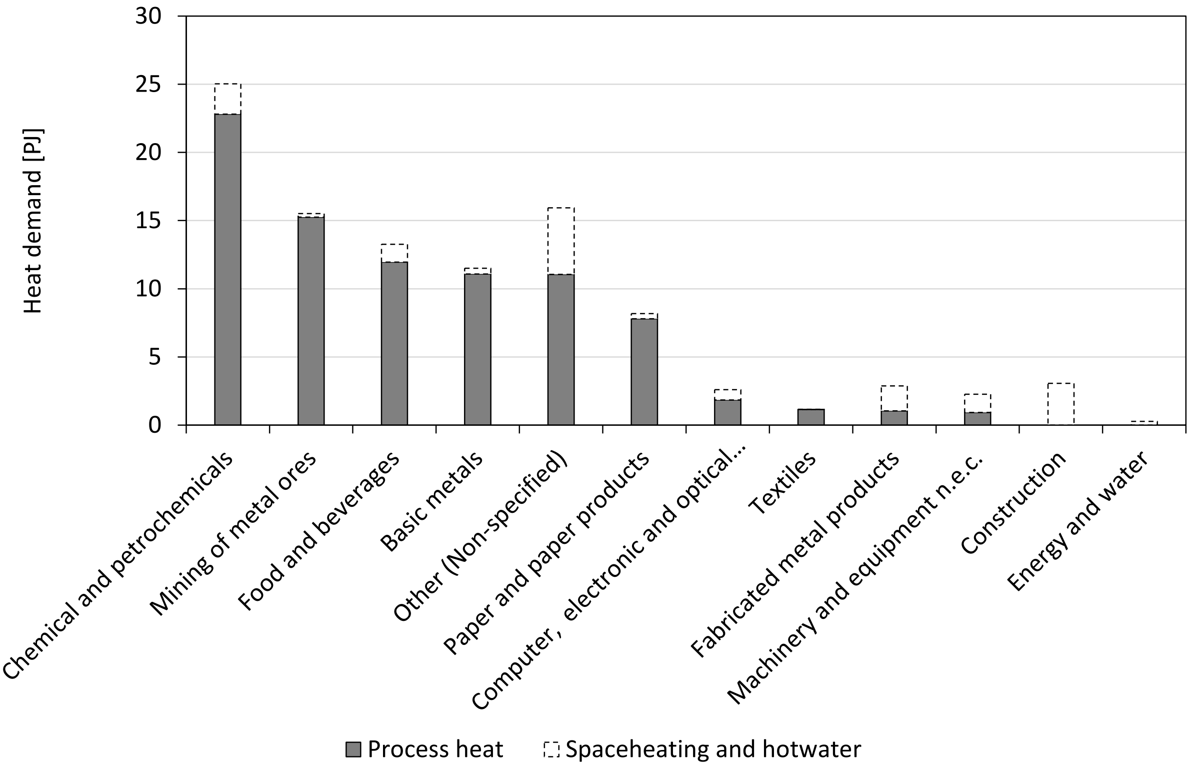

Figure 4: Theoretical potential of IHP for selected industrial divisions in Switzerland. Source: Adopted from Arpagaus *et al.* (2018)

Arpagaus *et al.* (2018) indicated that the total process heat demand is about 54% of the total heat demand; thus 84.9 PJ/annum] of the 159 PJ/annum]). The three divisions with the largest potential heat demand were the chemical and petrochemical division, mining and metal ores division, and the food and beverages division. The chemical and petrochemical division had a total heat demand of 22.81 PJ/annum] available, which is equal to 15% of the total heat demand in Switzerland.

Arpagaus *et al.* (2018) indicated in the Swiss industrial sector that process heat accounts for about 54% of the total heat demand (84.9 PJ of 156 PJ in 2015). The author gave no information on whether a top-down or bottom-up approach was used and no information on CO_2 avoidance potential.

2.4.4 Potential of IHPs in France by Arpagaus *et al.* (2018)

Arpagaus *et al.* (2018) originally showed the process heat demand in France between 60 °C and 140 °C with three temperature scales. They estimated the total heat demand between 60 °C and 140 °C as 119 PJ/annum] in 2009. However, no detail was given on the total energy demand of France and the heat demand below 60 °C.

As can be seen in Figure 5, in total, six industrial divisions were investigated, ranging from the paper and pulp products division to the transport equipment division with a maximum temperature of 140 °C. The analysis showed that the theoretical potential for high-temperature IHPs is around

46.3 PJ/annum] for temperatures below 100 °C. For process temperatures of 60 °C to 80 °C, the theoretical potential is about 23.2 PJ/annum].

The largest potential for IHPs up to 100 °C was for the food and beverage, basic metals, and the paper and paper products division. The food and beverages division had a total heat demand of 17.4 PJ/annum] available below 100 °C. The mining of metal ores division had a total of 5.1 PJ/annum] available, while the available heat demand for paper and paper products was 5.1 PJ/annum].

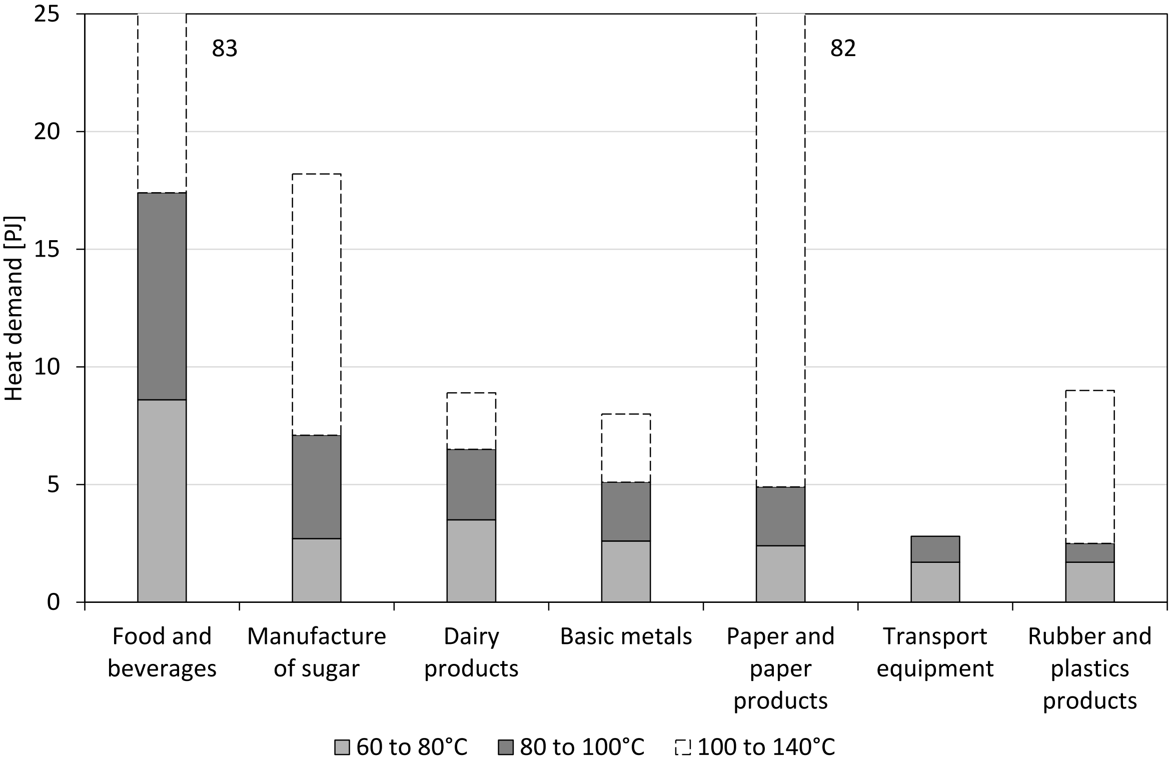

Figure 5: Theoretical potential of IHP for selected industrial divisions in France. Source: Adopted from Arpagaus *et al.* (2018)

2.4.5 The potential of IHPs for the United States by Arpagaus *et al.* (2018)

The thermal heat demand of the United States was originally investigated for temperatures of up to 200 °C for five industrial divisions (Figure 6). The divisions ranged from the food to the basic metals division. For process temperatures of 40 °C to 60 °C, the theoretical potential is around 140.4 PJ, which is mainly found in the food division. No detail was given for the total heat demand. By increasing the temperature from 60 °C to 100 °C, the theoretical potential heat demand increased by 243.3 PJ, which is 1.74 times the heat demand between 40 °C and 60 °C. For temperatures of up to 100 °C, the theoretical potential is found in the food division and the non-specified division.

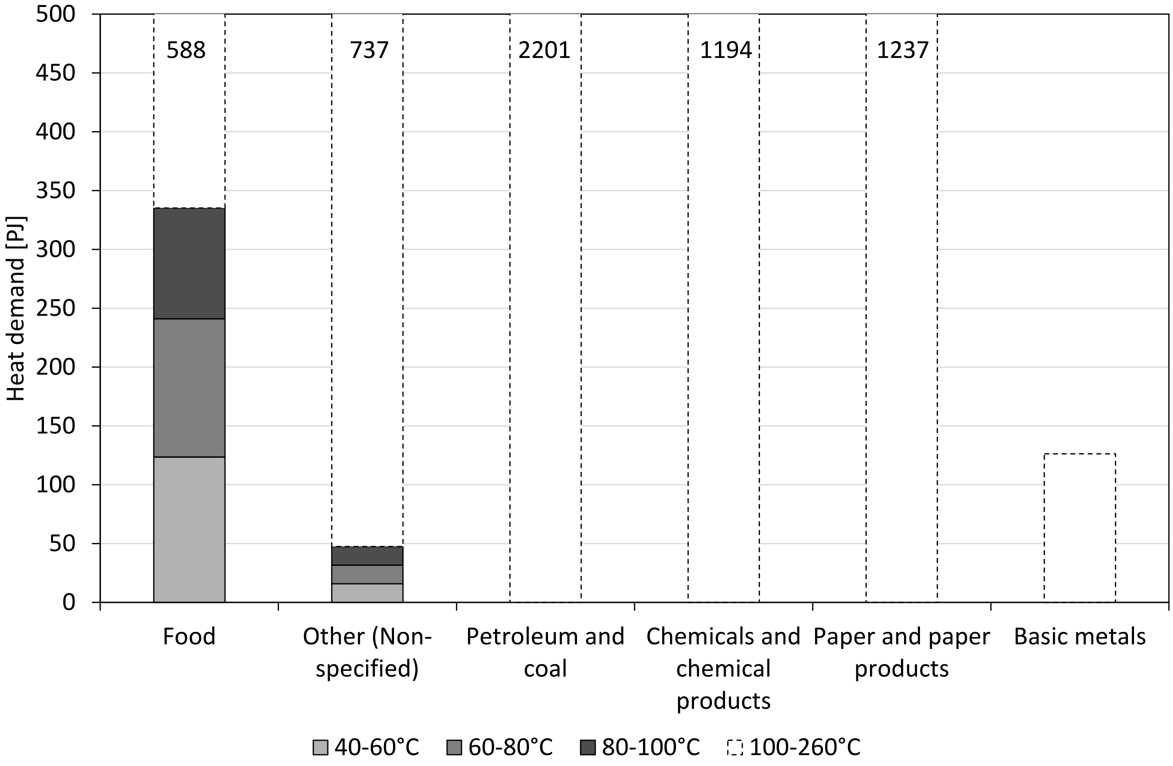

Figure 6: Theoretical potential of IHP for selected industrial divisions in the United States of America. Source: Data from Arpagaus *et al.* (2018)

2.4.6 Potential of IHPs for Europe by Arpagaus *et al.* (2018)

Arpagaus *et al.* (2018) originally showed the process heat demand in France for temperatures between 60 °C and 140 °C with three temperature scales. They estimated that the total heat demand below 150 °C was 626 PJ/annum] in 2009. According to Arpagaus *et al.* (2018), Nellissen and Wolf (2015) estimated the technical potential of IHPs in Europe as 626 PJ for temperatures up to 150 °C in 2012. However, no detail was given on the heat demand below 80 °C.

Figure 7 shows the data only up to 140 °C. In total, eight industrial divisions were investigated, ranging from the non-specified division to the textile division. The analysis showed that the theoretical potential for high-temperature IHPs is around 140 PJ/annum for temperatures below 100 °C. The space heating and hot water could not be separated, and they were thus ignored in the analysis. However, the total heat demand for temperature level was 370 PJ/annum.

The largest potential for IHPs up to 100 °C was for the paper and paper products, food and tobacco, and the wood and wood products divisions. The paper and paper products division had a total heat demand of 36.1 PJ/annum available below 100 °C. The food and tobacco divisions had a total of 36.1 PJ/annum available, while the wood and wood products' available heat demand was 20.4 PJ/annum.

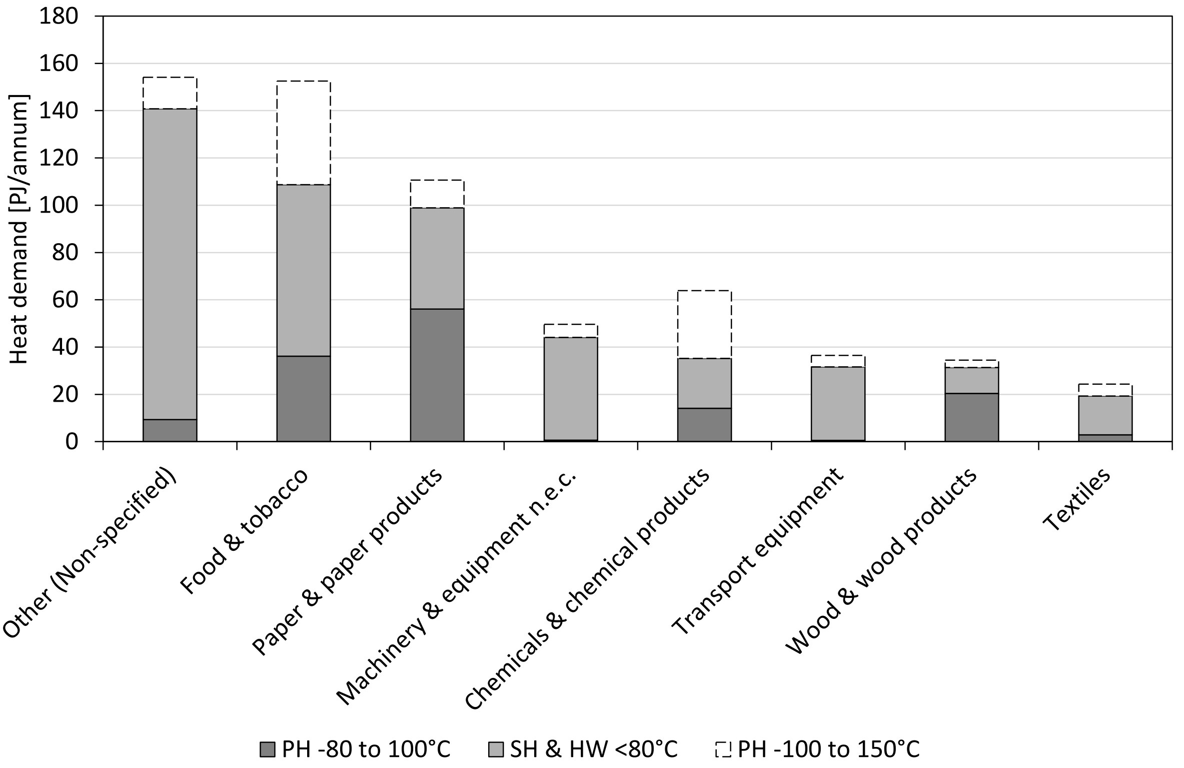

Figure 7: Theoretical potential of IHP for selected industrial divisions for Europe. Source: Adopted from Arpagaus *et al.* (2018)

2.4.7 Section summary

From the literature review, one can see that only a few authors investigated the potential application of IHP technology in the industrial division. Table 4 shows that the investigations by Wolf (2017), Wolf *et al.* (2014), and Arpagaus *et al.* (2018) for Switzerland and Germany are based on comparably new data.

Table 4: Overview of the countries and industrial division for the various evaluated potential studies.

Source	**Year**	**Countries**[3]
Wolf (2017)	2013	Germany (DEU)
Arpagaus *et al.* (2018)	2015	Switzerland (CHE)
Arpagaus *et al.* (2018)	2009	France (FRA)
Arpagaus *et al.* (2018)	2008	United States of America (USA)
Arpagaus *et al.* (2018)	2012	EUROPE (33 Countries)

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[3] Country codes are given in according to the ISO 3166 2014 ALPHA-3 Notation.

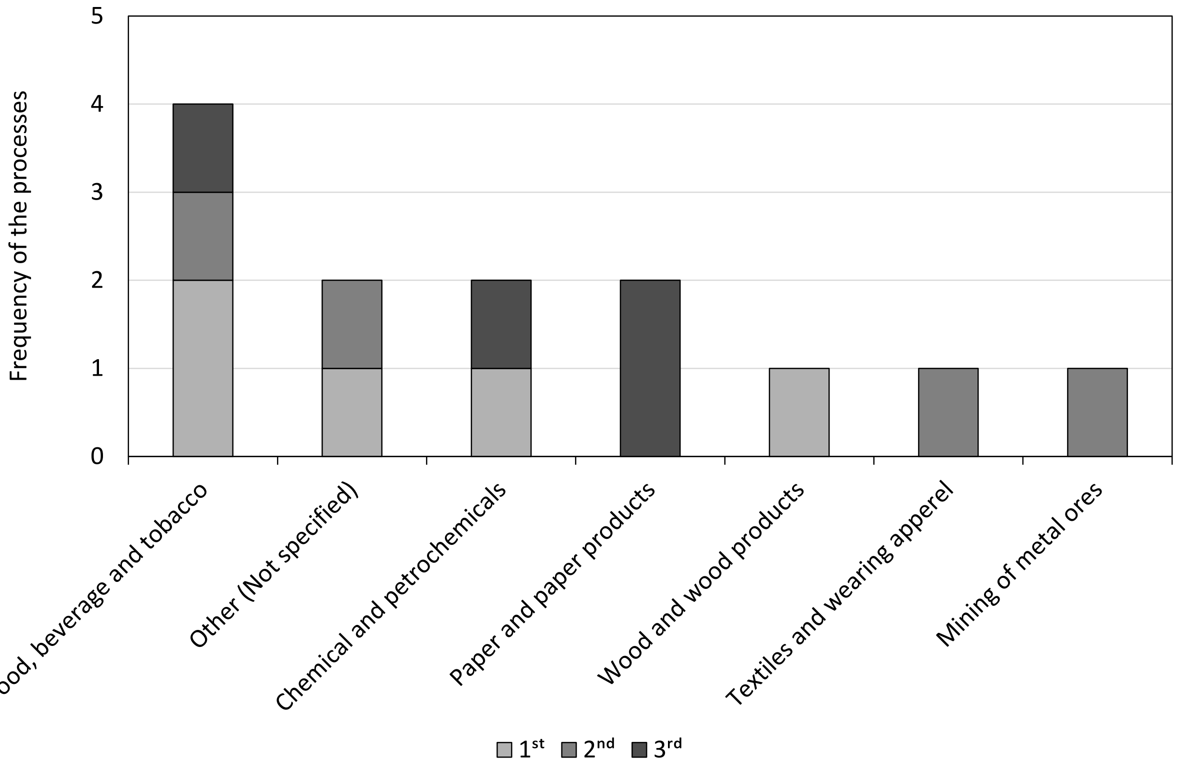


Figure 8: Frequency diagram of the highest technical potential for IHPs. Source: Data from Arpagaus *et al.* (2018); Wolf (2017);

Figure 8 shows the divisions that had the highest frequency for the various potential studies. The data was combined by conducting a frequency analysis of the divisions with the highest potential for the four countries and 32 European countries investigated by Arpagaus *et al.* (2018) and Wolf (2017). Figure 8 shows that the food, beverage, and tobacco division had the highest frequency of four in total. The second-highest division was the other non-specified division, chemicals and petrochemicals division and the paper and paper products division. These divisions thus have the highest potential for IHPs. At this stage, none of the articles found investigated the potential of IHPs in SA. In the next section, more detail is given on potential studies of processes for the various industrial divisions.

2.5 Potential of IHPs for specific industrial processes

2.5.1 Introduction

Three authors reported the potential of IHPs for specific industrial subdivisions in the literature, namely the IEA HPC Annex 21 (1995), Heat Pump and Thermal Storage Technology Centre of Japan (HPTCJ, 2010), and Hita *et al.* (2011). The author could not find articles that focused primarily on the potential of CO_2 HPs for a specific industrial process. Thus, the investigation was broadened to include IHPs in general.

The IEA HPC Annex 21 (1995) did an investigation on eight countries reporting on 79 subdivisions. A uniform approach was developed to provide consistency among the countries that performed the analysis. Each country followed this methodology in assessing the market potential and energy and environmental benefits of IHPs. From the aggregated data, it is possible to determine which subdivisions have large energy savings for IHPs and hence considerable environmental benefits.

The Heat Pump and Thermal Storage Technology Centre of Japan (HPTCJ, 2010) and Hita *et al.* (2011) investigated the various subdivisions in the food division. HPTCJ (2010) looked at the energy demand specifically while Hita *et al.* (2011) looked at the heat demand specifically. By analysing the data of the HPTCJ (2010) and Hita *et al.* (2011), it is possible to determine which subdivisions in the food division have the highest heat demand.

2.5.2 IHP experiences, potential and global environmental benefits – IEA Annex 21, 1995

As part of a larger project on IHPs, the IEA HPC Annex 21 (1995) conducted a study on the application of IHPs via its participating countries. In total, eight countries participated, namely Canada, France, Japan, the Netherlands, Norway, Sweden, the United Kingdom, and the United States. A uniform approach was developed to provide consistency among the countries that performed the analysis. Each country followed this methodology in assessing the market potential and energy and environmental benefits of IHPs.

A top-down method was used to determine the impact of the IHPs. The countries looked at various industrial subdivisions that had a combined total process heat consumption of between 5% and 38% of the total industrial process heating load.

In total, 79 subdivision were reported on, including pulp production, chlorine or soda production, and urea production, to name just a few. Figure 9 shows the 35 subdivision that had the largest potential energy savings and, therefore, a considerable environmental benefit. The subdivisions were categorised according to the aggregation, as defined in section 2.2. Figure 9 shows that the food, beverage, and tobacco division has the most promise with potential savings of between 20% and 35%.

In the food, beverage, and tobacco division, the subdivisions with the highest potential savings were beet/cane sugar, cheese, corn syrup and starch, dairies, and liquor distilling.

For all the other subdivisions investigated, only four showed a large savings potential. These subdivisions included aquaculture and fish farming (10%-30% saving), chlorine/caustic soda (5%-35% saving), pulp production (0%-25% saving), and textile (0%-15% saving). It is important to note that for some of these subdivisions, the lower bound of the average projected net energy savings was as low as 0%.

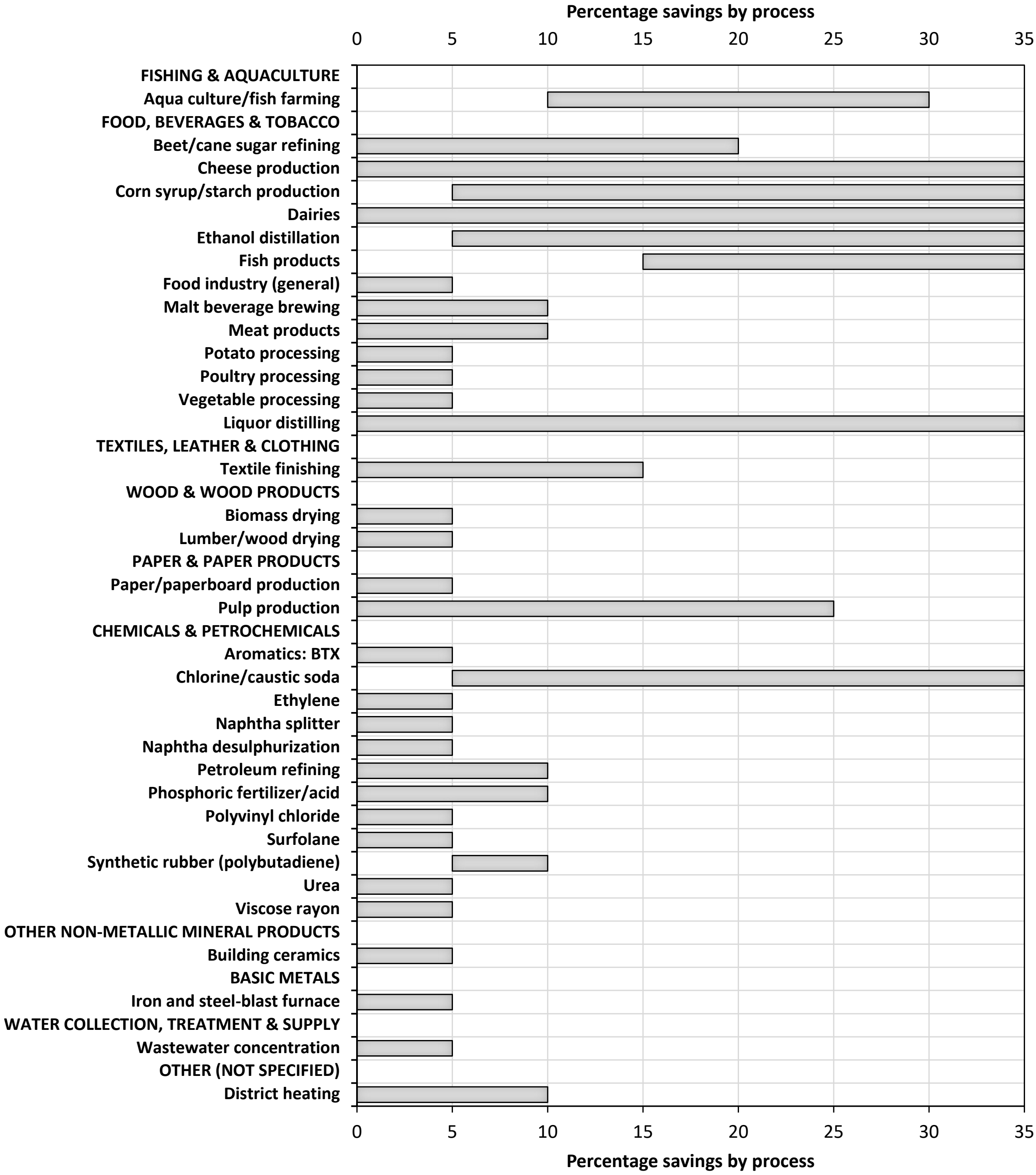


Figure 9: Estimated energy savings by process. Source: Data from IEA HPC Annex 21 (1995)

The market studies conducted for Annex 21 found that, on a combined basis and under the two IHP size scenarios examined, IHPs could provide the following levels of net emission reductions by 2010:

- SOx - 45-96 thousand tonnes/year.
- NOx - 36-77 thousand tonnes/year.
- CO - 12-27 thousand tonnes/year.

- CH_4 - 0.7-1.5 thousand tonnes/year.
- Particulates - 2.1-4.3 thousand tonnes/year.
- $C0_2$ - 21-42 million tonnes/year.

In conducting Annex 21, the participants recognised that the use of IHPs would reduce emissions associated with fossil fuel burning and provide net emission reductions when considering the increased electricity used by IHPs. At the same time, however, they acknowledged that the use of closed-cycle IHPs, which use refrigerants for heat transfer, could contribute some gas emissions with GWP. The use of CO_2 as a refrigerant would thus mitigate the negative impact of traditional refrigerants.

The country-specific IHP assessments clearly showed the sizeable potential energy and environmental benefits that might accrue through wider IHP implementation. However, they also highlighted that the applicability of IHPs and their potential benefits vary from country to country and are site specific. Local energy prices, the energy mix for process heating and electricity generation play a role in determining whether IHPs "make sense" technically and economically for a specific industrial site. These factors also play the same role in associated environmental benefits, both at the site and at national level.

2.5.3 Heat Pump and Thermal Storage Technology Centre of Japan (HPTCJ)

In a study using a top-down approach, the HPTCJ (2010) estimated the CO_2 emissions reduction through the use of IHPs in the production of food and beverages for 11 countries. The countries investigated were France, Germany, Italy, Japan, Netherlands, Norway, Spain, Sweden, the United Kingdom, the United States, and China. The food and beverage division was selected because the operating temperature level is relatively low. The introduction of IHPs into this field is considered relatively easy because for many processes the required temperature is below 100 °C (HPTCJ, 2010).

The total heat demand for the food, beverage, and tobacco division was 1 848.26 PJ for 2007. The value is equal to 57% of the total energy consumption of 3 242 PJ. China and the United States had a combined heat demand of approximately 48% of the total heat demand.

The HPTCJ (2010) indicated that many food and beverage manufacturing facilities used in Japan import equipment from Europe. Consequently, the HPTCJ extrapolated the survey findings to the various countries based on the survey data of Japan.

Table 5: The percentage share of energy consumption by the various industrial divisions and subdivision for the countries surveyed. Source: Adapted from HPTCJ (2010)

ISIC Code	Description	France	Germany	Italy	Japan	Netherlands	Norway	Spain	Sweden	United Kingdom	Total
10	Food	92.2%	77.3%	84.3%	82.6%	95.5%	94.4%	85.6%	92.9%	78.1%	84.6%
101	Processing and preserving of meat	12.8%	11.7%	18.8%	5.6%	15.2%	13.9%	18.2%	16.7%	15.5%	13.3%
102	Processing and preserving of fish, crustaceans and molluscs	1.3%	0.8%	0.9%	7.5%	0.0%	33.3%	4.2%	2.4%	1.8%	3.0%
103	Processing and preserving of fruit and vegetables	5.2%	4.7%	8.9%	2.7%	17.4%	2.8%	8.5%	7.1%	6.7%	6.4%
104	Vegetable and animal oils and fats	1.3%	7.0%	1.8%	3.9%	0.0%	8.3%	7.6%	7.1%	4.1%	3.9%
105	Dairy products	17.6%	16.2%	12.9%	8.7%	20.5%	11.1%	10.2%	14.3%	7.9%	13.0%
1061	Grain mill products	2.6%	1.6%	4.0%	1.4%	0.0%	2.8%	2.5%	4.8%	3.8%	2.5%
1062	Starches and starch products	8.5%	0.0%	2.5%	5.6%	0.0%	0.0%	2.1%	2.4%	3.2%	3.7%
1071	Bakery products	7.4%	8.6%	14.2%	10.9%	18.2%	8.3%	10.6%	11.9%	12.6%	10.9%
1072	Sugar	12.2%	15.1%	3.1%	4.3%	0.0%	0.0%	4.7%	4.8%	5.6%	7.3%
1073	Cocoa, chocolate, and sugar confectionery	4.1%	4.7%	2.5%	2.9%	6.8%	2.8%	2.5%	4.8%	5.6%	4.0%
1074	Macaroni, noodles, couscous, and similar farinaceous products	1.1%	0.0%	6.8%	3.4%	0.0%	0.0%	0.4%	0.0%	0.9%	1.9%
1079	Other food products n.e.c.	7.2%	0.0%	3.7%	24.2%	0.0%	2.8%	5.5%	14.3%	5.0%	7.7%
108	Prepared animal feeds	10.9%	6.8%	4.3%	1.7%	17.4%	8.3%	8.5%	2.4%	5.6%	6.9%
11	Beverages	7.8%	21.1%	15.4%	16.4%	1.5%	5.6%	13.6%	7.1%	21.1%	14.6%
1101	Distilling, rectifying, and blending of spirits	1.7%	1.6%	8.0%	2.9%	0.0%	0.0%	2.1%	2.4%	4.4%	3.1%
1102	Wine	1.1%	0.3%	3.1%	1.0%	0.0%	0.0%	3.4%	0.0%	0.3%	1.2%
1103	Malt liquors and malt	2.2%	15.9%	0.3%	6.3%	0.0%	2.8%	3.4%	2.4%	14.9%	6.7%
1104	Soft drinks; production of mineral waters and other bottled waters	2.8%	3.4%	4.0%	6.3%	1.5%	2.8%	4.7%	2.4%	1.5%	3.6%
12	Tobacco products	0.0%	1.6%	0.3%	1.0%	3.0%	0.0%	0.8%	0.0%	0.9%	0.8%

In total, 17 industrial divisions were investigated in the food and beverage division, ranging from the production of meat and meat products to soft drinks to the production of mineral waters. The entire tobacco division was investigated as a whole, which correlates with the ISIC rev. 4 (United Nations, 2008), which did not subdivide the tobacco division.

Table 5 illustrates that the highest energy users for all the countries combined were the processing and preserving of meat (13.3%), dairy products (13.0%), bakery products (10.9), other food products, nowhere else classified (n.e.c.) (7.7%), and sugar (7.3%). However, the dairy products demand percentage was as high as 20.5% for the Netherlands and 17.6% for France. Bakery products showed a similar pattern with a high energy percentage for Italy (14.2%) and the Netherlands (18.25). The subdivision with the lowest energy use were macaroni, noodles, couscous, and similar farinaceous products (1.9%), wine (1.2%) and tobacco products. However, the macaroni, noodles, couscous and similar farinaceous products percentage was as high as 6.8% for the Netherlands.

The share of energy intensity of the countries surveyed was more than 7% for each process, while the combined share represents more than 50% of the total energy used. The total percentage of energy consumption for the processing and preserving of meat was the highest at 13.3%. The total percentage of energy consumption for dairy products was 13%. Looking at the total data, one can see which industrial divisions have the highest and lowest percentages. However, the values can differ from country to country, depending on the size of the industry.

Figure 10 shows a frequency diagram of the top three subdivisions with highest energy percentage for each country. From Figure 10, one can observe that for the various countries investigated, the dairy products, bakery products, processing and preserving of meat products subdivisions have the highest frequencies. For the food and beverage divisions, these subdivisions thus have the highest potential IHP applications.

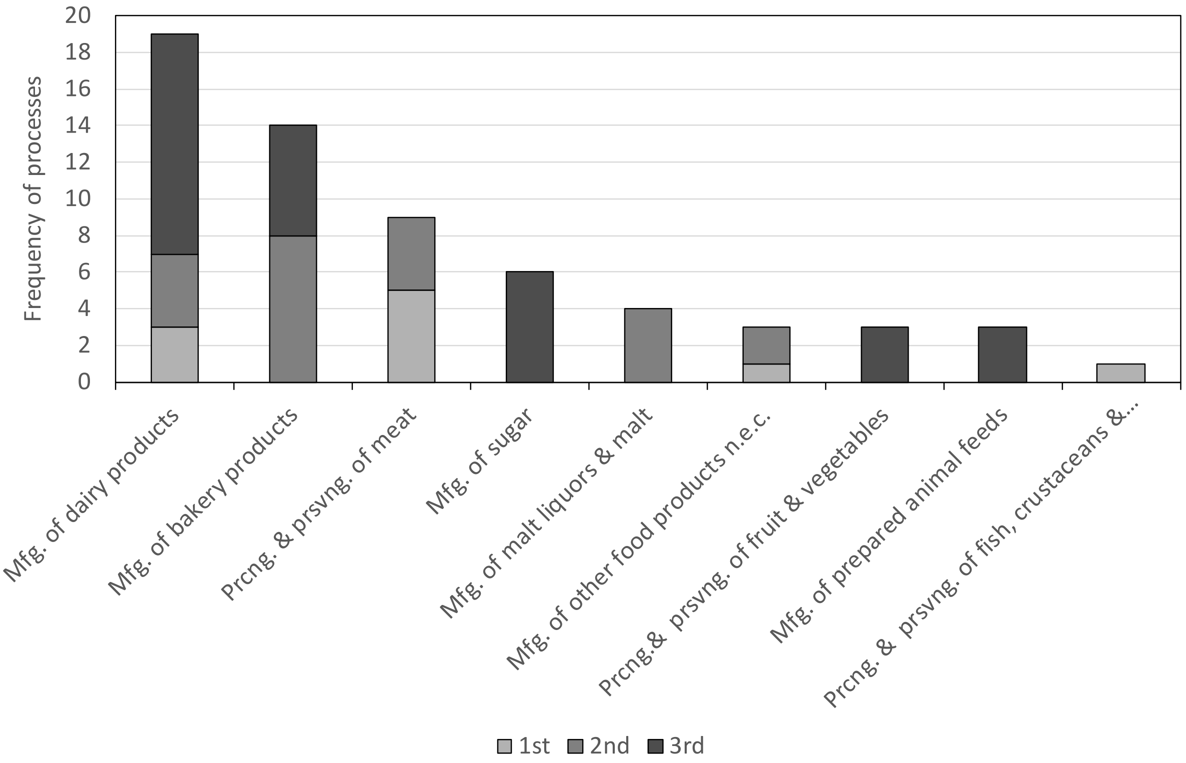


Figure 10: Frequency diagram of the highest energy users for the various countries. Source: Data from HPTCJ (2010);

The HPTCJ (2010) determined that IHPs could reduce the total CO_2 emission by 40 million tonneCO_2/year for all 11 countries investigated. The amount is equal to 1.3% of CO_2 emissions or 3 140 million tonne CO_2/year. They indicate that a significant reduction in CO_2 can be expected for China (15 million tonne CO_2/year). For the rest of the countries, a CO_2 reduction of 25 million tonne CO_2/year can be expected. The amount accounts for 1.8% of CO_2 emissions (1 380 million tonne CO_2/year).

2.5.4 Assessment of the potential of IHPs in the food and drink division by Hita *et al.* (2011)

In a bottom-up study, Hita *et al.* (2011) analysed the economic and CO_2 avoidance potential for the use of IHPs in the production of food and beverages in France. They investigated the food and drink divisions at a highly disaggregated level, focusing on 20 industrial subdivisions, ranging from sugar and milk to wine for various temperature ranges (Figure 11). For these industrial subdivisions, Hita *et al.* (2011) investigated the respective heat demand in seven temperature levels with increasing interval sizes from 60 °C to 200 °C. According to Hita *et al.* (2011), the French food and beverage division was the highest energy user in a study comparing 28 European countries in 2005. The food and beverage divisions use around 62 TWh/annum. The value represents about 12% of the French total industrial energy consumption. It had the third-highest energy consumption after the steel division and the chemistry division.

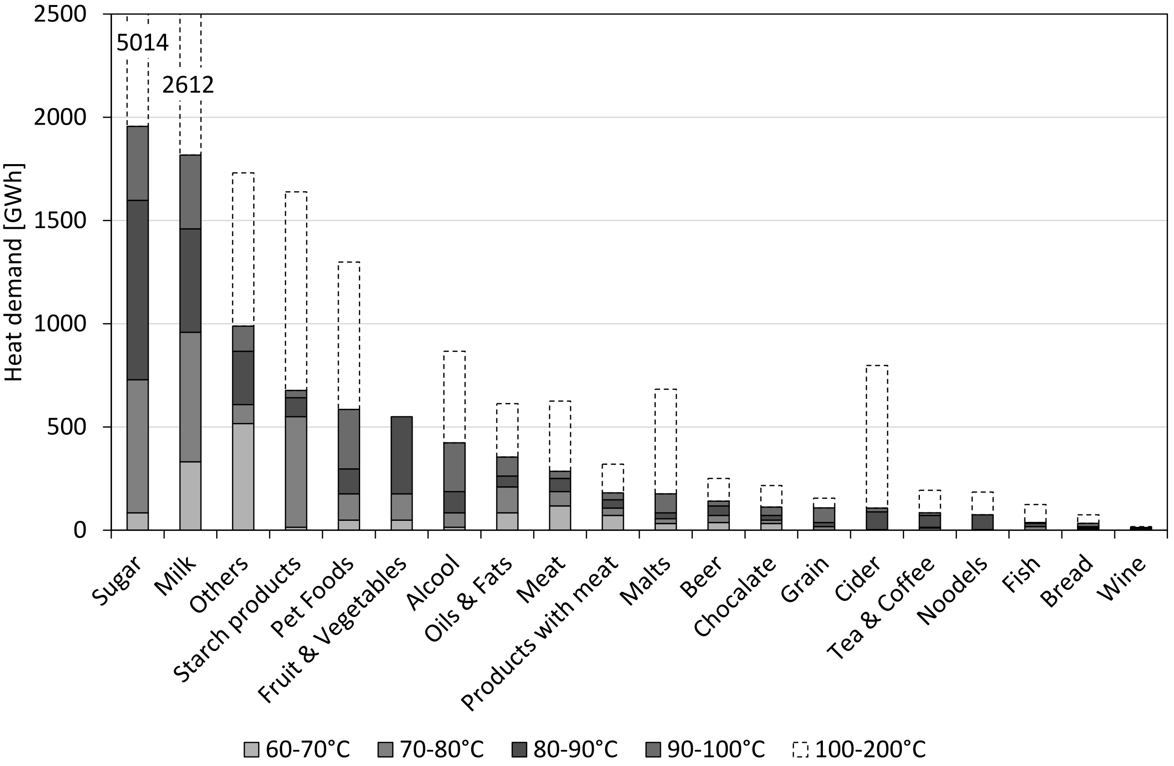


Figure 11: Heat demand in the French food and drink division. Source: Data from Hita *et al.* (2011)

By analysing the graphical data (Figure 11), it was found that for temperatures below 100 °C, the subdivision with the highest energy demand were sugar, milk, non-specified, and starch products. The subdivision with the least amount of savings were noodles, fish, bread, and wine.

Hita *et al.* (2011) estimated that the technical substitutable heat demand for a temperature of 60 °C-140 °C is around 11 TWh/annum of the total heat demand of the French food and beverage division. The value represents approximately 15% of the total consumed energy in this industrial division. For their analysis, Hita *et al.* (2011) compared two scenarios, namely IHPs with a maximum operating temperature of 80 °C and IHPs still in laboratory development to provide heat of up to 140 °C. When considering IHPs operating below 80 °C, they estimated that IHPs could technically substitute around 30% (3,578 GWh/annum of the 11,068 GWh/annum) of the available heat. The savings cause an estimated CO_2 emissions avoidance of 0.71 million tonne CO_2/year.

2.5.5 Section summary

In this section, three authors were considered for their investigation of the potential of IHP for specific industrial subdivision. The three authors included were the IEA HPC Annex 21 (1995), HPTCJ (2010) and Hita *et al.* (2011).

The IEA HPC Annex 21 (1995) conducted a country-specific analysis for eight countries investigating 71 processes in total, ranging from aqua and fish farming to district heating. They indicated that the food, beverage, and tobacco division was the most suited division. These furthermore included the beet/cane sugar, cheese, corn syrup and starch, dairies, and liquor subdivisions, which included aquaculture and fish farming, ethanol, chlorine/caustic soda, and pulp production.

The HPTCJ (2010) study on 11 countries revealed that the highest energy users for heat were the production of meat, dairy products, and bakery products. From the frequency diagram, it is observed that meat processing and preservation, dairy products, bakery products, other food products (n.e.c.), and sugar had the highest frequencies for the various countries. These subdivisions are well suited for IHP. The work of HPTCJ (2010) confirms the findings of the IEA HPC Annex 21 (1995), which indicated that the IHPs and their potential benefits are very country and site specific, as the data maximum percentage share of energy consumption changed for each country.

The study by Hita *et al.* (2011) on France indicated that the subdivision with the highest energy demand for temperatures below 100 °C were sugar, milk, non-specified, and starch products. The findings show the same trends as the work of HPTCJ (2010).

Table 6: Combined estimated savings with the percentage share of energy consumption. Source IEA HPC Annex 21 (1995), HPTCJ (2010)

ISIC code	**Description**	**Share of energy consump-tion**	**Percentage savings per process**		**Combined estimated savings i.t.o. of the share of energy consumption**	
		Average	**Lower limit**	**Upper limit**	**Minimum**	**Maximum**
105	Manufacture of dairy products	13.2%	0.0 %	35.0 %	0.0%	4.6%
102	Processing and preserving of fish, crustaceans, and molluscs	5.5%	15.0 %	35.0 %	0.8%	1.9%
101	Processing and preserving of meat	14.2%	0.0 %	10.0 %	0.0%	1.4%
1072	Mfg. of sugar	5.7%	0.0 %	20.0 %	0.0%	1.1%

Table 6 shows the combined data for IEA HPC Annex 21 (1995) with that of the HPTCJ (2010) for the top four combinations of estimated savings. Table 6 shows that the dairy division (ISIC code 105) has the highest share of energy consumption and appears to be the most suited for IHPs. The associated combined savings are between 0% and 4.6%. The second-best option was the processing and preserving of fish, crustaceans, and molluscs (ISIC code 105) subdivision. The estimated saving potential is between 0.8% and 1.9%. Meat processing and preserving of meat (ISIC code 101) was the third-best option. These subdivisions thus have the highest potential for IHPs. However, a detail investigation needs first to be done to determine which sectors and subsector have the highest potential for SA. At this stage, none of the articles found, investigate the potential of IHPs in SA.

IHPs are not always implemented in the specific subdivision that has the highest potential. For the implementation of IHP, one must look not only consider the temperature ranges but also the business cases of the IHPs. In the next section, an overview is given of installed IHPs found in the literature.

2.6 Installed IHPs in the industrial sector

2.6.1 Introduction

The main aim of this section is to present examples where IHPs have been previously installed. The findings of the previous work can be compared with what that of actual implemented IHP. By analysing the data from IEA HPC Annex 35 (2014) the author found that a CO_2 HP was used in only eight of 82 implemented projects. Therefore, the study was expanded to include not only CO_2 HPs but also IHPs, as this would give a better picture as to where HPs are applied in industry.

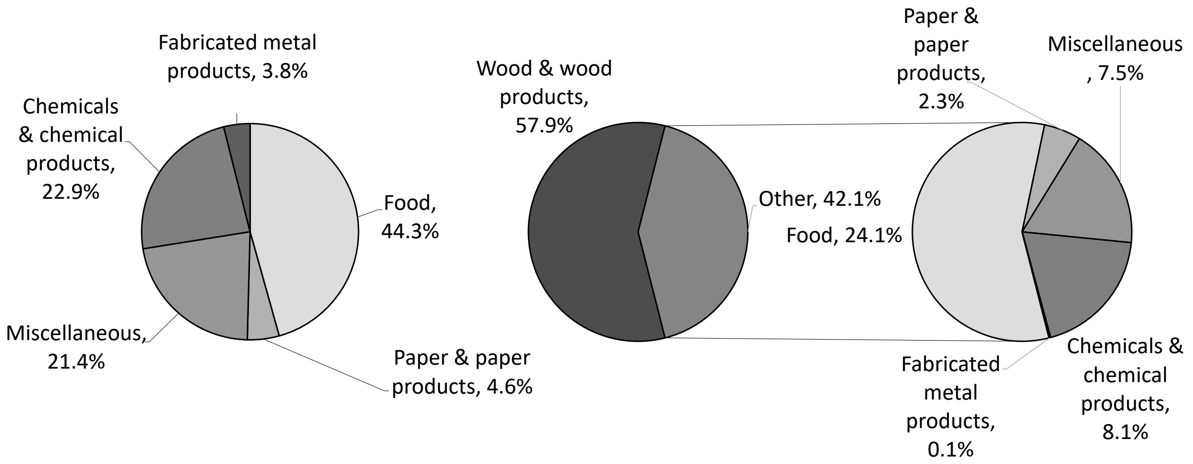
In section 1.1 the author indicated that a barrier on the implementation of IHPs is the long payback periods. Thus, the author investigated the payback periods of implemented projects. The information can then be used to determine which projects have a payback period of less than three years.

The following three studies were investigated, namely IEA HPC Annex 21 (1995), IHPs in China by Zhang *et al.* (2016), and IEA HPC Annex 35 (2014).

2.6.2 IHP experiences, potential and global environmental benefits IEA HPC Annex 21 (1995)

The IEA HPC Annex 21 (1995) conducted a study in its participating countries on the application of IHPs. In total, eight countries participated, which included Canada, France, Japan, the Netherlands, Norway, Sweden, and the United States. The countries sent out questionnaires to various industrial sectors. Only a limited number of direct responses were received from the questionnaires. In total, the countries reported on 121 installed IHPs. However, most of the Annex countries supplemented their responses with reports and information originally created for other projects. The results of the questionnaires and previous studies are shown in Figure 12 (a) and are discussed in this section.

From Figure 12 (a), one can observe that the food division had the largest percentage, 44.3%, of installed IHPs, with most of the IHPs used in evaporation operations. The second-largest division was the chemical and chemical products division, followed by the miscellaneous division, with a percentage of 22.9% and 21.4% respectively. The miscellaneous division is made up of the textile, manufacturing of petroleum products, and related applications such as sewerage.



(a) Data gathered during the IEA Annex 21 (b) IEA supplemented data of updated International IHP Status

Figure 12: IHP installations divided according to industrial divisions as by IEA HPC Annex 21 (1995). Source: Adopted from IEA HPC Annex 21 (1995).

Figure 12 (b) shows the supplemented data that was initially generated by reports of other projects. From these reports, the countries estimated that there are between 4 280 and 4 600 installed IHPs, with the United States having 2 300 installed IHPs. This equates to 54% of the total number of IHPs.

According to the IEA data in Figure 12 (b), the lumber division dominated with a 57.9% share. The food division had a percentage of 24.1%, and the chemical divisions had the third-largest share of 8.1%. It can thus be concluded that the lumber, food, and chemical divisions have shown the most popular for implementing IHPs in the past.

The United States (IEA HPC Annex 21, 1995) estimated that 2300 of the IHP that are in use, 2000 are for lumber drying. A probable reason IHP are so popular in the wood is because wood drying consumes up to 70% of all the energy used in the wood industry (Minea, 2013). In IHP assisted dryers, the process air is typically heated between 30 °CC and 57 °C (Minea, 2013).

According to SETA (2014), SA is lightly forested with a plantation area of approximately 1 268 443 hectares, which represents 1.1% of the country’s land area. This percentage is low in comparison to the plantation areas of 30% in the United States. Thus, the high percentage of IHPs in the wood and wood products division does not necessarily influence the potential of IHPs in SA.

For the chemical industry the IEA HPC Annex 21 (1995) reported on 30 installation, with a total heating capacity of 20 MW. In total 47% of the installations are in evaporation plants, and account for the 78% of the total heating capacity. A probable reason IHP are so popular in the evaporation industry is the low drying temperatures of 150°C (Mujumdar, 2006). Industrial drying competes with distillation as the most energy-intensive unit operation and use between 20–25% of the energy national energy consumption.

The food and beverage industry had more than 50 IHP installations in 1995 with a total heating capacity of 260 MW (IEA HPC Annex 21, 1995). The main applications are evaporation, word boiling, distillation, dying and waste heat recovery.

The other two divisions are larger in SA, with the food, beverage and tobacco division and the petrochemical division contributing 15.9% and 6.3% to the GVA of SA for 2015, respectively (Statistics South Africa, 2017). These divisions could thus have a higher potential to implement IHPs.

2.6.3 IHPs in China by Zhang *et al.* (2016)

Zhang *et al.* (2016) reported on 18 examples of IHPs used in the industrial field in China. Table 7 lists the various applications in the industrial division, including IHP types and heat supply temperature requirements. Unfortunately, no data was given on the COP for the designed systems, energy savings, and capital investment along with the payback period. These values could not be sourced from the original reference as they were all in Chinese.

From Table 7, one can observe that the subdivisions with the highest frequency were the chemical and chemical products, printing and reproduction of recorded media, land transport, and transport via pipelines. The food and tobacco divisions each had a frequency of two.

Table 7: Summary of IHP in China. Source: Zhang *et al.* (2016)

Division	**Number of projects**	**Minimum heat supply temperature [°C]**	**Maximum heat supply temperature [°C]**	**Average heat supply temperature [°C]**
Mining of metal ores	1	-	-	-.
Food	2	80	80	80
Tobacco products	2	68	80	74
Printing and reproduction of recorded media	3	40	95	75
Chemicals and chemical products	4	102	110	106
Fabricated metal products	1	75	75	75
Electricity, gas, steam, and air conditioning supply	1	82	82	82
Sewerage	1	85	85	85
Land transport and transport via pipelines	3	55	80	65

2.6.4 Installed IHP reported by the various countries of the IEA HPC Annex 35 (2014)

As part of a larger project on IHPs, the IEA HPC Annex 35 (2014) conducted a study on installed IHPs via its participating countries. In total, the nine countries reported on 82 projects with the application of IHPs. The purpose of these case studies was to present good examples of IHP technology and its application in industrial subdivisions. The participating countries reported on the impact of the IHPs but lacked consistency on the data presented. For example, all 82 projects reported on the thermal capacity, IHP system, and supply temperatures, However, only 18 of the projects reported on the CO_2 reduction percentage, five reported on CO_2 reduction in terms of tonnes per annum, 41 reported on the payback period, 14 on energy cost, and 14 of the projects gave no details. It is thus difficult to make generalisations on the impact of IHPs from the data, although some observations can be made.

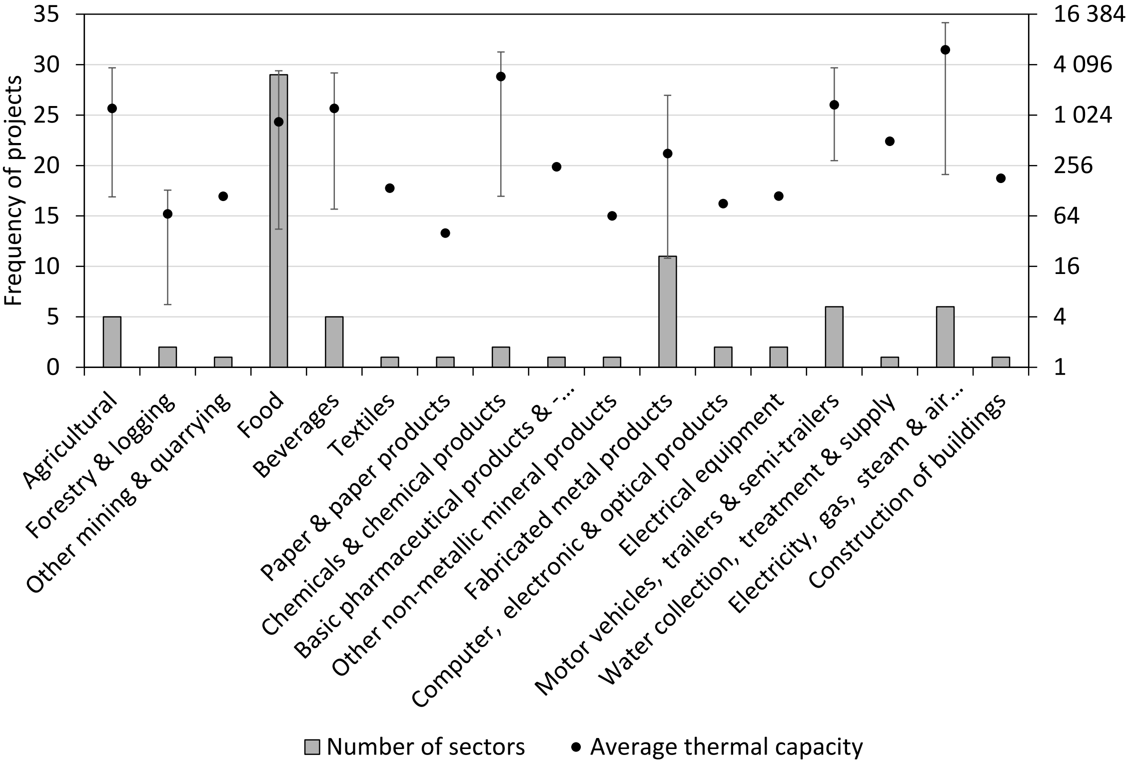


Figure 13: Summary of IHP projects as reported by IEA HPC Annex 35 (2014). Source: Data from IEA HPC Annex 35 (2014)

Figure 13 shows the frequency of the projects for which the payback periods were given, as well as the average, minimum, and maximum payback periods. From Figure 13, one can see that the agricultural, food, beverages, fabricated metal products, motor vehicles and electricity divisions have the highest number of IHPs. One can also observe that the thermal capacities of the plants range from as small as 5.6 kW in the agriculture sector to as large as 5 800 kW for chemicals and the chemical division.

According to Turner and Doty (2007), capital cost programmes with payback times of two years or less can often save 30%-50% on the utility bills. Furthermore, Germany indicated that companies expect very low payback periods of less than two or three years (IEA HPC Annex 35, 2014). Some companies were willing to accept payback periods of up to five years when it came to investments into their energy infrastructure (IEA HPC Annex 35, 2014). Thus, a straight payback of three years was chosen as a representative value for the analysis.

From Figure 13, one can observe that only the fabricated metal products and food divisions have a high frequency of projects with information on the payback data. These subdivisions had projects with a payback period as low as two years and as high as six years or longer.

The agricultural and the chemical and chemical products subdivisions have an average payback time of less than three years. For other mining and quarrying, the average was just above three, with a value of 3.2. For the divisions with a frequency of three or fewer projects, one cannot make any conclusions, as there is not enough data on the payback period. It is important to note that although seven of the subdivisions still had a longer payback period than three years, IHPs were still implemented.

Thus, the wide differences in the payback period show how local energy prices and the energy mix for process heating play a role in determining whether IHPs make sense technically and economically for a specific industrial site.

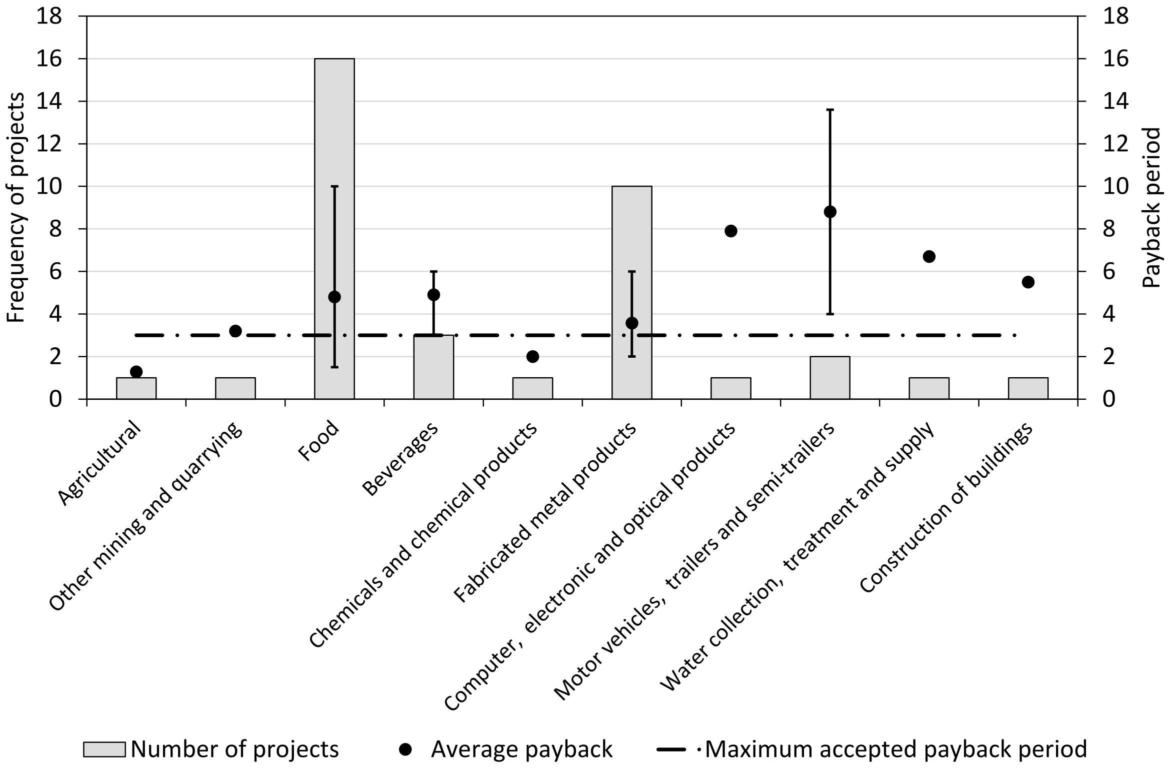


Figure 14: Payback periods for various projects organised by subdivisions. Source: Data from (IEA HPC Annex 35, 2014)

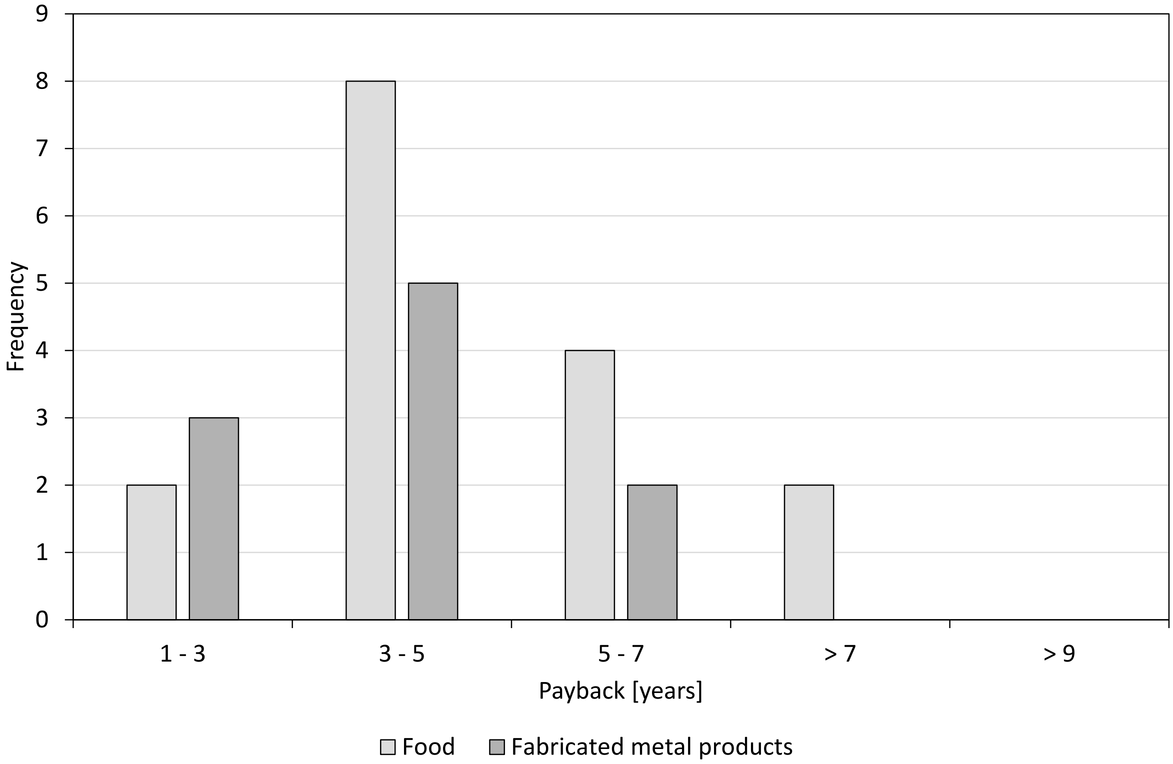


Figure 15: Frequency diagram of the food and fabricated metal division. Source: Data from IEA HPC Annex 35 (2014)

From Figure 15, one can observe that the majority of the projects in the food and fabricated metal products divisions had a payback period of less than five years. For the food division, most of these projects were in the milk and meat subdivisions. For the fabricated metal division, most of the projects were in sheet metal production. From the data presented, it thus seems that these two subdivisions are the most popular for implementing IHPs with relatively good payback periods.

2.6.5 Summary

In total, three sources were found that reported on IHPs that are installed in the industrial sector. Two of the sources reported on IHPs that were operational in recent years, while two of the sources reported on previous studies.

IEA HPC Annex 21 (1995) reported on a study via its participating countries that installed IHPs, and in total, data was gathered for 121 installed IHPs. The largest division was the food division, which made up 44.3% of the IHPs. The second-largest was the chemical division, with a percentage of 22.9%. These two divisions make up two thirds of the installed IHPs.

The countries also supplemented their responses with reports and information created for other projects. From this data, the lumber divisions accounted for nearly 58% of all the IHPs. The food divisions accounted for almost 24% of all the IHPs. Together they accounted for more than 80% of the installed IHPs.

Zhang *et al.* (2016) reported on 18 examples of IHPs used in the industrial field in China. As part of the larger IEA HPC Annex 35 (2014) project, the eight participating countries reported on 77 examples of installed IHPs. Thus, in total, data for 95 IHPs could be analysed. Unfortunately, Zhang *et al.* (2016) only reported on the type of IHP and heat supply temperature of the IHPs.

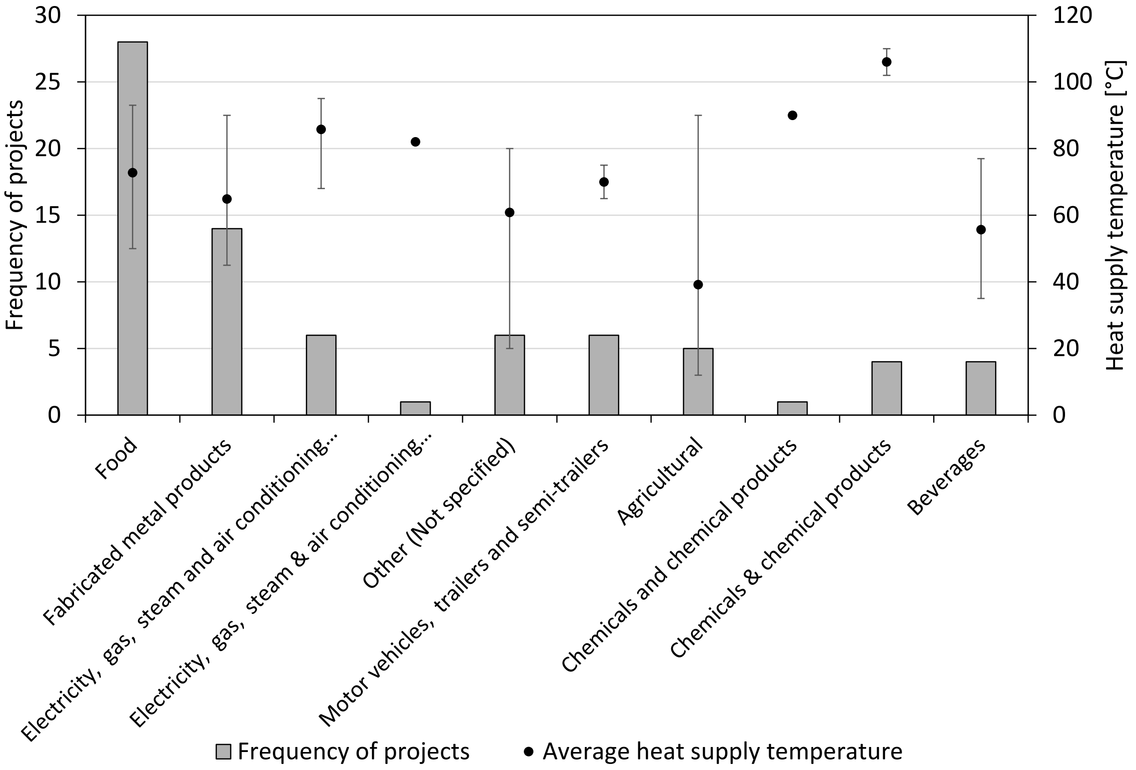


Figure 16: Frequency and temperature diagram of the 100 installed IHPs. Source: Data from Zhang *et al.* (2016); IEA HPC Annex 35 (2014)

Figure 16 shows only the data for the subdivisions that had more than two projects installed. From Figure 16, one can observe that the food and fabricated metal products divisions had the largest and second-largest number of projects. The food division is by far the most popular division, having nearly 30% of all the installed IHPs and the largest frequency of IHPs with payback data. For 11 of the projects, the straight payback was below five years. It can hence be concluded that IHPs are popular in the food division, and these projects have relatively low payback periods.

2.7 Conclusion

This chapter gave an overview of the potential of IHPs for various industrial subdivisions and existing data for installed IHPs. First, an investigation was done on the potential of IHPs in the various divisions. From a frequency analysis of the divisions with the highest potential for IHPs by Wolf (2017) and Arpagaus *et al.* (2018), it was found that the food, beverage, and tobacco divisions had the highest frequency. The division with the second-highest potential for IHPs was the other (non-specified) division, followed by chemicals and petrochemicals, and then paper and paper products.

Secondly, the literature focused on the various subdivisions. By combining the data of IEA HPC Annex 21 (1995) with that of the HPTCJ (2010), one can observe that the dairy subdivision (ISIC code 105) had the highest share of energy consumption and thus seemed to be the most suited for the implementation of IHPs. The associated combined savings is between 0% and 4.6%. The second-best option was the processing and preserving of fish, crustaceans, and molluscs (ISIC code 105). The estimated saving potential is between 0.8% and 1.9%. Meat processing and preservation (ISIC code 101) was the third-best option.

From the research of Zhang *et al.* (2016) and IEA HPC Annex 35 (2014), the highest number of installed IHPs was in the food division. The food division is by far the most popular division, having nearly 30% of all the installed IHPs. From data obtained from IEA HPC Annex 35 (2014), it was found that 11 of 16 projects in the food, beverage, and tobacco division had a straight payback period of less than five years. Most of these projects were in the milk and meat subdivisions, again iterating that this division is very favourable for the use of CO_2 HPs.

Only the IEA HPC Annex 21 (1995) indicated that the wood and wood products division had a higher percentage of installed IHPs. The high percentage was primarily driven by the high number of IHPs in this division for the United States and Canada. The wood and wood products divisions have a much smaller scale in SA, and thus this data should not dramatically influence the South African scenario.

In conclusion, several authors have investigated the potential of IHPs internationally, but no study that quantifies the potential of IHPs for SA was found. Only one analysis was found on the application of IHPs for SA, that of Kivevele and Huan (2013), which compared various drying technologies. The focus of the article was on the specific application of IHPs. The article gave no reference to what the impact would be of the application.

It is crucial to note that several factors determine whether IHPs make sense technically and economically for a specific industrial site. The factors include the energy mix for process heating and the energy mix for electricity generation. Thus, an investigation is required to determine which divisions in SA have the highest potential for the implementation of IHPs. In the next chapter, the technical potential of IHPs is estimated. Form this it is possible to determine which divisions have the highest potential for the implementation of IHPs.

Chapter 3. Identifying the most suited divisions for the SA industrial sector

3.1 Introduction

So far, no comprehensive study has been done on estimating the theoretical potential heat demand for SA nor has any study been done to identify the potential divisions where CO_2 HPs can be implemented in SA. Therefore, the aim of this chapter is to close the knowledge gap regarding the available industrial heat demand at a temperature below 100 °C. The author found, from the literature, that the heat demand was given for a temperature level of 100 °C. Thus, the heat demand could not be determined for the maximum operating temperature of the CO_2 HP. The information presents various other combined factors to identify the most suited divisions for the integration of CO_2 HPs.

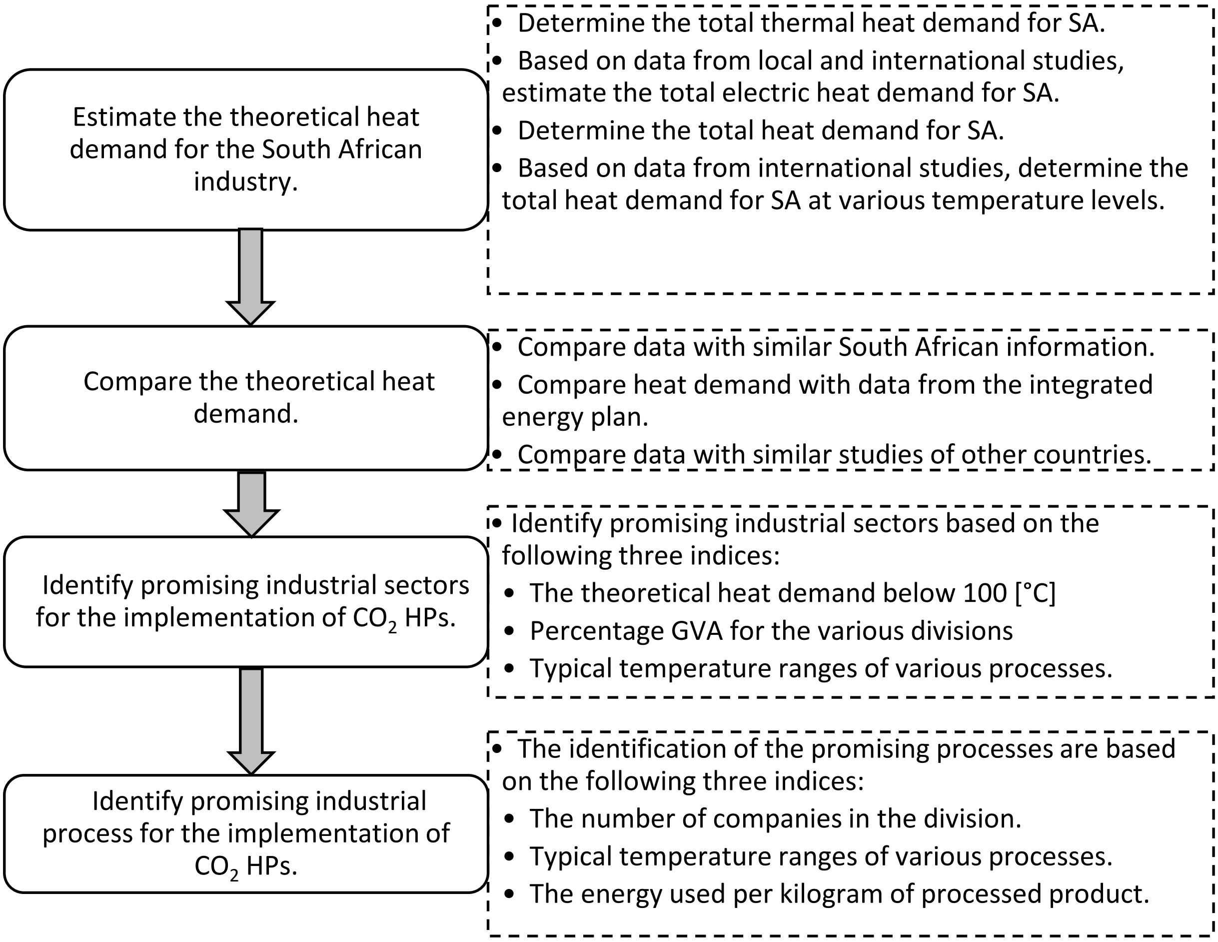


Figure 17: Overview of the various steps used to identify the most suited divisions for the integration of CO_2 HPs

Figure 17 shows the various steps that are used in this chapter to identify the most suited division for integrating CO_2 HPs. In the first step, the theoretical heat demand for the South African industry is estimated. The author did not distinguish between HP that use other refrigerant with the same operating temperature. Thus, the information can then also be used to determine the heat demand for any HP with a similar operating condition. To determine the specific heat demand of the CO_2 HP, one needs to estimate the market penetration of the CO_2 HP. The market penetration does not form part of this study.

This step is divided into four main parts. In the first part, the total thermal heat demand is determined for 14 distinct industrial sectors. In the second part, the electric thermal heat demand is determined. In total, three international and four local sources are combined to determine the electric heat demand. The third part entails determining the total heat demand by adding together the thermal and electric heat demand. In the fourth and final part, the percentage heat demand for various temperature levels is integrated with the total heat demand.

In the second step, the heat demand for each division at various temperature levels is validated against four sources. These sources are Knaack *et al.* (2019), ERC (2013), DoE SA (2013), and Fleiter *et al.* (2017).

In the third step, the most suited industrial division for the integration of CO_2 HP is identified. Three factors are evaluated and weighted to determine the most suited division. The factors include the total heat demand per division at various temperature levels, the number of division per sector at operating conditions below 100 °C, and the percentage that each division contributes to the SA GVA.

Finally, in the fourth step, the most suited process for the integration of CO_2 HP is identified. For the identification, three factors are used to determine the most suited process. These factors are the number of companies in the division, the typical temperature ranges of various processes, and the energy used per kilogram of processed product.

3.2 Estimating the theoretical potential industrial heat demand for SA

3.2.1 Introduction

For SA, the heat demand is disaggregated for five divisions, with no indication of the various temperature ranges. The heat demand in the industrial sector accounts for 66.77% of the total energy demand (DoE SA, 2016d). The Integrated Energy Plan (IEP) and the DoE SA (2016d) did an investigation on energy efficiency opportunities in the industrial sector. The purpose of the IEP is to provide a roadmap of the future energy landscape of SA which will guide future energy infrastructure investments and policy development. The IEP furthermore indicates how energy is used in various divisions. From the work done by the IEP, it is possible to estimate the total heat energy demand for SA.

According to the literature research, the food, beverage, paper, and paper products divisions showed great potential for IHPs in general. As seen in Table 8, the IEP did not include these divisions as part of its investigation. In fact, the data from the IEP only indicates the heat demand for five divisions. Table 8 shows that these five divisions accounted for 95.5% of the total energy use in 2015 (IEA, 2017a). Although the rest of the divisions make up less than 5% of the energy use, these divisions still need to be investigated for the potential application of CO_2 HPs.

Table 8: Electric heat demand for SA. Source DoE SA (2016d), IEA (2017a)

No	**Industrial Sector**	**Electrical energy [PJ]**	**Percentage process heating and water heating**	**Electric energy used for heating [PJ]**	**Percentage of industrial sector electric energy use**
1	Mining (excluding fuels) and quarrying	109.40	6%	6.56	25.0%
	Gold mining		6%		
	Coal mining		6%		
	Platinum mining		6%		
	Other mining		6%		
2	Chemical and petrochemicals	40.44	4%	1.74	9.2%
3	Iron and steel divisions	13.19	60%	7.86	3.0%
4	Non-ferrous metals divisions	60.00	23%	13.74	13.7%
5	Other (Non-specified)	195.19	38%	74.17	44.6%
	Total	418.22	25%	104.07	95.5%
	Industrial sector	**437.77**			

Furthermore, the heat demand for SA is not disaggregated for various temperature ranges. Hence, there is a need to quantify the heat demand for SA for the different industrial sectors. This data is used to identify which industrial sector CO_2 HPs have the highest theoretical potential for temperatures below 100 °C.

This chapter aims to estimate the theoretical technical potential for CO_2 HPs in SA. It commences by discussing the methodology that is used in this study. Secondly, the chapter provides an overview of the total energy use of SA, indicating the energy use per sector and division as well as the energy sources. Thirdly, the total theoretical heat demand for SA is estimated, which is divided into thermal and electric demand. Fourthly, the theoretical heat demand below 100 °C is determined. In the final instance, this chapter identifies the most suited industrial divisions and processes in SA for the implementation of IHPs.

3.2.2 Methodology to determine the theoretical heat demand for SA

Before the theoretical methodology is estimated, an understanding of the various definitions of potential demand is required. In general, there are three types of possible meanings; these are (Resch *et al.*, 2008):

1. Theoretical potential: To derive the theoretical potential, general physical parameters must be taken into account (e.g. based on the determination of the energy flow resulting from a certain energy resource within the investigated region). It represents the upper limit of what can be produced from a specific energy resource based on a theoretical, scientific, and knowledge-based point of view.
2. Technical potential: Once the technical boundary conditions (i.e. efficiencies of conversion technologies and overall technical limitations such as the available land area to install wind turbines) are considered, the technical potential can be derived. For most resources, the technical potential must be seen in a dynamic context – for example, with increased research and development (R&D), conversion technologies might be improved, which would increase the technical potential. Wolf and Blesl (2016) indicated that the technical potential of CO_2 HP applications is strongly dependent on the operating of CO_2 HPs. Thus, the coupling of heat sources and heat sinks requires more detail.
3. Realisable potential: The realisable potential represents the maximal achievable potential, assuming that all existing barriers can be overcome and all driving forces are active. Thereby, general parameters such as market growth rates and planning constraints are taken into account. It is essential to mention that this potential term must also be seen in a dynamic context – i.e., the realisable potential must refer to a specific year.

In this section, the technical potential is determined. This section aims thus to give an overview of the technique used to determine the theoretical potential for CO_2 HP integration in SA.

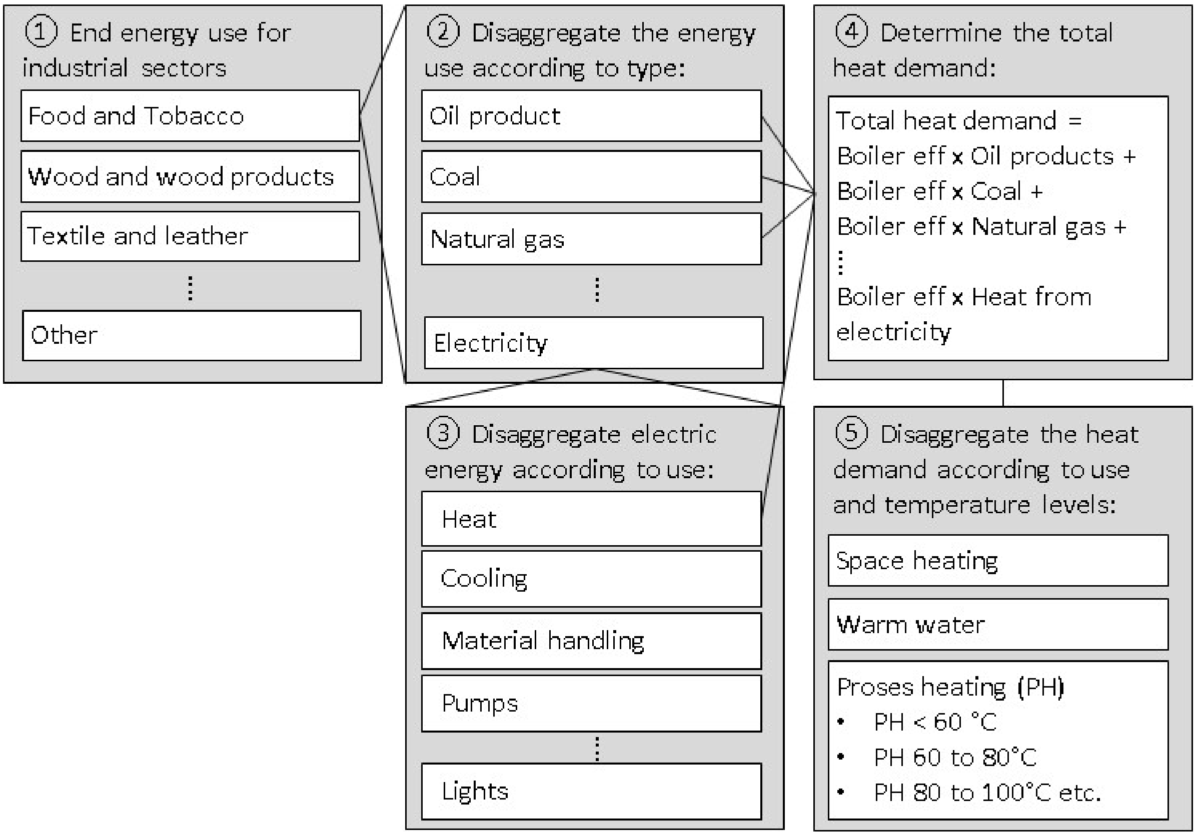


Figure 18: Structure of the theoretical data analysis. Source: Adapted from Wolf (2017)

To determine the theoretical heat demand for SA per division, it is necessary to disaggregate the total energy use per division, as shown in block ① of Figure 18. Table 9 shows in total the 13 divisions and subdivisions which are formulated according to the IEA (2016). The combined divisions and subdivisions are henceforth referenced as divisions.

Table 9: Limitation of the divisions included in the investigation of CO_2 HPs in each division. Source: Data from IEA (2017a)

ISIC rev. no.	Abbreviated description	Original ISIC rev. 4 description
B-F	Industry	Industry
07, 08, 99	Mining (excluding fuels) and quarrying	Mining (excluding fuels) and quarrying
10-12	Food, beverages, and tobacco	Manufacture of food, beverages, and tobacco
13-15	Textile, leather, and clothing	Manufacture of textiles, wearing apparel, leather, and related products
16	Wood and wood products	Manufacture of wood and of products of wood and cork, except furniture; manufacture of articles of straw and plaiting materials

ISIC rev. no.	Abbreviated description	Original ISIC rev. 4 description
17, 18	Paper, pulp, and print	Manufacture of paper and paper products. Printing and reproduction of recorded media
20, 21	Chemical and petrochemicals	Manufacture of chemicals and chemical products. Manufacture of basic pharmaceutical products and pharmaceutical preparations
23	Other non-metallic mineral products	Manufacture of other non-metallic mineral products
241, 2431	Iron and steel division	Manufacture of iron and steel industry
242, 2432	Non-ferrous metals division	Manufacture of non-ferrous metals industry
25-28	Machinery	Manufacture of fabricated metal products, computer, electronic, optical products, electrical equipment, machinery, and equipment nowhere else classified (n.e.c.)
29, 30	Transport equipment	Manufacture of motor vehicles, trailers and semi-trailers, and other transport equipment
41-43	Construction	Construction of buildings, civil engineering, and specialised construction activities
22, 31, 32	Non-specified (industry)	Manufacture of rubber and plastic products, furniture, and other manufacturing

For every division, the amount of heat that is used must be determined (Block ② in Figure 18). For this, the energy is disaggregated according to type. The DoE and IEA both disaggregate the energy use for SA for various energy sources, including coal, crude oil, petroleum (oil products), natural gas, nuclear power, hydro fuel, geothermal power, solar power, biofuels and waste, electricity, and heat. The author assumes all the heat from coal, oil, gas, biomass, waste and heat that is used for process heat in industry. This heat is classified as the thermal heat demand. The assumption is in line with the work done by HPTCJ (2010) and Janse van Vuuren *et al.* (2017). Lauterbach *et al.* (2012) also indicated that fossil fuels are used mainly for the supply of heat. The assumption is further supported by analysing data of the *"Arbeitsgemeinschaft Energiebilanzen"* (AGEB) in Germany, which shows that approximately 0,89% of fuels is used for mechanical power in industry (AGEB, 2013).

The author also assumes that petroleum (oil products) is used for propulsion. According to the IEA (2016), petroleum (oil products) consist of refinery gas, ethane, LPG, aviation gasoline, motor gasoline, jet fuels, kerosene, gas/diesel oil, heavy fuel oil, naphtha, white spirit, lubricants, bitumen, paraffin waxes, petroleum coke, and other petroleum products (IEA, 2003).

The assumption is in line with DoE SA (2016a), which states that motor gasoline (petrol) is highly flammable and volatile, generally highly toxic, and an aggressive solvent which is therefore dangerous to use outside of internal combustion engines, even as a workshop cleaning fluid. As a result, petrol does not find complete application outside of light vehicle road transport except as fuel for light machinery such as lawnmowers and small generators, usually with less than 5 kVA power ratings. According to DoE SA (2016a), Diesel is mainly used in road transport. Petroleum is only used by the mining and quarrying, construction, and non-specified industrial divisions. It makes up 63%, 93% and 4% of the total energy consumption of each of these divisions, respectively.

The next step is to determine the fraction electric heat demand for each division (Block ③ in Figure 18). No authors gave the fraction electric heat demand in all the divisions investigated. Thus, the data from the various authors must be combined. This includes data from the ERC (2013), the DoE SA (2016d), Janse van Vuuren *et al.* (2017), Howells (2006), the Department for Business (2018), the Energy Information Administration (EIA, 2010), and AGEB (2013).

For the next step, the boiler efficiency for each energy source must be determined. (Block ④ in Figure 18). Bessette (2002); Werner (2005), ERC (2013) investigated the boiler efficiency for various types of boilers. The data is combined to determine the boiler efficiency.

The total heat demand for each division is determined (Block ④ of Figure 18) with Equation (1).

$$E_{THD} = E_{TTHD} + E_{TEHD} \quad (1),$$

where

$$E_{EHD} = \eta_{Elec} \cdot E_{Elec} \cdot FR_{HD} \quad (2)$$

and

$$E_{THD} = \eta_{Coal} \cdot E_{Coal} + \eta_{Gas} \cdot E_{Gas} + \eta_{Bio} \cdot E_{Bio} + \eta_{Heat} \cdot E_{Heat} \quad (3),$$

with

E : Energy use [PJ]
η : Efficiency [%]
FR_{HD} : Fraction heat demand for electricity [-].

And the subscripts
THD : Total head demand
$TTHD$: Total thermal heat demand
$TEHD$: Total electric heat demand
$Elec$: Electricity
$Coal$: Coal

Gas : Gas
Bio : Biomass
$Heat$: Heat

To determine the heat demand (Block ⑤ in Figure 18), the percentage heat demand in terms of the total heat demand is multiplied with the total heat demand.

For example, the process heat demand for a temperature below 100 °C would be:

$$E_{THD,PH100°C} = PHD_{PH100°C} \cdot \left(E_{THD} + E_{EHD} \right) \quad (4),$$

where

$E_{THD,PH100°C}$: Total head demand for process heat with a temperature below 100 °C [PJ]
$PHD_{PH100°C}$: Percentage head demand for process heat with a temperature below 100 °C [%]
E_{THD} : Total thermal head demand [PJ]
E_{EHD} : Total electric head demand [PJ].

In the next section, more detail is given on the various values used and results obtained from the estimation of the theoretical energy demand. First, a concise overview is presented of the total energy use for SA. Secondly, the theoretical industrial heat demand is estimated. Thirdly, the heat demand below 100 °C is shown.

3.2.3 The total energy used by SA

The SA economy is extremely energy intensive, with only a few countries having higher energy intensities. SA had the 14th-highest total primary energy supply (TPES) per GDP, based on the power purchasing parity (PPP) of 2014[4]. Furthermore, SA has the highest energy intensity among the top 30 countries' GDP (PPP), as shown in Figure 19. SA's TPES per GDP PPP is 1.69 and 3.14 times as large as Malaysia and the Philippines, respectively. These two countries have roughly the same GDP based on PPP as SA. SA is also 2.75 and 2.2 times more energy intensive than Egypt and Brazil, respectively, having around the same GDP PPP per capita.

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[4] Based on data calculations from IEA (2016)

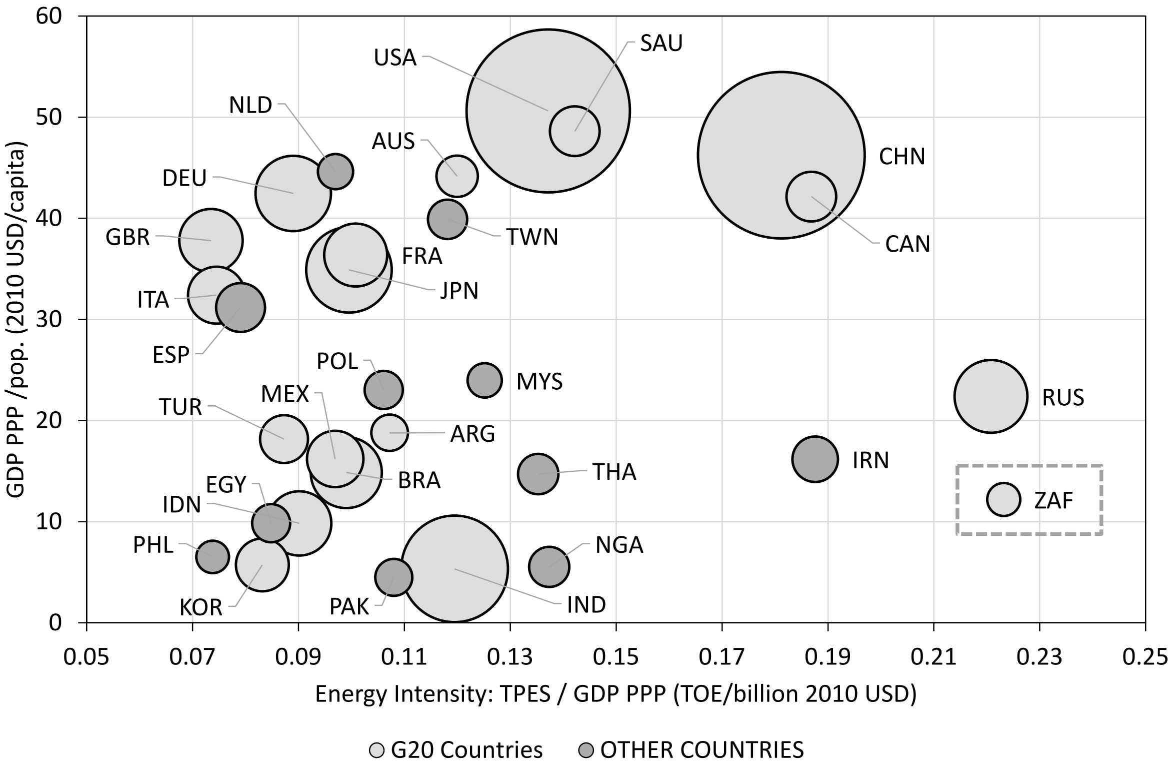

Figure 19: The TPES per GDP PPP per capita versus the energy intensity for the top 30 economies for 2014. Source: Data from (IEA, 2016)

The first step is to choose relevant input data for the total energy use of SA. In total, three authors published on the total energy use of SA, namely the DoE SA (2015), the IEA (2017a), and British Petroleum (BP, 2018). The data of the three authors are compared, from which the most representative data is then chosen.

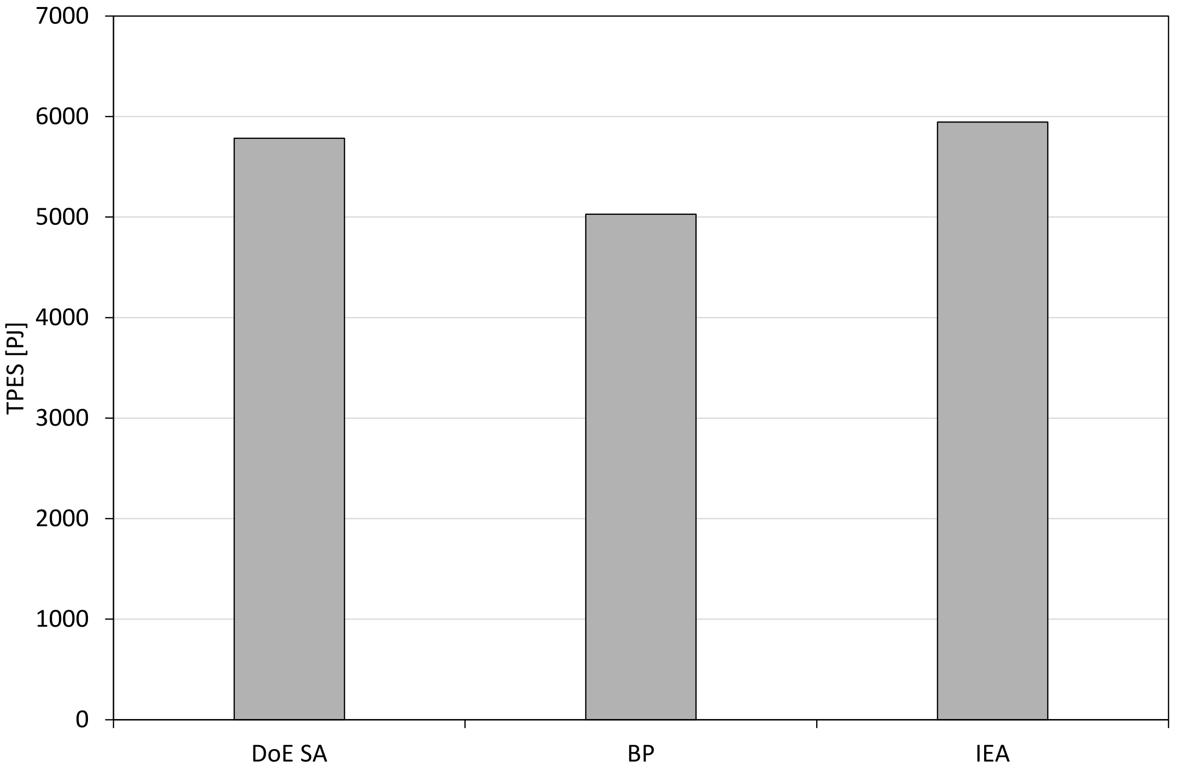

Figure 20: Comparing the TPES for SA. Source: Data from DoE SA (2015) IEA (2017a), BP (2018);

Table 10: Comparison of TPES for SA. Source: DoE SA (2015), BP (2018), IEA (2017a)

Source	TOTAL [TJ]	Difference i.t.o IEA [TJ]	Percentage i.t.o. IEA
DoE SA	5 783 907	162 437	97%
BP	5 028 807	917 537	85%
IEA	5 946 345	0	100%

Figure 20 and Table 10 illustrate that the various sources differ on the total TPES values for SA. The DoE SA and IEA are nearest in value and published data for the 13 divisions. BP (2018) only gives the data use for primary energy consumption by fuel and not by sector or division. The IEA uses 11 sources to determine the values of the energy use of SA (IEA, 2017a). These include direct communication with the DoE SA, Statistics South Africa, Eskom, and Sasol, to name just a few. For this thesis, the data of the IEA is thus used. The uncertainty for the data has been defined as the standard deviation for the DoE SA (2015) and IEA (2017a) data.

The IEA (2017a) reported on the energy use for various sectors and divisions. From Figure 21, one can see the total energy consumption of SA for 2015 is equal to 3 129.6 PJ. Petroleum is by far the largest contributor to energy consumption at 34.8%, followed by coal at 24.5%, and electricity at 22.8%. Solar, wind, and natural gas have a small footprint of only 2.6%. Furthermore, one can see that the industrial industry has the highest energy use of 37.3%. The residential, commerce, and agricultural sector used 32.4%. The transport sector used 24.3% of the total energy use.

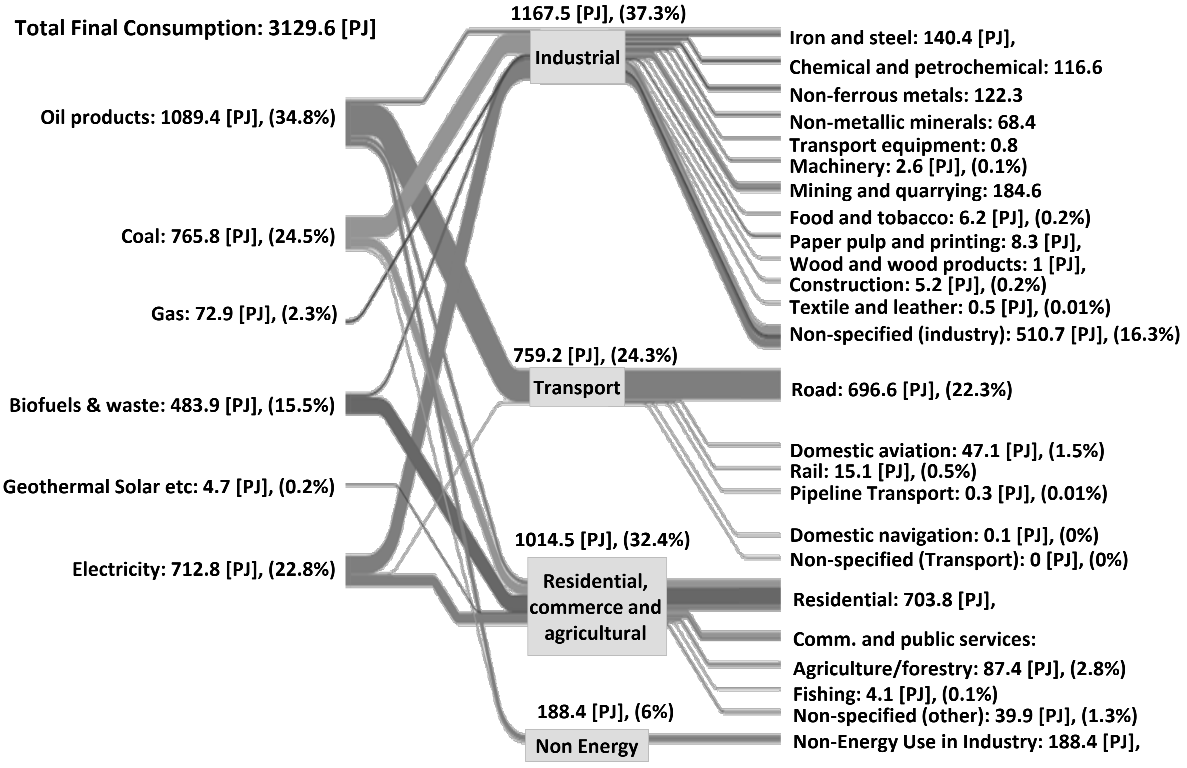

Figure 21: SA energy consumption Sankey diagram 2015. Source: Data from IEA (2016)

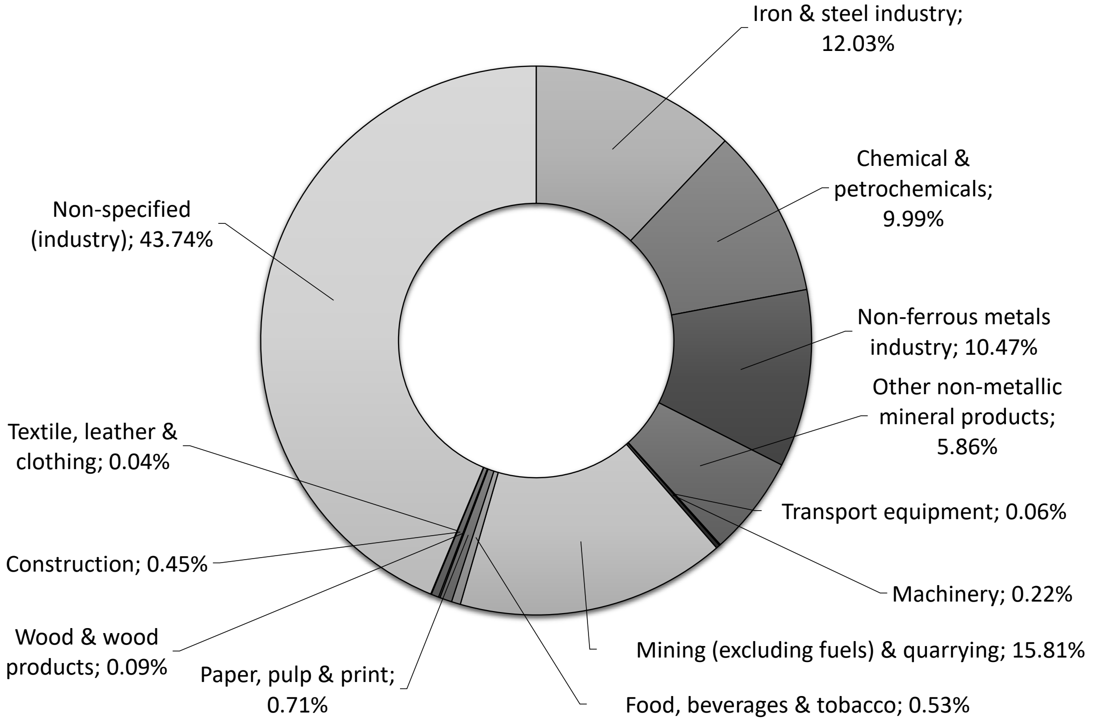

Figure 22: Pie chart showing the percentage of the industrial energy used. Source: Data from IEA (2017a)

To assist in understanding the industrial sector, Figure 22 shows a pie chart of the energy use. From Figure 22, one can see that the largest industrial sector energy user is the non-specified industrial division. According to the IEA (2016), the non-specified division consists of the rubber and plastics (ISIC code 22), furniture (ISIC code 31), and other manufacturing divisions (ISIC code 32). The United Nations (2008) defines the other manufacturing division (ISIC code 32) explicitly as produced goods that can vary widely and that have not been classified elsewhere. The subdivisions of this division include the following: the manufacture of jewellery, musical instruments, sport goods, games and toys, medical and dental instruments, and other manufacturing not elsewhere classified. According to the United Nations (2008), the division of other manufacturing not elsewhere classified includes the manufacture of various products, such as protective safety equipment, brooms and brushes, pens and pencils, umbrellas, and cigarette lighters, to name just a few. Thus, although this division is the largest energy user, it appears to comprise a small part of the economy.

The mining and quarrying division and the non-ferrous metals division were the second- and third-largest divisions. From Figure 22 one can observe that there were several much smaller divisions, including machinery; transport equipment; food and tobacco; paper, pulp and printing; textile, leather and clothing; wood and wood products; and construction. When combined, these divisions make up less than 2.5% of the total industrial sector energy demand, which is very small. On the other hand, the value of the non-specified division appears to be large. Consequently, an investigation is done to determine whether the values are an accurate representation of SA’s energy demand.

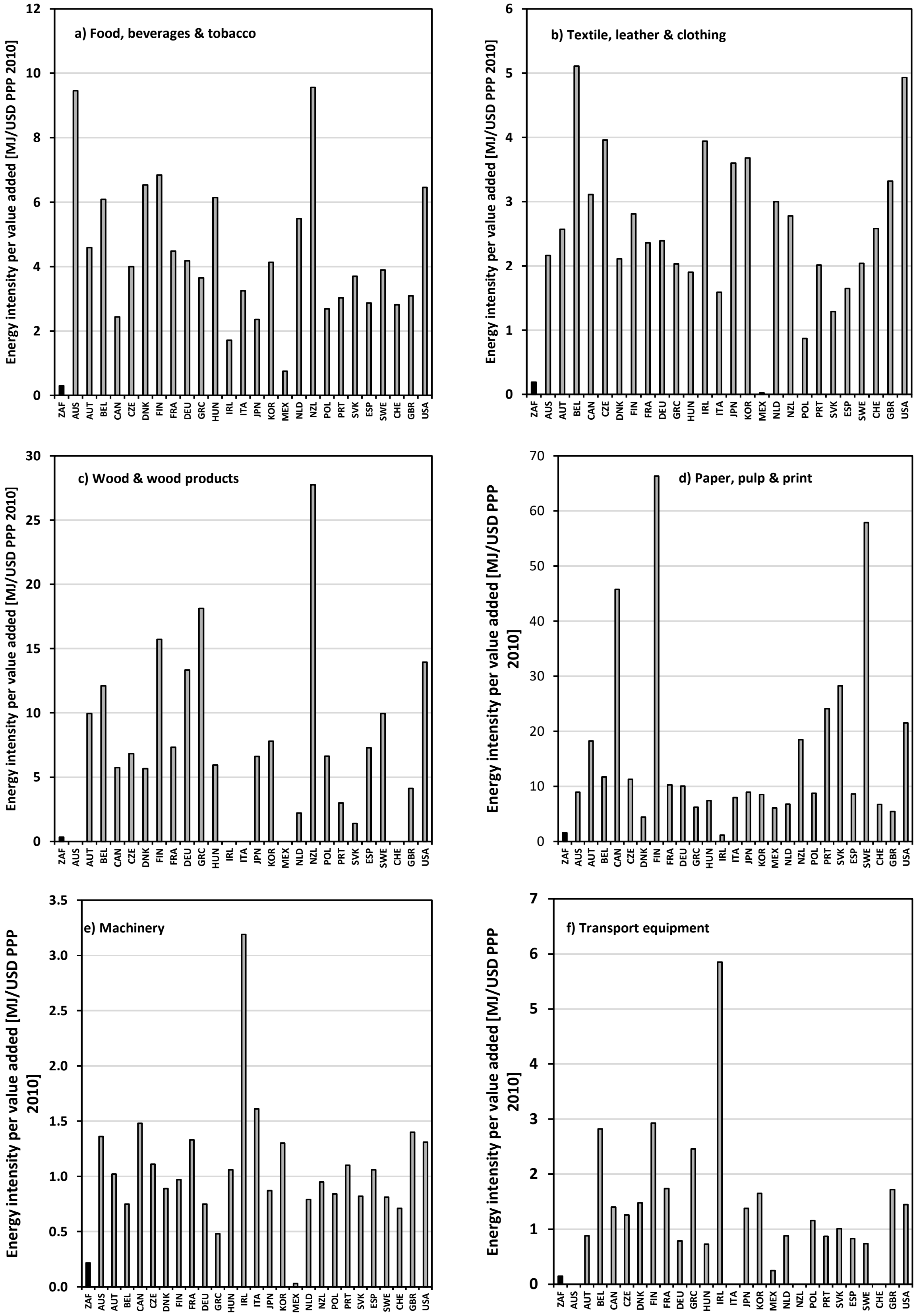

Figure 23: Energy intensity for various divisions. Source: Data from IEA (2016); Statistics South Africa (2019a); IEA (2018b);

Figure 23 shows the energy intensity for all the small divisions in comparison with the other countries. Evidently, SA's energy intensity is much smaller than that of most of the countries. According to the DoE SA (2009), high energy intensities indicate a high price or cost of converting energy to GVA while low energy intensities indicate a lower price or cost of converting energy to GVA. Thus, the divisions mentioned seem to have a low cost of converting energy to GVA. An alternative is that the energy data for the divisions are from a small number of sources. The IEA used the DoE SA as a source for compiling the world energy balances (IEA, 2017b). According to Statistics South Africa (2008), the DoE SA does not have any systems in place to do quality checks but rely heavily on their suppliers for the quality of the data. Usually, the DoE does manual checks for comparing current data with previous data. When anomalies are found, the supplier is contacted for explanations of such inconsistencies, after which revisions are made.

Secondly, the non-specified industrial division is compared between various countries. Figure 24 illustrates that SA's non-specified industrial division percentage energy in terms of the total industrial sector is the fifth highest. Only India, Indonesia, Mexico, and Saudi Arabia have a larger non-specified industrial division than SA, while only India, Indonesia, Mexico, Saudi Arabia, Great Britain and SA have a non-specified division with a value of more than 20%.

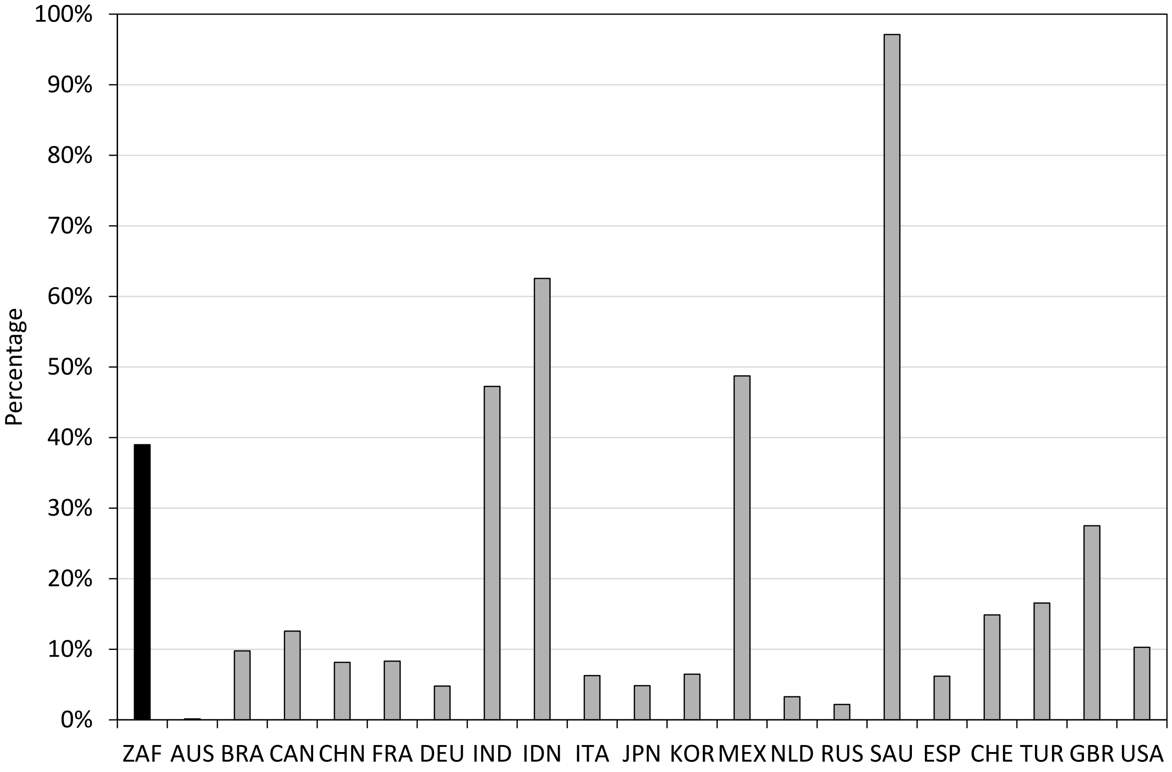

Figure 24: Percentage of the Non-specified industrial division i.t.o. of the total industrial energy demand. Source: Data from IEA (2018a);

It is thus the opinion of the author that the data for the smaller divisions is incomplete. It seems that a part of the energy of the non-specified industrial division needs to be allocated to the smaller divisions. The only other data available for comparison is that of the SA TIMES Model (SATIM) (ERC, 2013). The SATIM model was developed by the University of Cape Town and is now in its third generation. The SATIM base year is 2006, which implies that the data is outdated. Therefore, the current data is used as-is in the next section to generate an estimated theoretical heat demand for SA.

3.2.4 Estimated industrial theoretical heat demand

In this section, the theoretical industrial heat demand of SA is estimated. For this thesis, the data of the IEA is further used. The first step is to divide the industrial energy use into the various industrial divisions and different energy uses. For the industrial sector, the primary energy sources are coal and electricity. The energy consumption for coal and electricity is 476.0 PJ and 437.8 PJ. The share of the total energy use for the industrial sector for coal is 41% and for electricity is 38%.

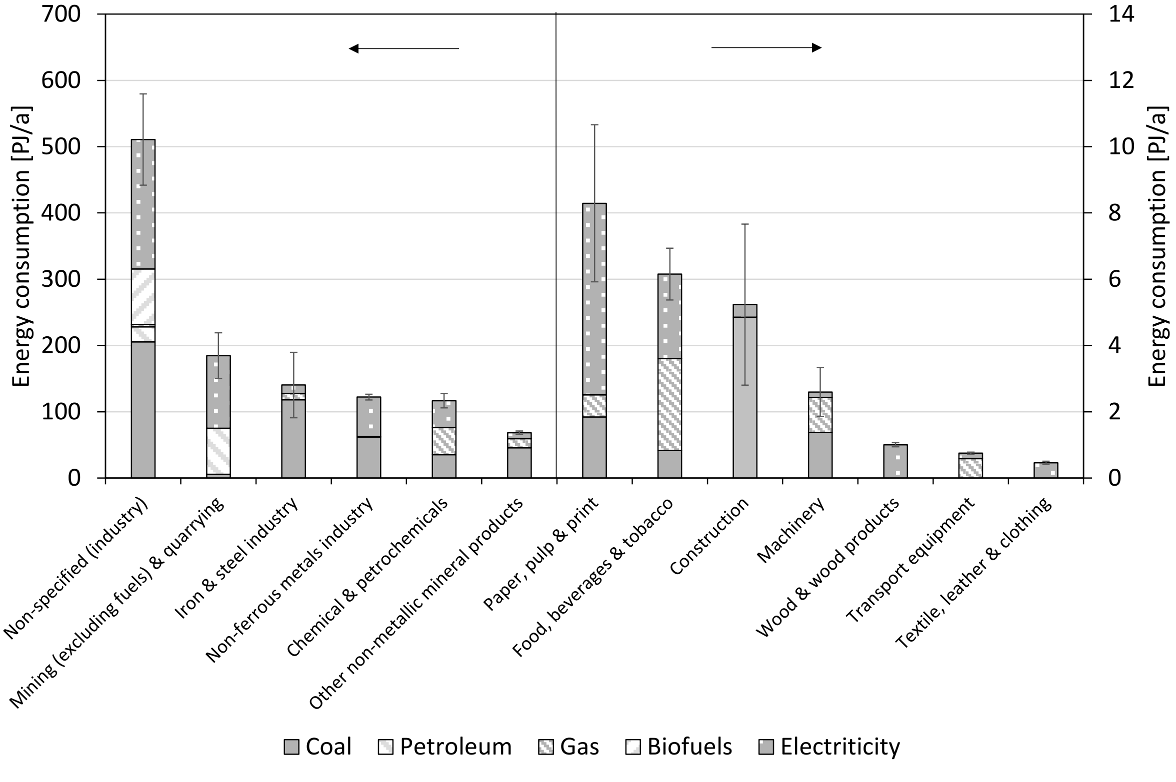

Figure 25: Energy consumption for the industrial sector

Figure 25 illustrates that for the industrial sector, the top three contributors of the total energy consumption are the non-specified division, followed by the mining and quarrying and iron and steel divisions. The uncertainty of the values is due to the difference between the data of the DoE SA (2015) and the IEA (2017a). The construction division; iron and steel division; and the paper, pulp and print division had a very high degree of uncertainty.

The top three divisions' electric use may not necessarily be dominated by process heat but rather by other energy uses. The different energy uses include compressors, material handling, and pumps, among others. To determine which divisions have the highest potential for using CO_2 HPs, it is necessary to consider the heat required for each industrial division. The next step focuses on the industrial electric heat demand.

To determine the electric heat demand in the second step, the fraction heat demand must be determined, as shown in the Equation (2). The IEP (DoE SA, 2016d), ERC (2013), Janse van Vuuren *et al.* (2017) and Howells (2006) indicate the electric heat for the various divisions in SA. Not all the authors stated the electric heat demand for all the divisions as defined in Table 9. To ensure a complete picture, and given that some of the sources are based on international values, the research is extended to include international references. Thus, the following international sources are added: AGEB (2013), the Department for Business (2018), and EIA (2010). The next few paragraphs give a short background of the various authors used to determine the electric heat demand. The complete list of authors is therefore DoE SA (2016d), ERC (2013), Howells (2006), Janse van Vuuren *et al.* (2017), AGEB (2013), the Department for Business (2018), and the EIA (2010).

The IEP (DoE SA, 2016d) reported on the (electric) energy use in five divisions. These divisions include the iron and steel division; the chemicals division; and the non-ferrous metals division. The mining division is further divided into four divisions and other manufacturing. The IEP (DoE SA, 2016d) report did not include the non-metal minerals division in the report, even though this division uses 2% of the energy. However, the IEP included the iron and steel division, which uses 3% of the energy. The data of the IEP (DoE SA, 2016d) report is based on work done by Eskom's Integrated Demand Management (IDM). The author gave no further detail on the source or how the various divisions were subdivided and which standard industrial codes were used for the different divisions. However,, the National Energy Act 34 (2019) indicated that energy data will be recorded according to SA SIC. The author thus concludes that IEP document used the SA SIC standard (Statistics South Africa, 2013)..

As part of the SATIM model, the ERC (2013) had to make assumptions based on the share of electricity consumption by energy services within the industrial divisions. The ERC (2013) approach was to supplement the SA data available from local studies with those from the EIA Manufacturing Energy Consumption Survey (MECS) of 1998 (EIA, 1998). Where no data was available, the ERC (2013) used their personal opinions. For this thesis, the most recent set of MECS data (EIA, 2010) is used.

Howells (2006) did an investigation to establish which divisions to target for energy audits and demand-side management (DSM) projects. As part of the project, an assumption was made on the electricity end-users (motors, process heat, lighting, etc.) in the different divisions. These assumptions were based on the United States Department of Energy’s EIA, the British Department of Trade and Industry, and the mining division the SA DoE’s IEP.

Janse van Vuuren *et al.* (2017) investigated the theoretical potential of solar thermal heaters in SA. The publication was funded by The Green Trust, a partnership between the WWF and Nedbank. The author investigated the food and beverages division and the textile division. For this, the author used the SA DoE and SATIM data. Janse van Vuuren *et al.* (2017) assumed that 10% of the electric demand is used for heating. The 10% seems to be based on the author's personal opinion, as no secondary source was given. For the food, beverage, and tobacco division, the values are approximately the same as for the SATIM data. No other South African data was found for the textile division.

It seems that only the IEP data (DoE SA, 2016d) is based solely on South African data. Janse van Vuuren *et al.* (2017) did not provide secondary sources for their assumptions. The approach of Howells (2006) and the ERC (2013) was to supplement the South African data available from local studies with international benchmarks. It is important to note that the international values are outdated and not based on local practice. The values are thus only indicative of the South African scenario. Finally, some of the divisions left out by the IEP are of specific importance for the CO_2 HP research in this study. These include the food, beverage, and tobacco division and the paper and paper products division.

The AGEB annually publishes the primary energy balance, transformation range, and the final energy balance for the various divisions. Based on the energy balance of a consumer division, the application balance provides additional information on the energy used by several divisions. To obtain a more representative value, the average values from 2009 to 2016 are determined for the various industrial divisions; only the process heating data is included. As with the literature study, it is assumed that space heating does not apply to the industrial sector of SA. The combined data for warm water and space heating is thus excluded.

The Department for Business’ Energy and Industrial Strategy provides information for overall energy consumption in the United Kingdom (Department for Business, 2018). The high- and low-temperature process data was combined to determine the electric heat demand for the United Kingdom. According to de Haan and Bosch (2013), drying and separation may be carried out mechanically with phase changes or by evaporation through the supply of heat. No detail was given on the percentage share between drying and separation. Thus, it is not possible to determine from the data how much electric energy is used for evaporation; therefore, the data is excluded. To ensure a more representative value, an average is taken for the data from 2010 to 2017.

The MECS (EIA, 2010) is a national sample survey that collects information on the stock of United States manufacturing establishments, their energy-related building characteristics, and their energy consumption and expenditures.

The 2010 MECS EIA (2010) is EIA's eighth survey of the manufacturing industry and covers the 50 States and the District of Columbia. The 2010 MECS took a sample size of approximately 15 500 establishments from a nationally representative sample frame representing 97% to 98% of the manufacturing payroll. This sample allows the EIA to report separate estimates of energy use for 21 three-digit industrial subdivisions, according to the NAICS. The classification of the NAICS is different from that of the ISIC rev. 4. Due to these differences, there is a degree of uncertainty when comparing values with other international sources.

The various data sources use different classification systems are combined to determine the best value for the amount of electric heating available. The various authors used various standards for the naming of the sectors and divisions. These differences make it difficult to make exact conclusions from the multiple sources for a specific division classification used. Furthermore, the various authors results are not disaggregated on a lower level than the division level. Thus, the uncertainty cannot be quantified, and the results are thus an only an estimation of the theoretical heat demand.

Table 11: Comparison of total electric heat demand for the various divisions. Source ERC (2013), DoE SA (2016d); Janse van Vuuren *et al.* (2017); Howells (2006); Department for Business (2018), EIA (2010); AGEB (2013)

ISIC no	Description ISIC	Chosen value	Uncer-tainty	IEP#	IEP	TIMES	Janse v Vuuren *et al.*	Howell	MECS	ECUK	AGEB '09-16
07, 08, 99	Mining (excluding fuels) & quarrying	6.0%	1.9%	6.0%	6.0%	2.0%		2.0%			
10-12	Food, beverages & tobacco	8.2%	1.5%	8.2%		9.0%	10.0%	6.0%	7.7%	34.9%	13.3%
13-15	Textile, leather & clothing	8.2%	1.7%	8.2%			10.0%	6.0%	8.6%	21.1%	
16	Wood & wood products	7.4%	3.5%	7.4%		2.0%		9.0%	7.7%	10.8%	
17, 18	Paper, pulp & print	12.2%	7.0%	12.2%					5.1%	19.2%	
20, 21	Chemical & petrochemicals	4.1%	0.8%	4.3%	4.3%	3.0%		4.0%	5.1%	10.4%	19.9%
23	Other non-metallic mineral products	19.0%	7.9%	19.0%		23.0%		8.0%	26.1%	53.8%	
241, 2431	Iron and steel division	59.6%	9.5%	59.6%	59.6%	40.0%		39.0%			
242, 2432	Non-ferrous metals division	22.9%	10.3%	22.9%	22.9%	1.0%		1.0%			
25-28	Machinery	27.7%	12.4%	27.7%					15.3%	40.1%	
29, 30	Transport equipment	18.0%	10.1%	18.0%					11.4%	32.3%	10.3%
41-43	Construction	5.0%	5.0%	5.0%							
22, 31, 32	Non-specified (industry)	38.0%	12.8%	38.1%							
xx	Other (Non-specified)	38.1%	12.8%	38.1%	38.1%	10.7%		11.0%			

From Table 11, one can see that the author based the chosen value for the electric heat demand mainly on the values from the IEP (DoE SA, 2013), Howells (2006), and ERC (2013). Where little data was available on SA, the author supplemented this data with data from international sources. Where no data was available, the author's personal opinions were used. It is important to note that these values are indicative, with some values based on local practice while other values are based on international practice.

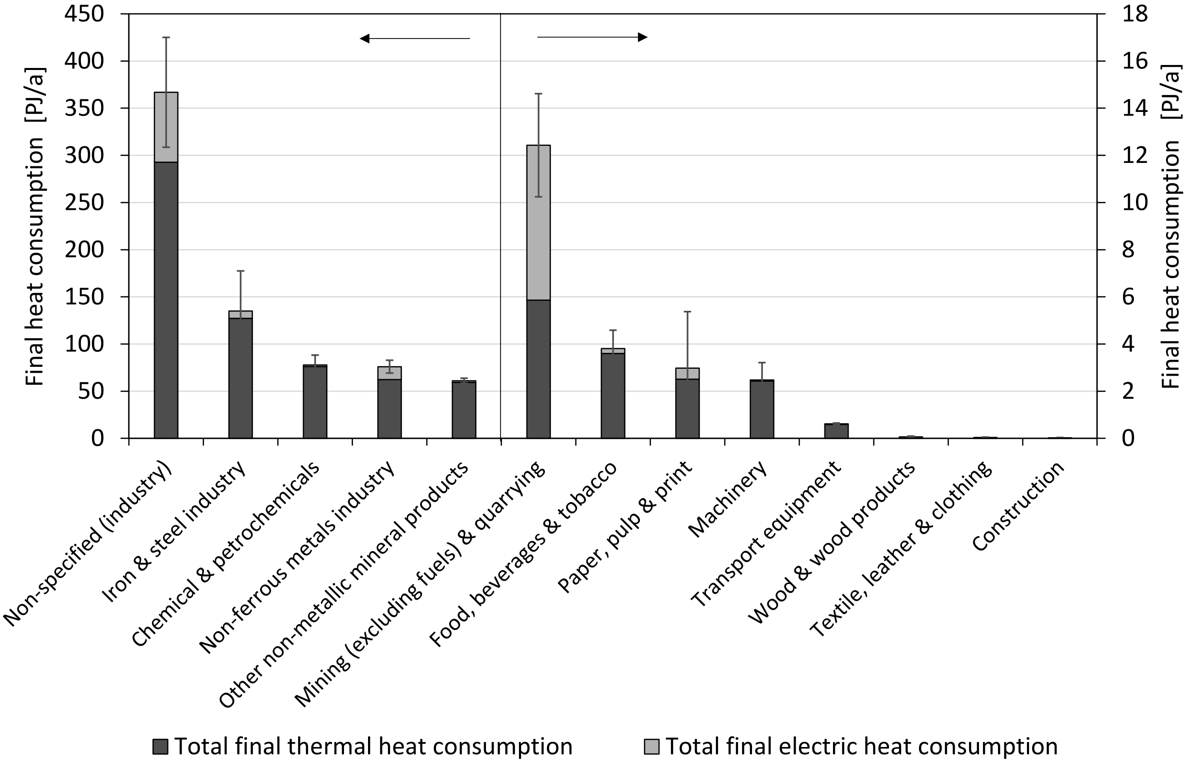

Figure 26: Total final heat consumption for the various industrial divisions in SA

Figure 26 shows the final heat consumption for SA. From Figure 26, one can see that the non-specified industrial division has the largest heat consumption, namely 366.8 ±58.1 PJ/annum. The iron and steel division had the second-highest heat consumption at 135.1 ± 42.3 PJ/annum.

To determine the total thermal heat demand, the boiler efficiency of the various processes must be integrated, as shown in Equation (3). Boiler and steam distribution plant efficiency is dependent on several factors. These include the state of insulation, state of steam traps, and the state of feed water treatment, among others (Turner & Doty, 2007). According to Bessette (2002), energy efficiency for industrial boilers is a highly boiler-specific characteristic, and no two boilers are alike. For example, two identically designed side-by-side constructed stoker-fired boilers in the same location burning the same fuel have quite different performance characteristics. According to Taole *et al.* (2015), Johns and

Harris (2009) indicated that in 2009, there were approximately 6 000 boilers in SA. Currently, no database exists for SA boiler efficiency.

ERC (2013), Bessette (2002), and Werner (2005) reported on the efficiency of industrial boilers. In the next few paragraphs, an introduction is given on the various authors. As part of the SATIM model, the ERC (2013) had to make assumptions on boiler efficiency. The ERC (2013) did not indicate any secondary sources or how the values were obtained.

As part of the Steam Digest of 2002, which is published by the United States Department of Energy, Bessette (2002) did an article on the energy efficiency of new industrial boilers. The article addressed the efficiency-related aspects of the four primary factors affecting the industrial boiler and the factors affecting the application of combined heat and power systems to industrial facilities (Bessette, 2002).

For the ECOHEATCOOL project, Werner (2005) had to determine general averages of energy conversion efficiencies. The vales of the various authors are combined in Table 12. The uncertainty is chosen to ensure that all the values are accommodated for. For heat distribution systems, an efficiency of 95% with an associated uncertainty of 5% is chosen.

Table 12: Typical efficiency for boilers. Source: Bessette (2002), Werner (2005), ERC (2013)

Boiler	**Chosen value**	**Uncertainty**	**Maximum continuous rating, Bessette (2002)**	**Low-load efficiencies, Bessette (2002)**	**Energy conversion efficiencies, Werner (2005)**	**Boiler efficiency; ERC (2013)**
Coal	77%	13%	85%	75%	85%	64%
Oil (paraffin) [5]	73%	7%	80%	72%		68%
Natural petroleum gas (LPG)	77%	13%	75%	70%	90%	72%
Biomass and waste	69%	16%	70%	60%	85%	60%
Electricity	88%	12%			100%	76%
Heat	90%	5%			100%	

The boiler efficiency, combined with the total thermal consumption, can thus be used to determine the theoretical industrial heat demand.

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[5] All the values are show for completeness. Although the amount of Oil used for heating is not given for South Africa.

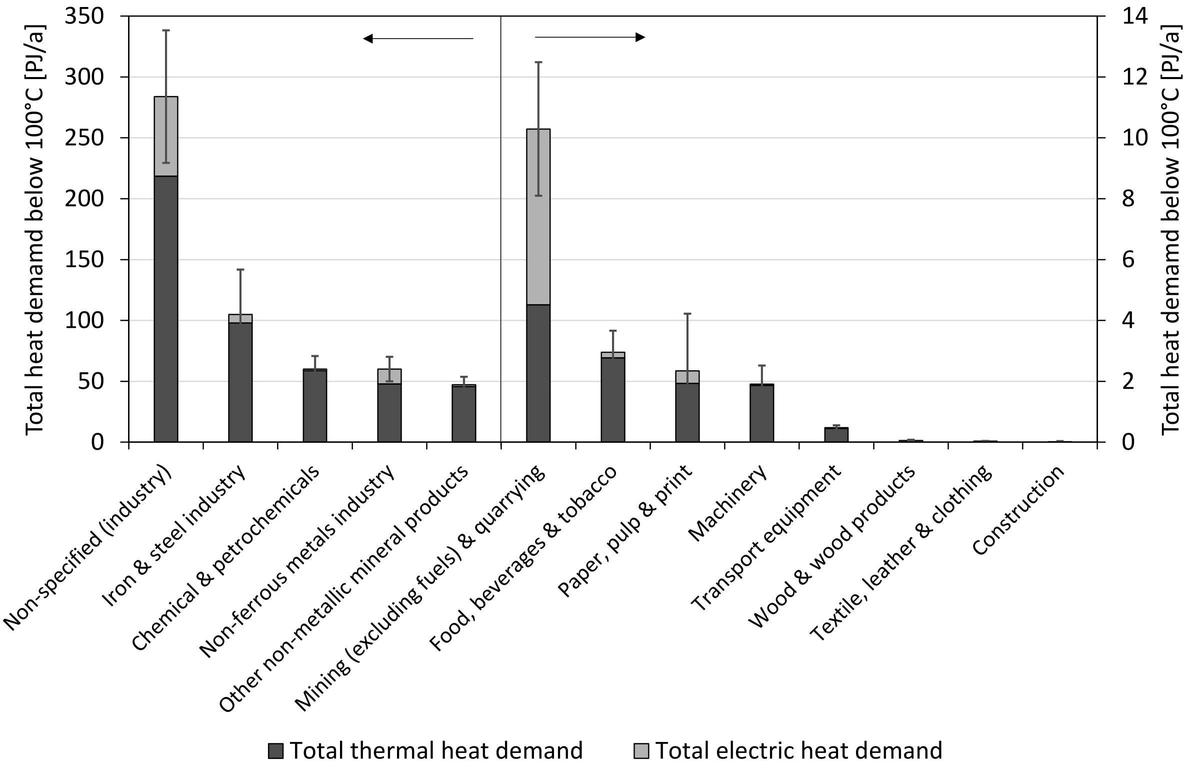

Figure 27: The total theoretical heat demand for SA for the various industrial divisions. Source: IEA (2016)

Figure 27 shows the total theoretical heat demand for SA for the various industrial divisions. From Figure 27 one can determine that the total heat demand for SA is 574.28±54.48 PJ, with an associated uncertainty of 9.5%. The percentage of the total heat demand is 52%. The non-specified, iron and steel, chemical and petrochemical, non-ferrous metals, and non-metallic minerals divisions have the highest heat demand. No significant conclusion can be made from the non-specified division.

The divisions on the right have a much smaller heat demand, with a total heat demand of less than 16 PJ/annum. This is equal to roughly 3% of the total thermal heat demand in the division. It is vital to note that the thermal demand for the values of the divisions of wood and wood products, textile, leather and clothing, and construction are zero.

The electrical heat demand for machinery, transport equipment, wood and wood products, textile and leather, and construction is minimal with a total of 0.175 PJ. The value is only 0.17% of the total electric heat demand.

Before it is possible to determine which divisions have the highest potential for CO_2 HP integration, the heat demand must be disaggregated according to the various temperature levels. The next section focuses on the heat demand at a temperature below 100 °C.

3.2.5 Estimated heat demand below 100 °C

To determine the theoretical potential for heat in industrial processes, a thorough analysis of the industrial heat demand and its temperature levels is necessary. No heat demand data at low-temperature levels for SA could be found; thus, an investigation is done to estimate the value from international sources.

Various authors have investigated the heat demand for different temperate levels. These include Pardo *et al.* (2012), Arpagaus *et al.* (2018), Lambauer *et al.* (2008), Wolf *et al.* (2014), Wolf (2017), and Werner (2005). To ensure that the data is representative, a large data pool from with the most recent data must be considered. Pardo *et al.* (2012) analysed the heating demand situation in the 27 EU states for 2009. They followed the approach defined in Werner (2005) in considering three temperature intervals in the industrial sector.

The processes such as washing, rinsing, and food preparation correspond to a temperature range lower than 100 °C. The temperature range may also compare to the energy needed for space heating of the industrial facilities and hot water preparation. This data is constructed using the 2009 final energy data published by Eurostat together with the breakdown by temperatures, the energy that goes to the processes for heating in each division, and the energy efficiency of each equipment based on the type of fuel.

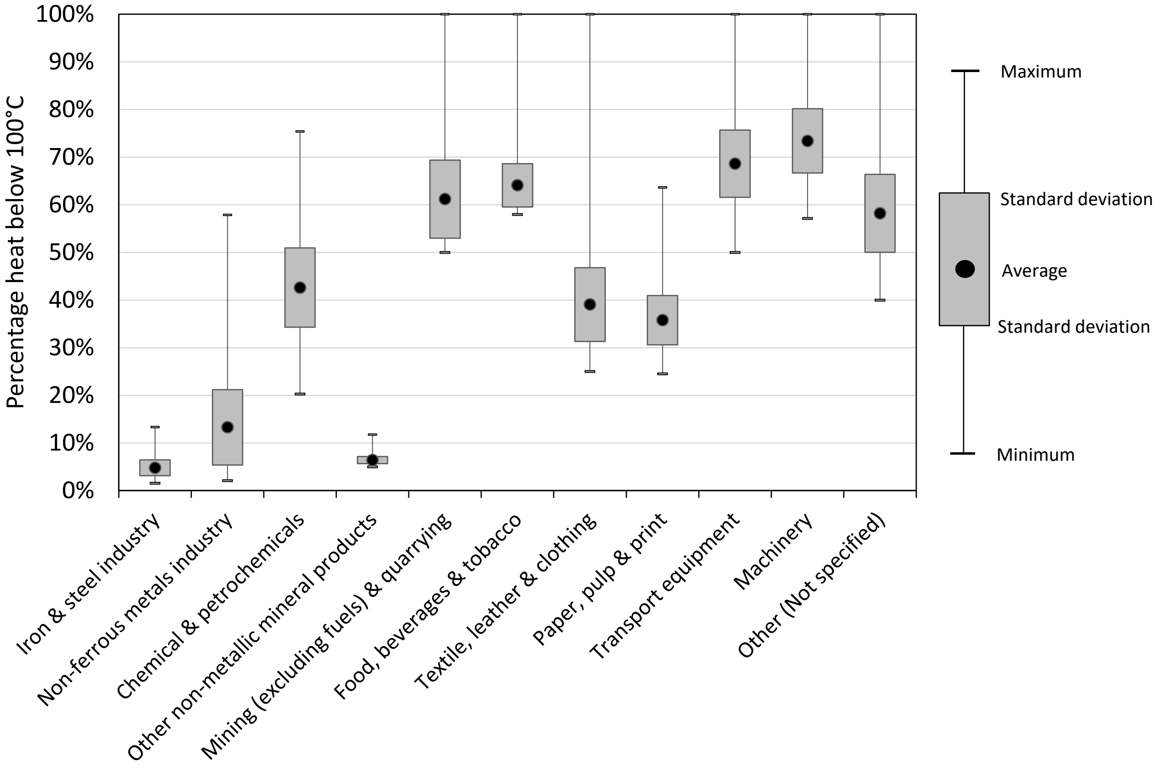

Figure 28: Percentage heat below 100 °C for 27 EU members. Source: Pardo *et al.* (2012)

Figure 28 illustrates that for the most divisions, the heat demand below 100 °C for the various 27 EU states has a large standard deviation. Only the iron and steel division and the other non-metallic mineral products division have a standard deviation of below 4%. Using this data as-is results in great uncertainty on the final answer.

Consequently, the data is reduced by ranking the energy demand of the divisions for the various countries. The energy demand is obtained from IEA (2011) for 2009, which is the same year for which Pardo *et al.* (2012) determined the heat demand. The IEA (2011) did not offer detailed energy data for Bulgaria, Cyprus, Lithuania, and Malta, and these countries are thus excluded. For each division, the top three energy users, as well as the combined data for Europe, are chosen as a representative sample of the heat demand below 100 °C.

The wood and wood products division was not included by Pardo *et al.* (2012). Consequently, the data of Frisch *et al.* (2010) and Lauterbach *et al.* (2012) is included. No source could be found for the heat demand below 100 °C in the construction division. This division is then also excluded, as it only uses 0.02 PJ of the total energy demand.

From Figure 29 can be seen that the standard deviation for most divisions is much less than the values in Figure 29. For the chemicals and petrochemicals division, wood and wood products division, and the non-specified division, the standard deviation is still high. These divisions should therefore be compared at the process level. However, as this information is not readily available, the data is, consequently, taken as is.

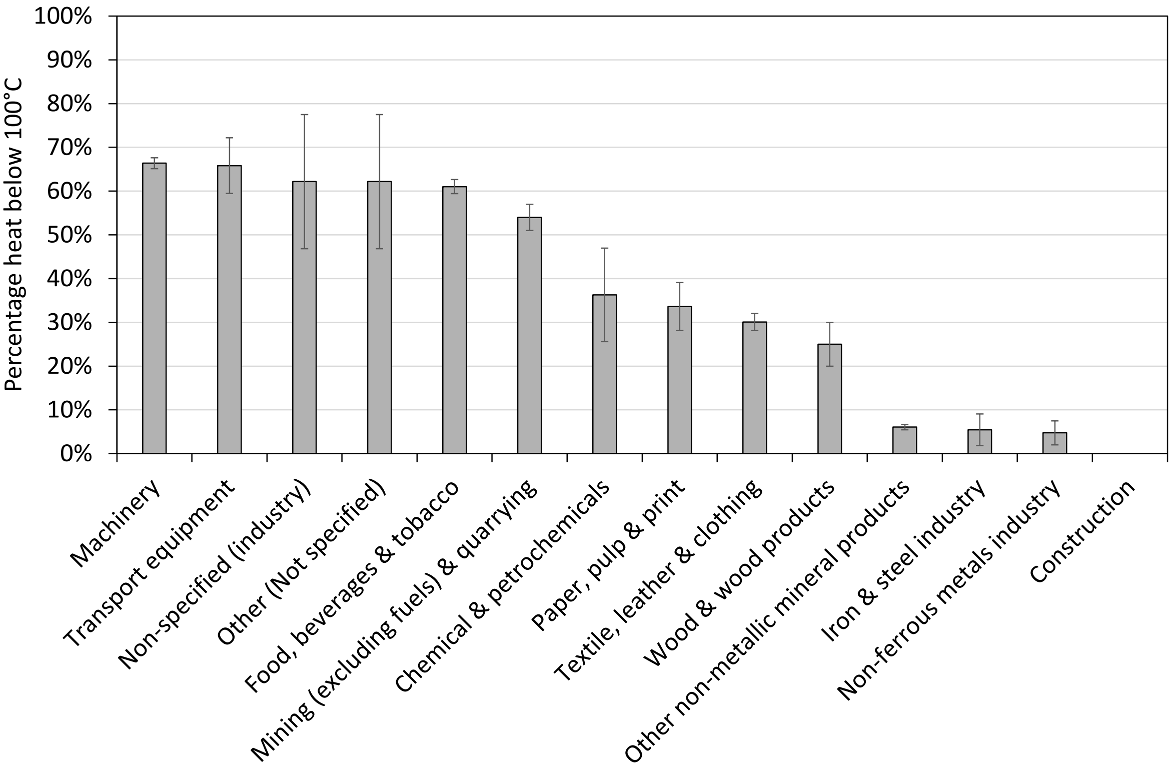

Figure 29: Percentage heat below 100 °C for top thee energy users, including the EU total. Source: Pardo *et al.* (2012)

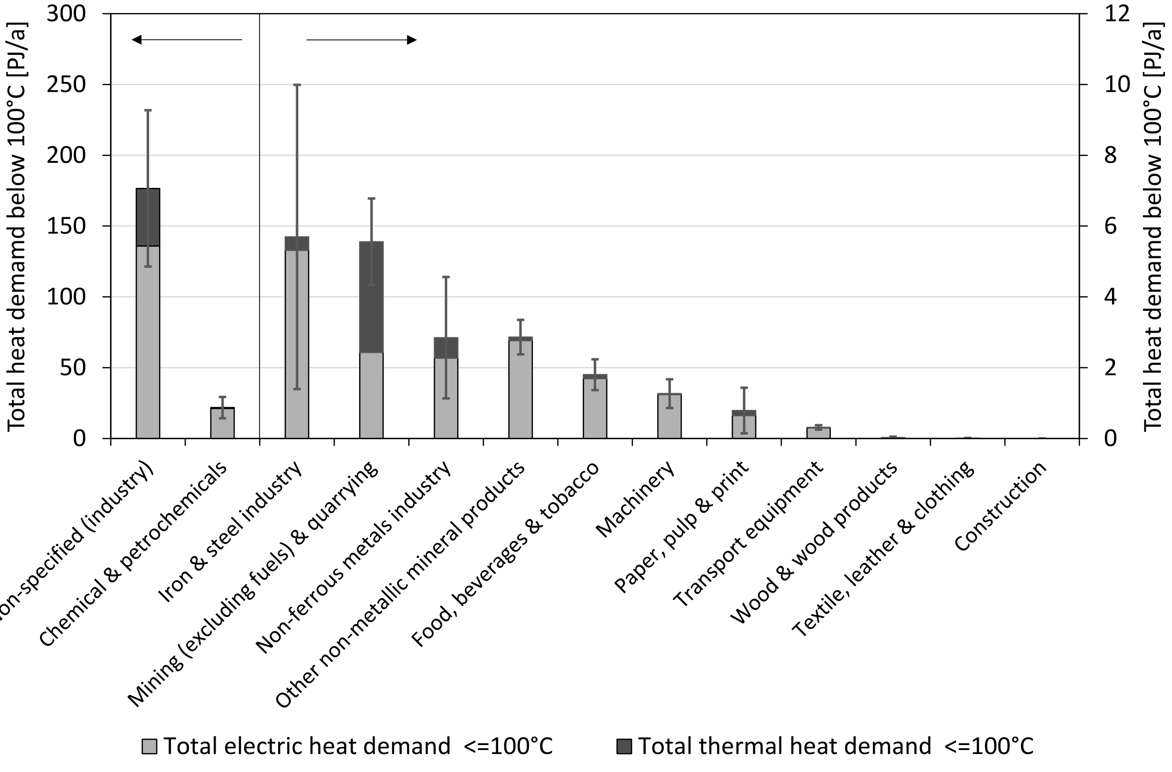

Figure 30: Theoretical potential heat below 100 °C SAs

Figure 30 shows that for SA, the non-specified industrial division has by far the largest theoretical potential for heat below 100 °C, with a share of nearly 80.4% (176.5±55.1 PJ/annum). As previously mentioned, this division is highly diversified; therefore, no significant conclusion can be made.

The chemical and petrochemicals division has the second-largest theoretical potential for CO_2 HP integration, with a share of nearly 9.9% (21.8±7.5 PJ/annum). The rest of the division altogether makes up about the remaining 9.6% (21.1 PJ/annum).

For SA, the food, beverage, and tobacco division has the seventh-highest theoretical potential with a share of only 0.8% (1.8±0.4 PJ/annum) of the total heat demand below 100 °C. This observation contradicts the literature research, which showed that the food, beverage, and tobacco division has the highest heat demand for various countries.

From the literature, the most popular divisions where CO_2 HPs were installed are the paper, pulp and print division; the food, beverages, and tobacco division; the chemicals and petrochemicals division; and the mining of ores division. For SA, the chemical and petrochemicals division has a large heat demand. Thus, the division compares well with the literature research.

The total theoretical heat potential below 100 °C for SA is thus 219.5 ±71.93 PJ/annum. The value is equivalent to 18.8%±6.2% of the total industrial energy demand of SA. From the data one can conclude that the theoretical heat potential below 100 °C of the industrial sector is between 80% and 160% of the combined heat demand of the residential and commercial sector. CO_2 HP thus have the same impact on the industrial sector than conventional heat pumps on the residential and commercial sector.

The uncertainty is very high, at 33%. The high uncertainty is due to the uncertainty of the heat demand below 100 °C and the efficiency of the coal boilers. These variables affect the uncertainty by 62.3% and 9.1%, respectively. These two variables account for more than 71.4% of the total uncertainty. To reduce the uncertainty of the heat demand below 100 °C one need to reduce the data using a different criterion. An alternative criterion is that one rather base the heat demand the GVA size of each sector.

The total theoretical heat potential, excluding the non-specified division's heat potential for SA, is 42.98 ±0.003 PJ/annum. This value has a very low degree of uncertainty. Thus, the non-specified division causes a high degree of uncertainty.

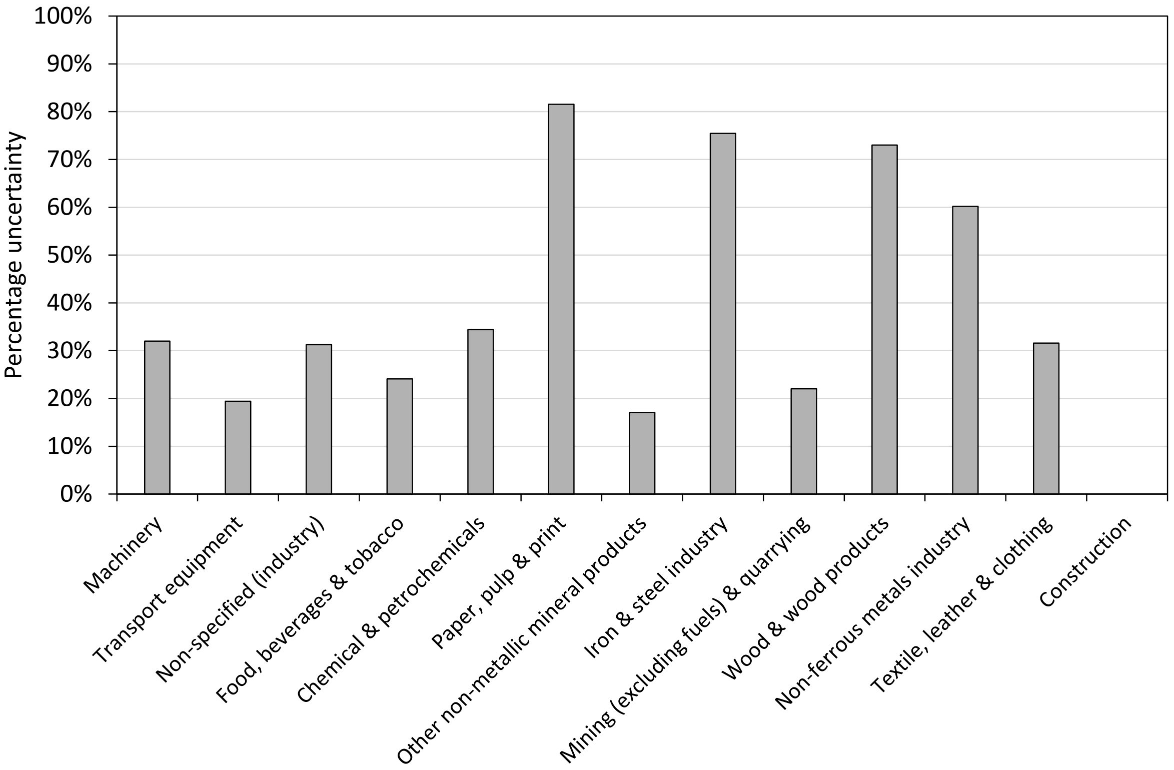

Figure 31: Percentage uncertainty of the total thermal demand for temperatures below 100 °C s

Most of the divisions have a relatively high degree of uncertainty. Figure 31 shows that the highest uncertainty is for the paper, pulp and printing division, with a relative uncertainty of 81%. This uncertainty is driven by the high uncertainty of the gas and coal values. The second-highest relative uncertainty is 75% for the iron and steel division. This uncertainty is caused by the fraction of the heat demand below 100 °C, which contributes 78.2% to the total uncertainty.

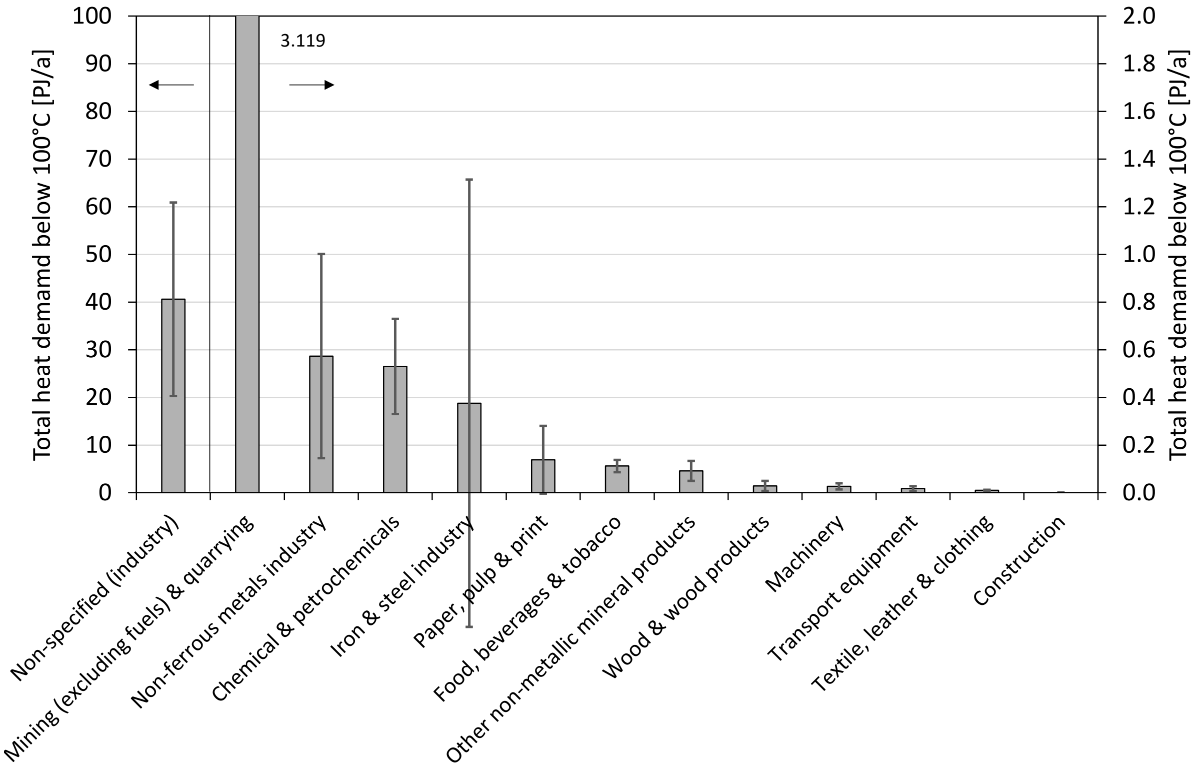

Figure 32: Theoretical electric potential heat below 100 °C in SAs

Traditionally, HP were used to replace commercial electric boilers. If one thus assumes that CO_2 HPs were to replace the electrically heating in industry the theoretical potential is much smaller. The theoretical electric heat potential for SA is 45.61±20.3 PJ/annum. The theoretical electric heat potential uncertainty is nearly 45%. This uncertainty is driven by the uncertainty of electric heat and of the fraction heat demand below 100 °C. These factors contribute 45.4% and 24.3% to the uncertainty, respectively.

From Figure 32 one can see that for SA, the non-specified industrial division has the largest theoretical electrical potential for heat below 100 °C, with a share of nearly 89.0% (40.5 PJ/annum). The second-largest theoretical potential for CO_2 HP integration is the mining (excluding fuels) and quarrying division, with a share of 6.8% (3.1 PJ/annum). The rest of the divisions altogether make up about the remaining 4.2% (1.9 PJ/annum).

From this analysis, the mining (excluding fuels) and quarrying division; the chemical and petrochemicals division; the non-ferrous metals division; and the iron and steel division have the largest potential for CO_2 HP integration. The observation contrasts the literature study, which indicated that the food, beverage, and tobacco division has the highest frequency for the potential study. The food, beverage, and tobacco division also has the highest number of installed HPs, with a large share of CO_2 HPs that had a straight payback of less than five years.

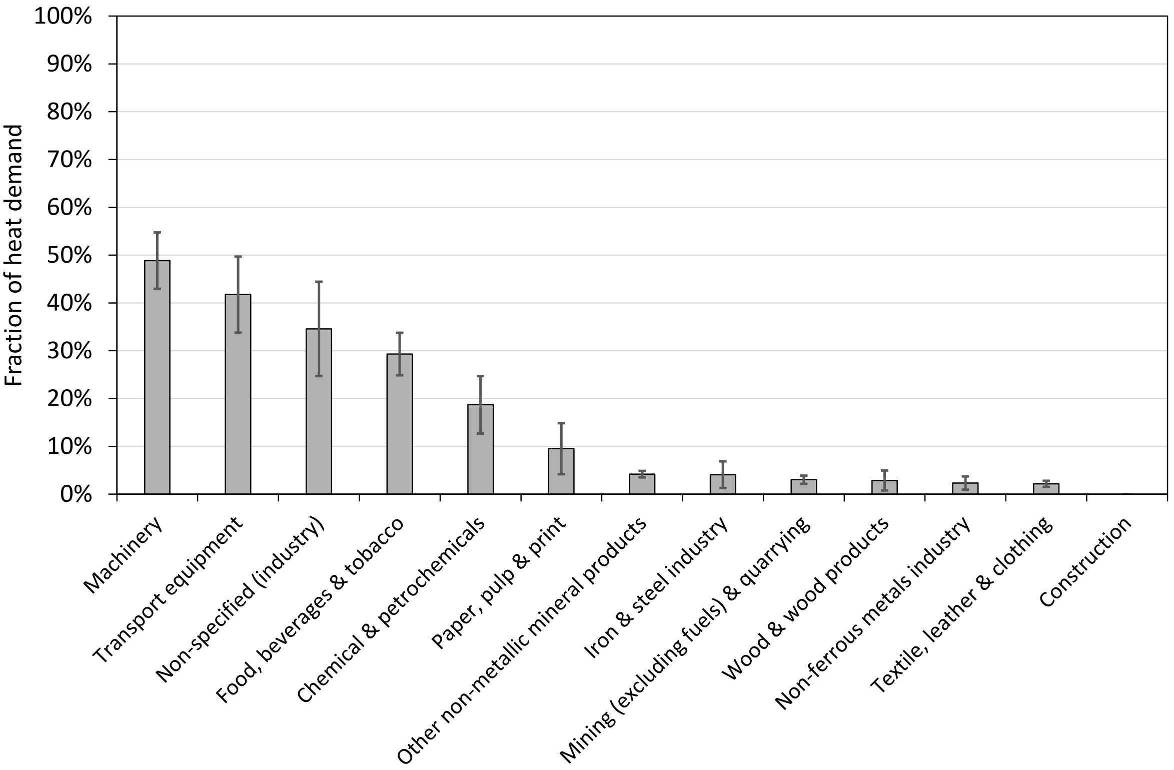

Figure 33: Fraction heat demand below 100 °C in terms of the total energy demands

Figure 33 shows that the machinery, transport equipment, and food, beverage, and the tobacco divisions have the highest share of temperatures of below 100 °C. The available heat below 100 °C is respectively 48.9%; 41.8% and 34.6%. These three divisions thus have the highest fraction heat demand. Therefore, although the divisions' heat demand is not the highest, they may still be a viable option for the integration of CO_2 HPs.

Before it can be determined which division is the best to implement CO_2 HPs, the values must be compared first. In the next section, a comparison is made to ensure the results obtained are in line with various other sources found.

3.3 Comparison of the total heat demand and theoretical heat demand

In this section, a comparison is done of the total heat demand and theoretical heat demand. This section is divided into three subsections. First, the estimated industrial theoretical heat demand of the six divisions in SA is compared with IEP (DoE SA, 2013). Secondly, four of the smaller divisions are compared to those in Knaack *et al.* (2019) and ERC (2013). Thirdly, the percentage heat demand below 100 °C is compared with those of 28 European countries, based on data from Fleiter *et al.* (2017).

3.3.1 Comparing the total heat demand for the six largest divisions against values from the IEP (DoE SA, 2013)

The IEP (DoE SA, 2013) indicated the percentage process heating in terms of the final energy end-use for six divisions. This data can then be used to compare the thermal heat demand for the six divisions listed. The IEP (DoE SA, 2013) indicated that these values were based on the DoE SA's calculations. However, the secondary sources were not listed in their reference list. Consequently, the percentage thermal demand of the six divisions is determined for 1999 to 2015, as shown in Figure 34.

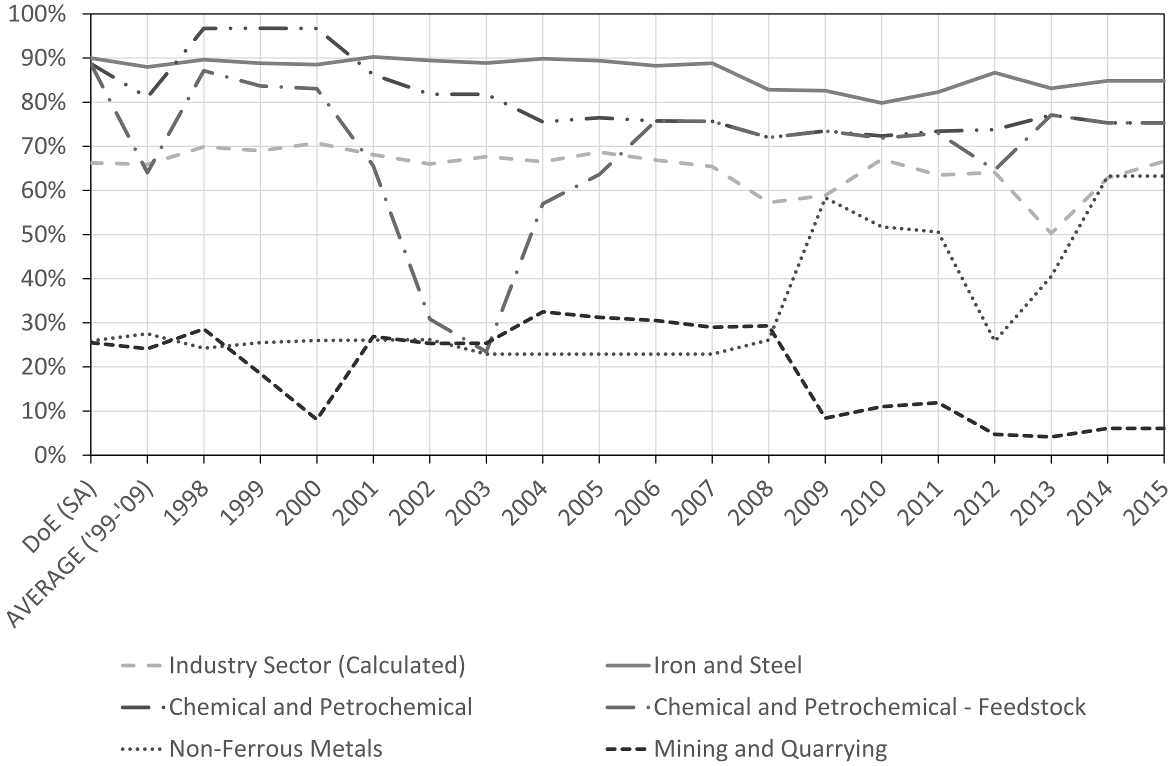

Figure 34: The percentage thermal energy in terms of the total energy use of the divisions. Source: DoE SA (2013)

From Figure 34, one can see that the percentage thermal energy in terms of the total energy end-use of the industry sector is not constant for the various years investigated. The values also differ widely from the values indicated by the IEP (DoE SA, 2013). For example, for the industrial sector, the values differ only by 0.32% for 2015 while for 2008, the values were off by up to 9%.

However, when comparing the tenth year with the IEP values, the industrial sector thermal heat demand is off by less than 0.35%. The iron and steel division; the non-ferrous metals division; and the mining and quarrying division differ from the IEP values by less than 3%. The chemical and petrochemical division differ by 7.66%. Thus, these industrial sectors compare well with the data of IEP.

3.3.2 Comparison of the total heat demand below 100 °C for four small divisions

As part of the Solar Heat for Industry Project in SA, Knaack *et al.* (2019) estimated the steam boiler heat for various divisions in 2017. According to Knaack *et al.* (2019), steam is the dominant heat transfer medium in industrial applications that require heat at temperatures below 400 °C. Although the steam is the primary heat transfer fluid for many plants from a centralised boiler system, the actual process temperature required is lower than 100 °C. Knaack *et al.* (2019) consulted with experts within the steam boiler field to get an indicative view of the installed heating capacity in the industrial sector. Large boilers exceeding 16 MW in the sugar, chemicals and paper and pulp divisions are not included in their analysis.

Knaack *et al.* (2019) also conducted a study to analyse the fuels used for process heating in different divisions. For the comparison of the results, three sets of independent data sources are consulted. These include the aggregated energy audit data from the National Cleaner Production Centre, registered combustion emissions sources from the City of Cape Town, and industrial market research data from the South African company Ozone Business Consulting. In total, data for 506 South African companies has been gathered.

As part of the SATIM model, the ERC (2013) estimated the energy consumption per fuel or energy carrier for eight divisions. The ERC (2013) had much higher values for the food, beverage, and tobacco as well as the paper, pulp, and print division. These values were estimated for 2006 and are thus outdated. However, one can still compare the current values to that of the SATIM model (ERC, 2013).

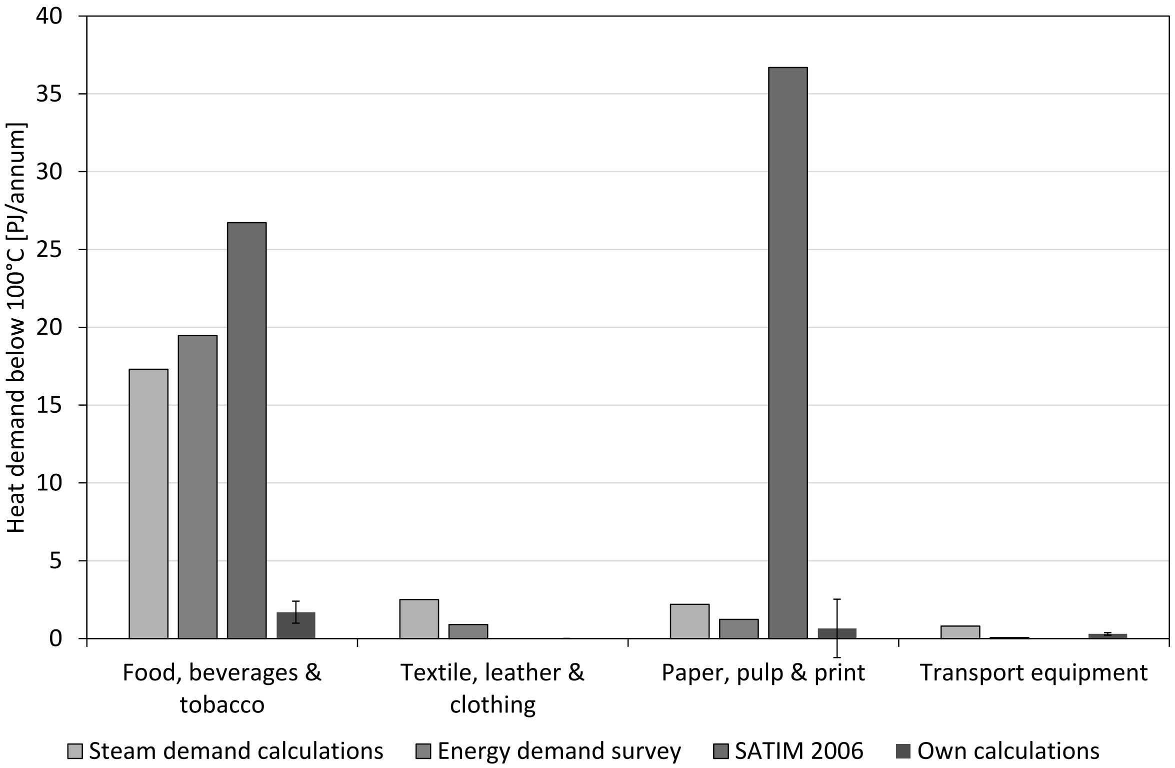

Figure 35: Comparison of the thermal heat demand below 100 °C in SA. Source: Knaack *et al.* (2019); ERC (2013)

From Figure 35, one can observe that the values for two of the divisions investigated by Knaack *et al.* (2019) are much larger than those based on the data of the IEA (2017a). The values from the data survey as indicated by Knaack *et al.* (2019) show that the heat demand for the food, beverage, and tobacco division is more than six times greater than that based on the IEA (2017a). The SATIM model data for the food, beverage, and tobacco division is 15.8 times greater than those based on the IEA (2017a). For the paper, pulp, and print division, the values are more or less the same as the values in the data from Knaack *et al.* (2019). However, the SATIM model data is about 56.4 times greater than those based on the IEA (2017a). For the textile divisions, Knaack *et al.* (2019) indicated that the steam demand is 2.2 PJ/annum while the energy demand from the surveys is 0.89 PJ/annum. The value is also much greater than the values based on the data of the IEA (2017a). The observation thus confirms the comment, as mentioned in section 3.2.3, that some of non-specified industrial divisions' heat demand should be considered part of the other smaller divisions.

3.3.3 Comparison of the theoretical heat demand below 100 °C

The theoretical potential for industrial process heat below 100 °C in SA has been estimated at 219.5 ±71.93 PJ/annum. The value equates to approximately 18.8%±6.2% of the energy demand of SA. When comparing the percentage heat demand below 100 °C with various European countries (Figure 36), the heat demand for SA is relatively high. Only Lithuania and Bulgaria's heat demand is higher than that of

SA. The value is much higher than the average for the countries investigated, which is 9.7% ±6.4%. When excluding the non-specified industrial division (ZAF 1 in Figure 36), the percentage of the theoretical potential for industrial process heat below 100 °C is about 70% of the EU28. The value is well within the range of the average for the countries investigated by Fleiter *et al.* (2017). It seems that more work needs to be done on the non-specified industrial division, as previously mentioned.

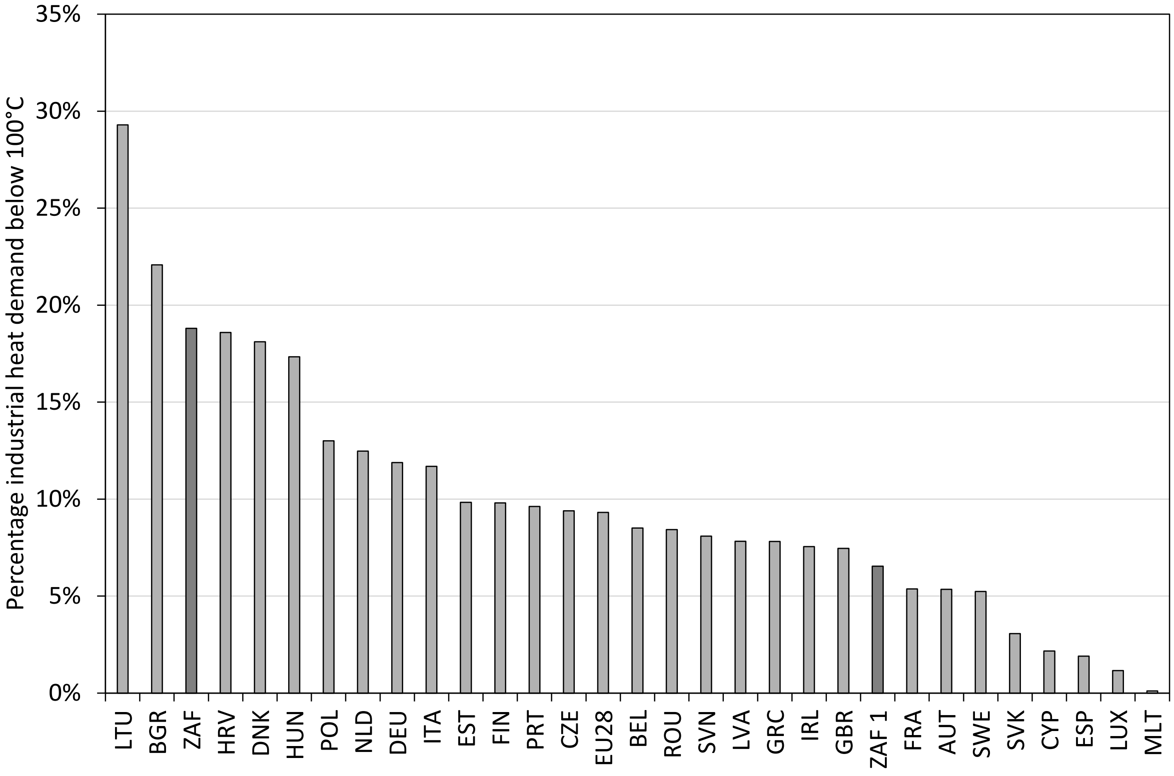

Figure 36: Comparison of the percentage thermal heat demand below 100 °C. Source: Fleiter *et al.* (2017)

Now that the comparison of the estimated heat demand is done, the information can be used to determine the most suited industrial sectors for the integration of CO_2 HPs.

3.4 The most suited industrial divisions and processes for CO_2 HP

In this section, the most suited divisions for the use of CO_2 HPs below 100 °C are selected. To determine which industrial division is the most suited, the three indices are considered. These are:

1. the theoretical heat demand below 100 °C,
2. percentage GVA for the various divisions, and
3. the typical temperature ranges of various processes.

In the next few paragraphs, an overview is given of the various indices and how they are used to determine the most suited division. Finally, the three indices are combined to determine the most suited division for CO_2 HP integration.

The first selection of the most suited divisions is made by considering the theoretical heat demand below 100 °C. The previous section indicated that the non-specified division has the largest theoretical potential for heat below 100 °C, with a share of nearly 80.4% (176.5±55.1 PJ/annum). This division is too diverse; therefore, no conclusion can be made for this division. The chemical and petrochemicals division has the second-largest theoretical potential for CO_2 HPs, with a share of nearly 9.9% (21.8±7.5 PJ/annum). The third and fourth divisions with the largest theoretical potential are the iron and steel division and the mining (excluding fuels) and quarrying division, with their share of 2.6% (5.693 PJ/annum) and 2.5% (5.557 PJ/annum), respectively.

Secondly, the percentage that the division contributes to the GVA is investigated. From Figure 37, the top four divisions that contributed to the industrial sectors GVA are the mining (excluding fuels) and quarrying (27.3%), food, beverages, and tobacco (15.9%), construction (15.5%), and machinery (9.47%) divisions.

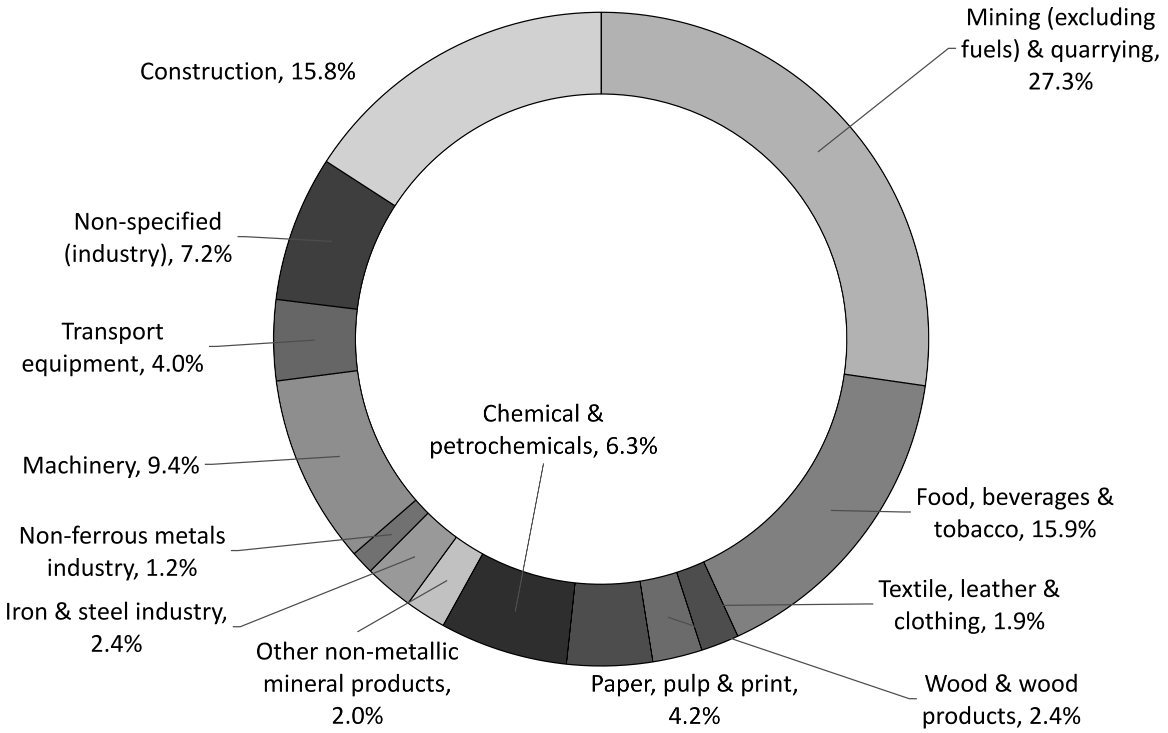

Figure 37: Percentage contribution of various divisions’ GVA in terms of the industrial sectors GVA for 2015. Source: (Statistics South Africa, 2019a)

Thirdly, the typical temperature range of various processes is investigated. Several studies have been conducted on the temperature ranges of different industrial processes, including the studies by Wolf *et al.* (2012), Wolf *et al.* (2014), IEA HPC Annex 35 (2014), Schweiger *et al.* (1999), Kalogirou (2003), Arpagaus *et al.* (2018), Lauterbach *et al.* (2012), and Lauterbach *et al.* (2011). The various authors' data was combined and compared against each other. The investigation finds that some process temperatures were as high as 700 °C. The complete list consists of over 360 processes. The data has consequently been reduced to include only processes with a maximum temperature of 100 °C, as this is the maximum operating temperature of the CO_2 HP. The abbreviated list of these processes still spans several pages and can be found in Appendix A.

By combining these percentages, the division with the highest potential can be determined. From Table 13, one can see that the food, beverage, and tobacco division has the greatest potential for implementing CO_2 HPs in SA. The second-highest rank is the chemical and petrochemical division, and third is the machinery division.

Table 13: Divisions with the highest potential of CO_2 HP in SA

Division	Percentage GVA of the divisions investigated	Percentage of the total head demand below 100 °C	Percentage processes that are below 100 °C	Combined factor	Rank
Mining (excluding fuels) & quarrying	27.3%	2.5%	0.0%	0.00	8
Food, beverages & tobacco	15.9%	0.8%	49.6%	6.47	1
Textile, leather & clothing	1.9%	0.0%	10.1%	0.00	7
Wood & wood products	2.4%	0.0%	7.8%	0.00	6
Paper, pulp & print	4.2%	0.4%	5.4%	0.08	4
Chemical & petrochemicals	6.3%	9.9%	6.2%	3.89	2
Other non-metallic mineral products	2.0%	1.3%	0.0%	0.00	8
Iron & steel division	2.4%	2.6%	0.0%	0.00	8
Non-ferrous metals division	1.2%	1.3%	0.0%	0.00	8
Machinery	9.4%	0.6%	20.2%	1.09	3
Transport equipment	4.0%	0.1%	0.8%	0.00	5
Non-specified (industry)	7.2%	80.4%	0.0%	0.00	8
Construction	15.8%	0.0%	0.0%	0.00	8
TOTAL	**100.0%**	**100.0%**	**100.0%**		

For this thesis, the South African food, beverage, and tobacco division is further investigated for the integration of CO_2 HPs. The introduction of CO_2 HPs into this field is considered relatively easy because the temperature required in many processes is below 100 °C (HPTCJ, 2010). From the literature study, the food, beverage, and tobacco division had the highest frequency for potential studies on IHPs and the largest number of installed IHPs. This food, beverage, and tobacco division also has the fourth-largest fraction of 29.3% of the total heat demand.

As mentioned in section 3.2.2, it is the author's opinion that the amount of energy should be much higher for the food, beverage, and tobacco division. From the survey data of Knaack *et al.* (2019), one can estimate the heat demand below 100 °C for the food, beverage, and tobacco division as 9.2 PJ/annum. The values of Knaack *et al.* (2019) are more than five times the values based on the IEA (2017a) data. If one assumes the SATIM (ERC, 2013) data to be accurate, then the heat demand below 100 °C for the food, beverage, and tobacco division is 20.75 PJ/annum. The impact of is that the food, beverage, and tobacco division is the third-largest division for both cases, just behind the chemical and petrochemicals division. The food, beverage, and tobacco division also contributed 25.5% to the manufacturing GVA (Statistics South Africa, 2019a). The division has the highest percentage contribution to the industrial sector. Finally, the division has a total of 64 processes that could potentially be integrated with CO_2 HPs (See Appendix A).

According to Knaack *et al.* (2019), SA has a well-established food, beverage, and tobacco division. The value chains in the food division include protein (meat, poultry, and seafood), fruit and vegetables, dairy, grain, and confectionery. Knaack *et al.* (2019) indicated that many manufacturers in this division operate state-of-the-art production facilities. Typically, the value chains in this division are based in urban areas, although there are exceptions for some products like fruit juices.

In the next section, an investigation is done to determine the most suited food, beverage, and tobacco division for the integration CO_2 HPs.

3.5 The most suited food beverage and tobacco division for the integration of CO_2 HPs

To determine which specific division of the food, beverage, and tobacco division has the greatest potential for CO_2 HP integration, the author investigates three indices: These are:

1. the number of companies in the division,
2. the typical temperature ranges of various processes, and
3. the energy used per kilogram of processed product.

In the next few paragraphs, an overview is given of the various indices and how they are used to determine the most suited division. Finally, the three indices are used to determine the most suited division.

Firstly, the number of companies in this division is investigated. In SA, once a company's wage bill exceeds R 500k per annum, it is required to pay a skills development levy to a sector education and training authority (SETA). Thus, the data provided by SETAs in each sector gives an indication of the number of sizeable companies that are active in the sector. SETA defines company sizes by the number of employees, where company sizes are defined as micro (<10), small (<49), medium (49-149), and large (>149). Figure 38 shows the total number of paying companies for 2010.

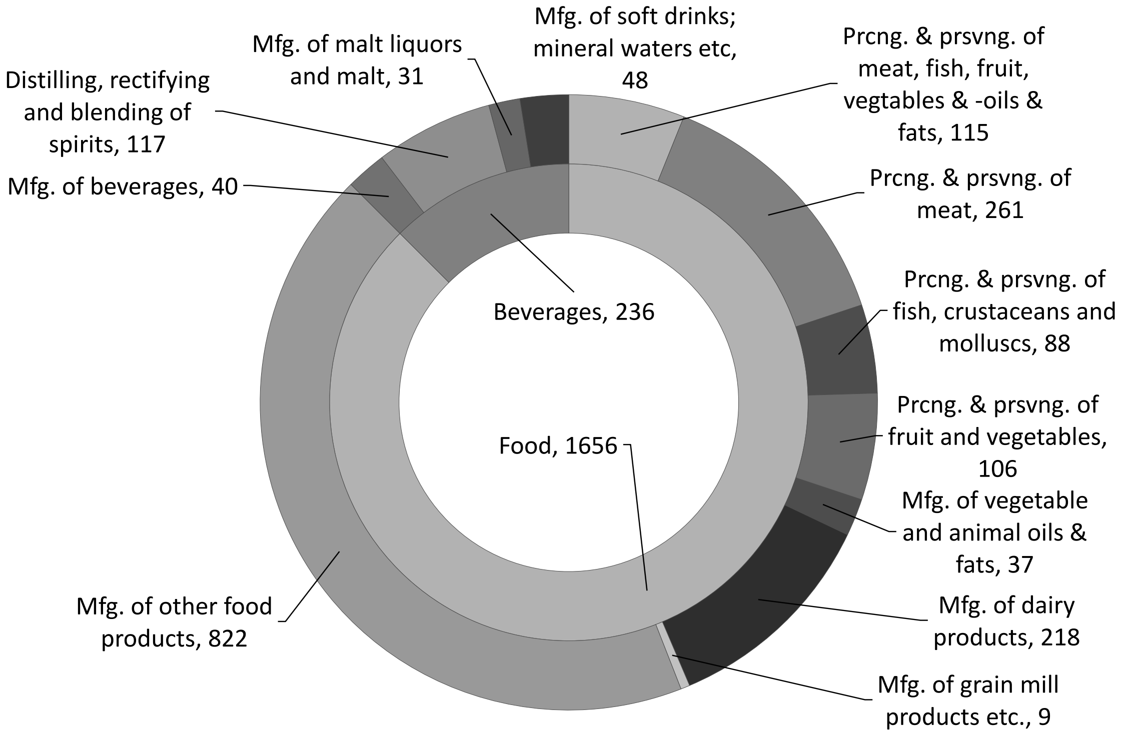

Figure 38: Food and beverage companies with wage bills exceeding R500k pa[6]. Source: FoodBev SETA (2011)

Figure 38 shows that the food division has the largest number of registered companies. For the food divisions, the manufacturing of other food products is the largest division (822 companies), with the

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[6] Mfg -Manufacturing Prcng – Processing

Prsvng -Preserving

second-largest division being the processing and preserving of meat (106 companies). For the first criterion, the author investigated the five divisions with the highest number of companies for the potential integration of CO_2 HPs (Table 14).

Table 14: Top five divisions of companies with wage bills exceeding R500k pa. Source: FoodBev SETA (2011)

Description	Small	Medium	Large	Total	Rank
Manufacturing of bakery products	174	39	26	239	1
Manufacturing of other food products n.e.c.	173	36	15	224	2
Manufacturing of dairy products	167	25	26	218	3
Processing and preserving of meat	164	27	17	208	4
Manufacturing of prepared meals and dishes	178	18	11	207	5

According to Table 14, the largest three divisions are the manufacturing of bakery products, other food products n.e.c., and the processing and preserving of meat. To determine whether these divisions are options for the integration of CO_2 HPs, the temperatures ranges of various processes must be considered.

Secondly, the typical temperature ranges of various processes are investigated. The same data as that in section 3.4 is used. Figure 39 shows an overview of the processes identified as suitable for the integration of CO_2 HPs below 100 °C for the food division[7]. From Figure 39, one can see that there are no process options for bakery products. The manufacturing of other food products n.e.c. and the manufacturing of prepared meals and dishes are too diverse to identify a specific process for the integration of CO_2 HPs. Figure 39 shows that there are 19 options in total for the processing and preserving of milk division, with the processing and preserving of meat, fish, fruits and vegetables division and the processing and preserving of meat division having nine options. The two groupings are there because the various authors grouped the data on several levels. Thus, the author further investigates the processing and preserving of milk division and the processing and preserving of meat, fish, fruits, and vegetables division.

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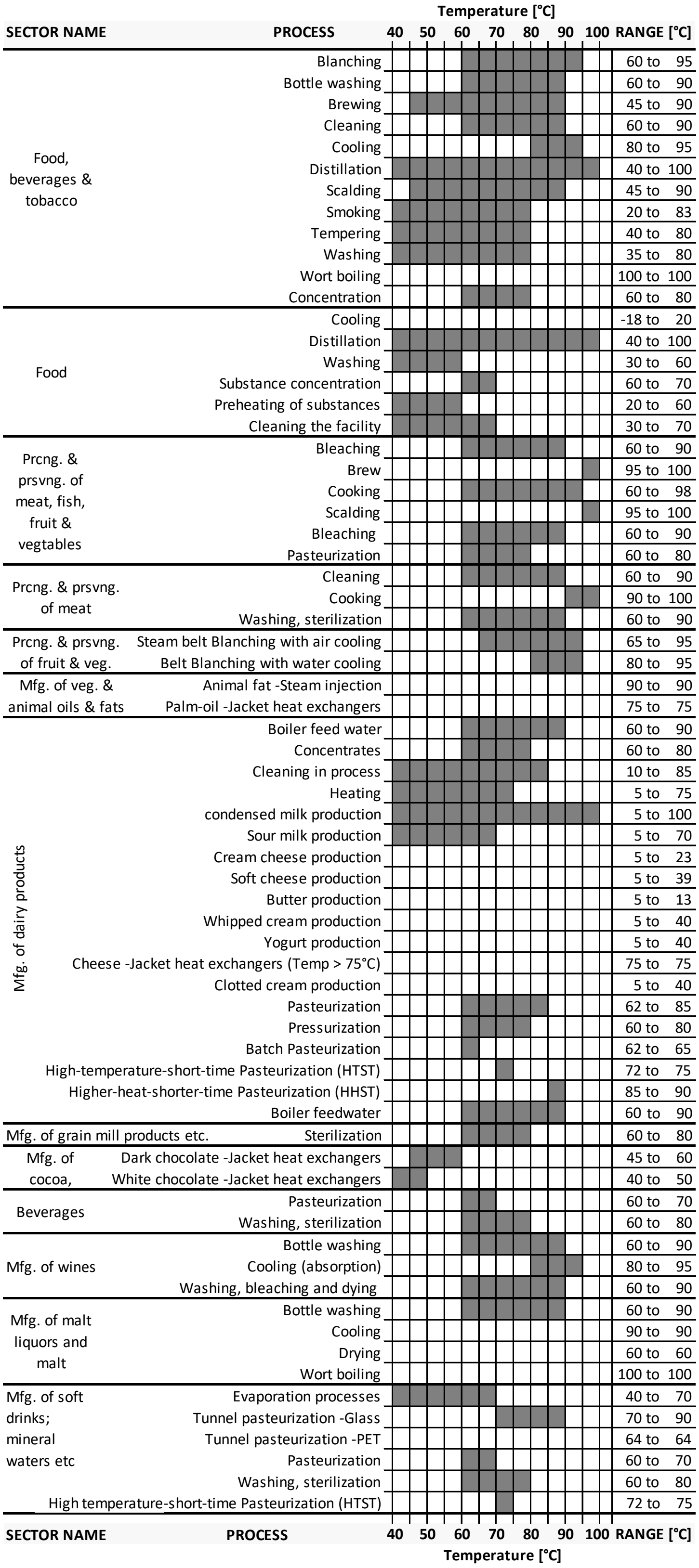
[7] For a complete list, please refer to Appendix A.



SECTOR NAME	PROCESS	RANGE [°C]
Food, beverages & tobacco	Blanching	60 to 95
	Bottle washing	60 to 90
	Brewing	45 to 90
	Cleaning	60 to 90
	Cooling	80 to 95
	Distillation	40 to 100
	Scalding	45 to 90
	Smoking	20 to 83
	Tempering	40 to 80
	Washing	35 to 80
	Wort boiling	100 to 100
	Concentration	60 to 80
Food	Cooling	-18 to 20
	Distillation	40 to 100
	Washing	30 to 60
	Substance concentration	60 to 70
	Preheating of substances	20 to 60
	Cleaning the facility	30 to 70
Prcng. & prsvng. of meat, fish, fruit & vegtables	Bleaching	60 to 90
	Brew	95 to 100
	Cooking	60 to 98
	Scalding	95 to 100
	Bleaching	60 to 90
	Pasteurization	60 to 80
Prcng. & prsvng. of meat	Cleaning	60 to 90
	Cooking	90 to 100
	Washing, sterilization	60 to 90
Prcng. & prsvng. of fruit & veg.	Steam belt Blanching with air cooling	65 to 95
	Belt Blanching with water cooling	80 to 95
Mfg. of veg. & animal oils & fats	Animal fat -Steam injection	90 to 90
	Palm-oil -Jacket heat exchangers	75 to 75
Mfg. of dairy products	Boiler feed water	60 to 90
	Concentrates	60 to 80
	Cleaning in process	10 to 85
	Heating	5 to 75
	condensed milk production	5 to 100
	Sour milk production	5 to 70
	Cream cheese production	5 to 23
	Soft cheese production	5 to 39
	Butter production	5 to 13
	Whipped cream production	5 to 40
	Yogurt production	5 to 40
	Cheese -Jacket heat exchangers (Temp > 75°C)	75 to 75
	Clotted cream production	5 to 40
	Pasteurization	62 to 85
	Pressurization	60 to 80
	Batch Pasteurization	62 to 65
	High-temperature-short-time Pasteurization (HTST)	72 to 75
	Higher-heat-shorter-time Pasteurization (HHST)	85 to 90
	Boiler feedwater	60 to 90
Mfg. of grain mill products etc.	Sterilization	60 to 80
Mfg. of cocoa,	Dark chocolate -Jacket heat exchangers	45 to 60
	White chocolate -Jacket heat exchangers	40 to 50
Beverages	Pasteurization	60 to 70
	Washing, sterilization	60 to 80
Mfg. of wines	Bottle washing	60 to 90
	Cooling (absorption)	80 to 95
	Washing, bleaching and dying	60 to 90
Mfg. of malt liquors and malt	Bottle washing	60 to 90
	Cooling	90 to 90
	Drying	60 to 60
	Wort boiling	100 to 100
Mfg. of soft drinks; mineral waters etc	Evaporation processes	40 to 70
	Tunnel pasteurization -Glass	70 to 90
	Tunnel pasteurization -PET	64 to 64
	Pasteurization	60 to 70
	Washing, sterilization	60 to 80
	High temperature-short-time Pasteurization (HTST)	72 to 75

Figure 39: Overview of processes in different industrial divisions structured by typical temperature ranges. Source: Wolf *et al.* (2012), Wolf *et al.* (2014), IEA HPC Annex 35 (2014), Schweiger *et al.* (1999), Kalogirou (2003), Arpagaus *et al.* (2018), Lauterbach *et al.* (2012), and Lauterbach *et al.* (2011); FoodBev SETA (2011)

The third option investigated is the amount of energy that is used to process the products. From Table 15, one can observe that the chicken and meat division has the largest total energy use and energy intensity. The total energy use for the processing of chicken meat is nearly 53% of the total energy use investigated. Thus, although the milk division has a much larger number of processes for which CO_2 HPs can be applied, the processing of chicken meat is therefore further investigated.

Table 15: Total estimated energy use for the meat and fresh milk subdivision: Source: Murray and Lagrange (2011); Smil (2008); DAFF (2018b)[8]

Product	Energy intensity [MJ/kg]	Annual consumption for 2015/2016 [1000 Tonnes /annum]	Total energy use [GJ]	Rank
Meat - Beef	1.5	1032	1548	**3**
Meat - Pork	2.0	263	526	**6**
Meat - Chicken	3.0	2200	6600	**1**
Fresh milk	0.18-0.75	3173	2380	**2**
Fresh fruit and vegetable	5			
Pears		146	735	**4**
Peaches		138	689	**5**
TOTAL			**12 477**	

3.6 Conclusion

The aim of this chapter was to estimate the theoretical heat demand below 100 °C. The total theoretical heat potential below 100 °C for SA is thus 232.8 ±56.06 PJ/annum. The non-specified industrial division has the largest theoretical potential for heat below 100 °C, with a share of nearly 80.6% (187.7 PJ/annum). The chemical and petrochemicals division has the second-largest theoretical potential for CO_2 HPs, with a share of almost 9.7% (22.6 PJ/annum). The rest of the divisions altogether make up about the remaining 9.6% (22.4 PJ/annum).

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[8] Department of Agriculture, Forestry and Fisheries (DAFF)

The theoretical electric heat potential for SA is 49.24±21.2 PJ/annum. For SA, the non-specified industrial division has the largest theoretical electric potential for heat below 100 °C, with a share of nearly 89.0% (43.8 PJ/annum). The second-largest theoretical potential for CO_2 HPs with a share of approximately 6.8% (3.4 PJ/annum) is the mining (excluding fuels) and quarrying division. The rest of the divisions altogether make up about the remaining 4.2% (2.1 PJ/annum).

Based on the values of the IEA (2017a), the food, beverage, and tobacco division does not show a significant potential for the SA, with a value of 6.15 PJ/annum. The division has the seventh-highest theoretical potential with a share of only 0.8% (1.9 PJ/annum) of the total heat demand below 100 °C.

However, if one assumes the data from the survey of the 506 companies by Knaack *et al.* (2019) to be correct, the theoretical potential below 100 °C is 17.3 PJ/annum or 10.2 times greater than the values based on the IEA (2017a). If one assumes the SATIM (ERC, 2013) data to be accurate, then the heat demand below 100 °C for the food, beverage, and tobacco division is 19.47 PJ/annum. This value is 15.8 times greater than the values based on the IEA (2017a). It is thus of the authors opinion that food, beverage and tobacco division should have a much higher theoretical heat demand below 100 °C.

The literature review showed that the best option for the integration of CO_2 HPs is the food, beverage, and tobacco division. It is thus still the opinion of the author that the food, beverage and tobacco division is the best option for the integration of CO_2 HPs in the South African context. The main reason for this the significant share of the industrial heat demand at low temperatures, the high contribution to the GVA, the large number of companies, and the number of processes below 100 °C.

Finally, the processing of meat division and the milk division are identified as the best two options for the integration of CO_2 HPs. The processing of chicken meat, or poultry abattoirs, has the highest energy use. The division used 52% of the total energy use. Thus, the processing of chicken meat is further investigated. In the next chapter, the author estimates and discusses the potential savings for CO_2 HPs in the processing and preserving of chicken meat subdivision.

Chapter 4. Identifying opportunities for the integration of multi-function CO_2 HPs in poultry abattoirs

4.1 Introduction

In the previous chapter, the food, beverage, and tobacco division was identified for further investigation, and, more specifically, poultry abattoirs for the implementation of CO_2 HPs. This chapter aims to determine which processes in the poultry abattoirs are the best suited for a commercially multi-function CO_2 HP. The CO_2 HP is available in SA and can deliver hot water at temperatures of 65 °C and 90 °C, respectively, as well as chilled water as low as -9 °C (Mayekawa, 2013a). The chapter will thus investigate both the heating and the cooling applications in the poultry abattoirs.

This chapter firstly provides an overview of the poultry subdivision. Secondly, the process flow of a high-throughput abattoir is discussed with a focus on the steps in the process and the operating temperatures. Thirdly, the energy management opportunities in a poultry plant are discussed briefly to show which processes use the most energy. Finally, an overview of a CO_2 HP is given, with a focus on the operating temperatures and how this can be matched with the requirements of the poultry abattoir. An overview of the chapter is shown in Figure 40.

Identifying opportunities for the integration of CO_2 HPs in poultry abattoirs

- Overview of the poultry sector
- Overview of the poultry abattoirs
- Identify energy management opportunities
- Integrate multi-function CO_2 HP operting temperatures with that of the poultry abatoir

Figure 40: An overview of identifying opportunities for the integration of CO_2 HP in the poultry abattoirs

4.1 Overview of the poultry division

In this section, a brief overview is given of the poultry division. Firstly, the section discusses the annual consumption of poultry meat in SA, followed by a discussion of the division's economic contribution. Finally, an overview is given of the distribution of poultry farms and abattoirs in SA.

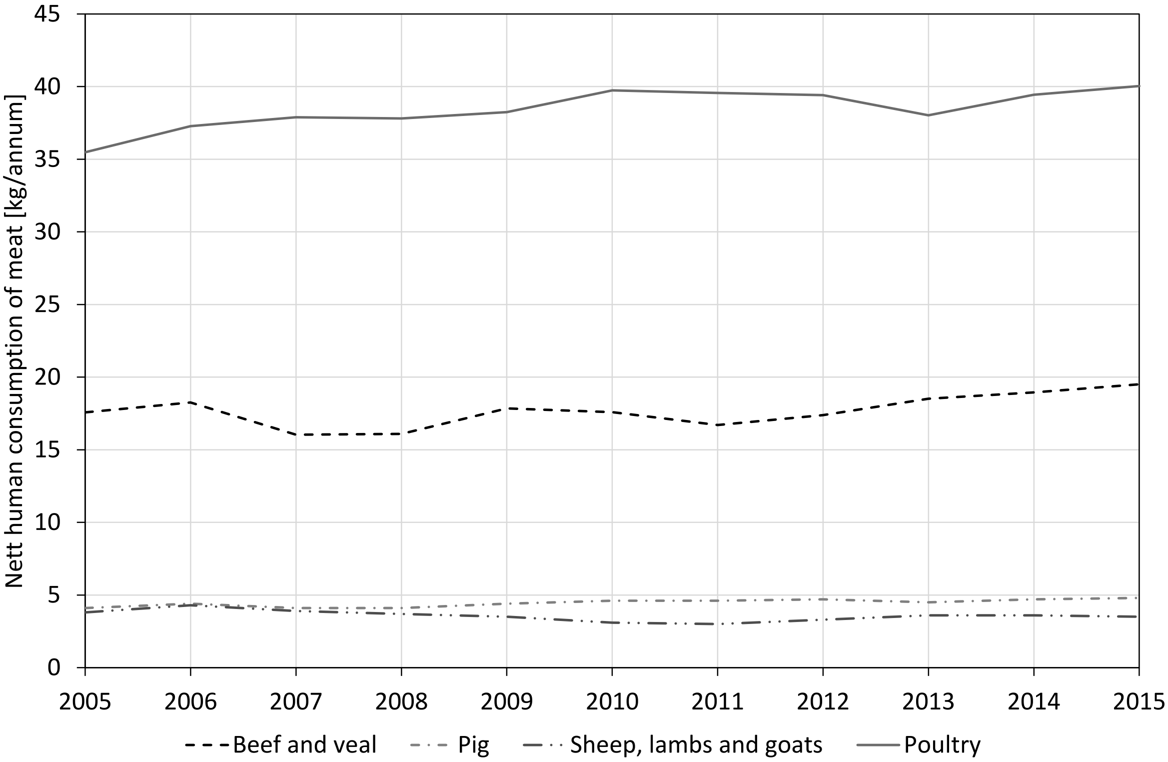

Figure 41: Annual meat consumption per capita. Source: Data from DAFF (2018b)

The annual consumption of meat in SA was 67.85 kg per person in 2015. The South African poultry (broiler) subdivision continues to dominate, with an annual consumption of 27.76 kg or 59% of the total annual meat consumption. The poultry subdivision continues to grow, with an average consumption per capita growth rate of 1.2% over the last ten years, and a total consumption per capita growth of 13% since 2005 (DAFF, 2018b).

According to the DAFF (2017), poultry is the primary subdivision within the agricultural sector of SA in terms of production value. In 2015/16, the subdivision generated R38.6 billion gross value, which was about 15.6% of the total gross value of agricultural products. In comparison to other livestock products, poultry accounts for 33% of all animal products in SA in rand terms. SA remains the major poultry producer in Southern Africa, accounting for 80% of the total poultry production in the region. Poultry production dominates the agricultural sector, and it remains the cheapest supplier of protein of all other animal proteins.

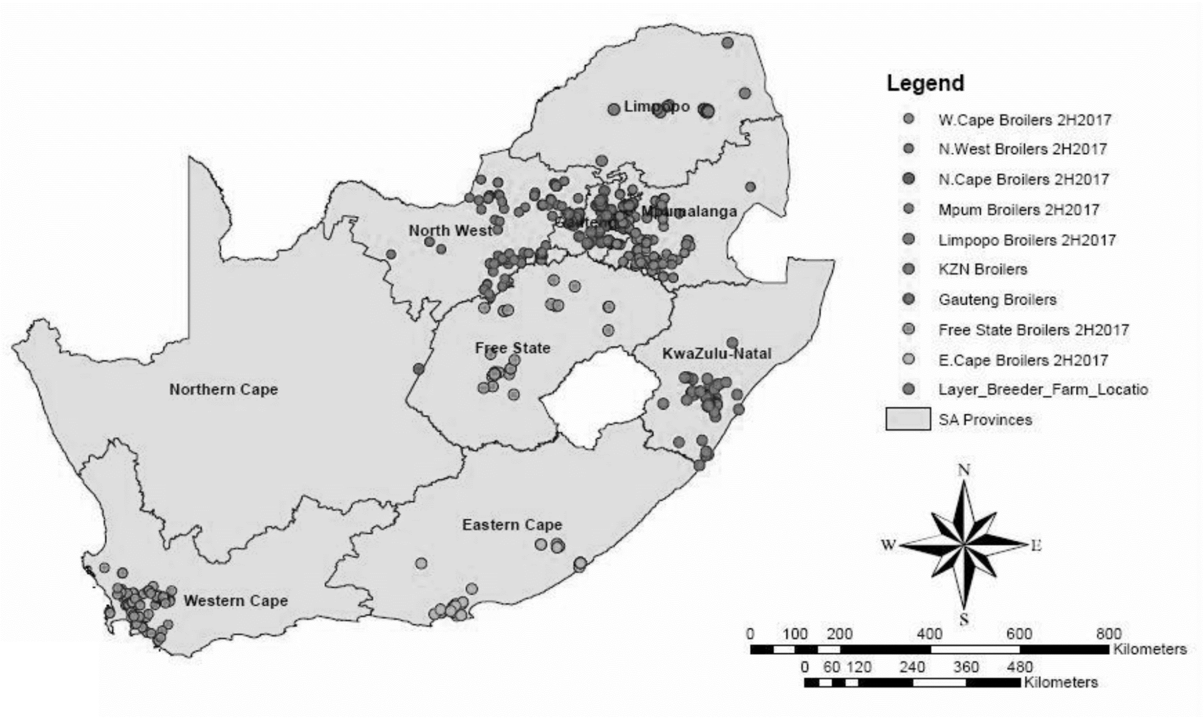

Figure 42: Geographical location of poultry farms. Source: SAPA (2017)[9]

Figure 42 shows that the poultry farms are distributed around the large urban areas (SAPA, 2017). The largest cluster is around the Gauteng Province, with the largest number of poultry farms established in the western part of Mpumalanga and eastern part of the North West Province. Other large areas include the regions close to Cape Town, Pietermaritzburg, Durban, and Port Elizabeth. Based on the data from SAPA (2017), for 2017, the North West Province produced 23.5% (Figure 42) of the total poultry meat in SA, followed by the Western Cape at 22.3%, the Mpumalanga Province at 18.0%, and the KwaZulu-Natal Province at 12.5%.

The DAFF publishes a list of registered abattoirs each year. The list details the abattoir's name, province, grading, and location. According to the Meat Inspector's Manual for Poultry (DAFF, 2007), abattoirs are graded into three sizes (Table 16). The focus of this thesis is on high-throughput (HT) abattoirs, as they use mechanical lines and require more automated systems.

Table 16: Throughput requirements for different abattoir grades. Source: Data from DAFF (2007)

Abattoir grade	Abbreviation	Throughput requirement
Rural throughput poultry abattoirs	(RT)	Maximum throughput of 50 units per day
Low-throughput poultry abattoirs	(LT)	Maximum throughput of 2 000 units per day
High-throughput poultry abattoirs	(HT)	More than 2 000 units per day

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[9] South Africa Poultry Association (SAPA)

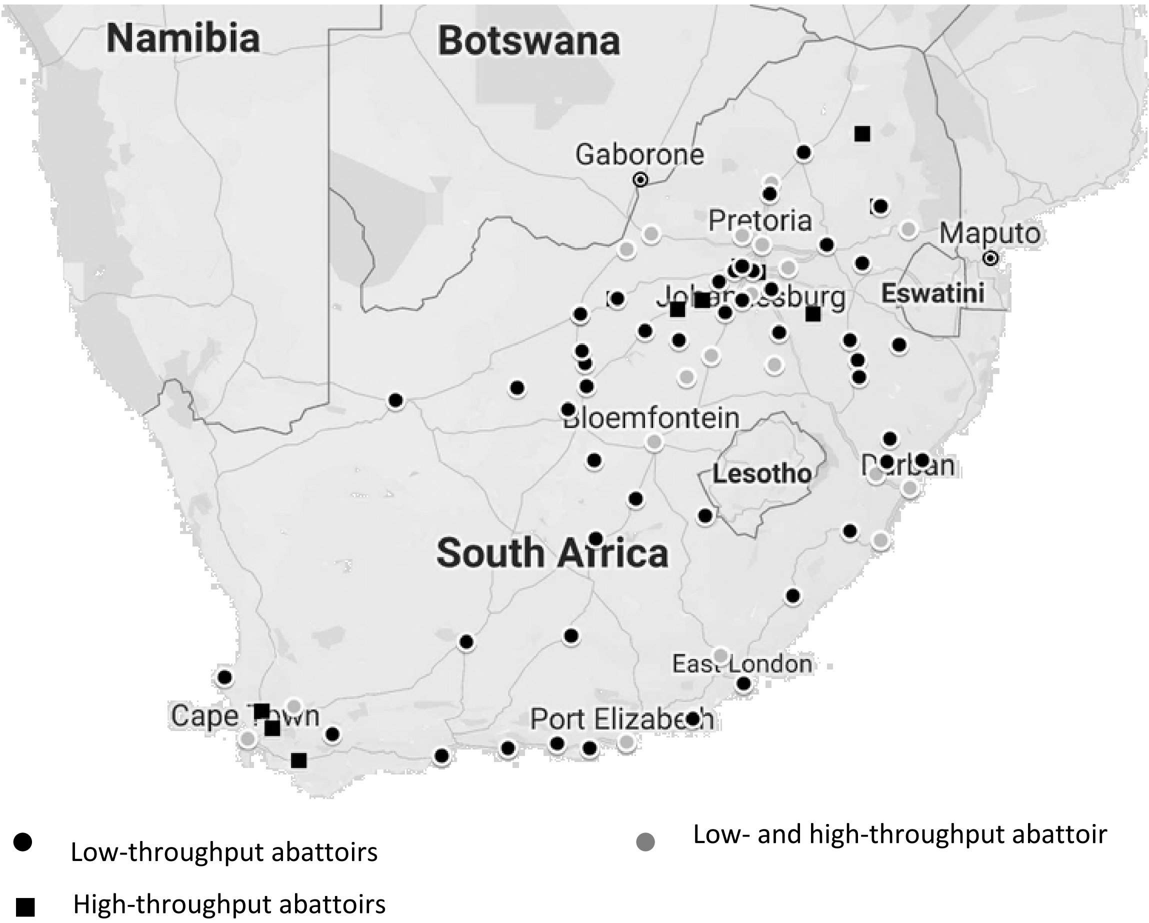


Figure 43: Geographical location of poultry abattoirs. Source: Data from DAFF (2018a);

Figure 43 shows the distribution of the various LT and HT abattoirs in SA. According to Figure 43, most abattoirs are located in and around the Gauteng area. The second- and third-highest number of abattoirs is in the Free State and KwaZulu-Natal.

According to the WRC (2017), HT abattoir functions use mechanised process lines. In total, SA has 41 HT abattoirs. The DAFF (2017) indicated that the poultry meat subdivision in SA is dominated by two large HT producers, namely RCL and Astral Foods. Together, these two companies produce 46% of the total poultry meat production (Figure 44). Rainbow produces around 235 million broilers per annum, and Astral Food produces about 220 million broilers per annum. Country Bird is the third-largest HT poultry producer, producing 68 million broilers per annum. The other four medium-sized producers (Tydstroom, Daybreak, Fourie’s poultry farms, and Rocklands) produce more than 50 million broilers per annum, and collectively they supply 22% of the market. These top seven companies thus supply about 75% of the total South African poultry meat, and the remaining 25% is supplied by hundreds of smallholder producers. Thus, the HT abattoirs are representative of the largest production portion in SA.

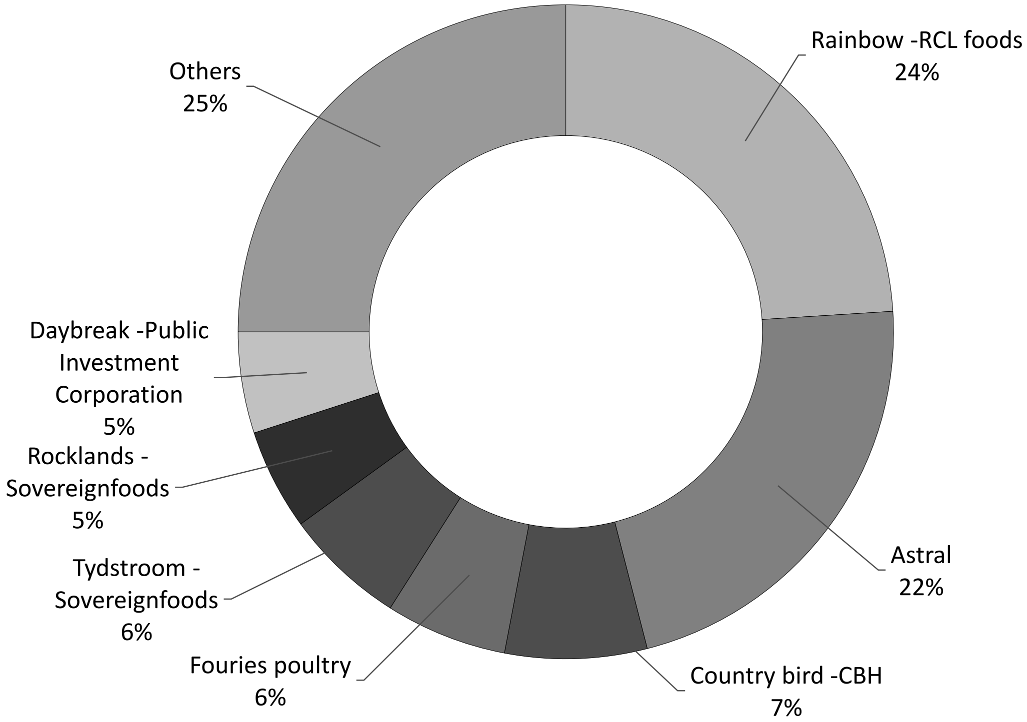
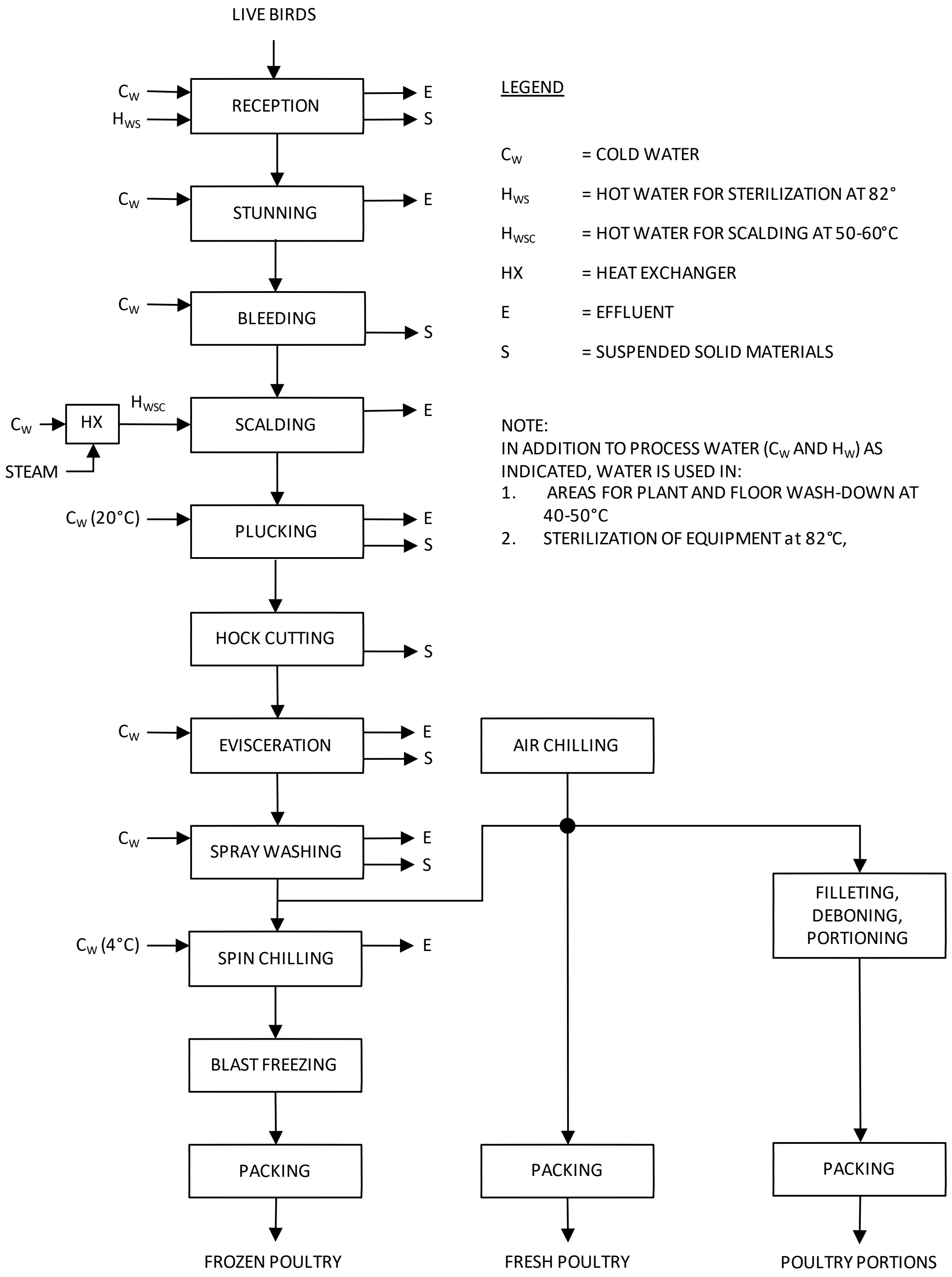


Figure 44: Major producers in the broiler subdivision of SA. Source: Data from DAFF (2017)

4.2 Overview of poultry abattoirs

This section aims to determine where multi-function CO_2 HPs with a maximum hot water temperature of 90 °C and a chilled temperature as low as -9 °C can be integrated with the poultry abattoir process. The processes investigated thus focus on both the heating and the cooling applications in the poultry abattoirs.

Figure 45 shows an overview of the various stages of the HT poultry abattoirs. The next subsection provides a summary for each of these sections.



LEGEND

C_W = COLD WATER

H_{WS} = HOT WATER FOR STERILIZATION AT 82°

H_{WSC} = HOT WATER FOR SCALDING AT 50-60°C

HX = HEAT EXCHANGER

E = EFFLUENT

S = SUSPENDED SOLID MATERIALS

NOTE:
IN ADDITION TO PROCESS WATER (C_W AND H_W) AS INDICATED, WATER IS USED IN:

1. AREAS FOR PLANT AND FLOOR WASH-DOWN AT 40-50°C
2. STERILIZATION OF EQUIPMENT at 82°C,

Figure 45: Block diagram of typical poultry abattoir processing steps. Source: Data from WRC (1993), DAFF (2007), WRC (2017)

4.2.1 Reception

In the reception area (Figure 45), live birds are generally delivered to the abattoirs in crates. The birds are offloaded onto a conveyor travelling to the slaughter area (WRC, 2017). As part of the overall hygiene requirement, this area must be kept clean (WRC, 2017). The cleaning is usually achieved by frequent washing down at temperatures between 40 °C and 50 °C (DAFF, 2007). Also, large abattoirs have crate washing facilities, which, besides for washing down, represent another considerable water demand (WRC, 2017). According to the DAFF (2007), the product crates must be sterilised at temperatures of 82 °C. The crate washing reduces the spreading of disease between younger and older birds.

4.2.2 Stunning

Birds are stunned by immersing the head and neck in an electrified water bath, and the throats are slit mechanically or by hand (WRC, 2017). The bird should bleed for at least 90 seconds to ensure that respiration has stopped; the bird must be dead before entering the scalding tank (WRC, 2017). The birds have to stop breathing to prevent water in scalding tanks from entering the lungs. Most large abattoirs have blood collection facilities consisting of a trough into which the blood flows from the birds as they pass along the process line (WRC, 1993).

4.2.3 Scalding

After bleeding, the birds are scalded by either spray-type or immersed-type scalding to loosen the feathers before plucking (WRC, 1989). The birds are immersed in a scalding tank containing water at 50-55 °C. Scalding tanks are operated with a flow of hot water and a corresponding overflow from the tanks so that the scalding water quality and temperature are maintained. High organic and solid pollution loads arise from scalding tank overflows, and considerable shock loads occur when scalding tanks are emptied (WRC, 1993).

Hard-scald or full-scald systems typically use water temperatures of ± 54-60 °C and an immersion time of 90-150 seconds (DAFF, 2007). According to Buhr *et al.* (2014), the scalding temperatures is higher, at ± 60-66 °C, with an immersion time of 45-90 seconds. Hard scalding results in a near-complete removal of the outermost epidermal or cuticle layer together with the feathers during defeathering, resulting in the yellow-skinned carcasses becoming pale white (Buhr *et al.*, 2014).

On the other hand, soft or cold scalding is done at ± 50 °C-53 °C for 150-210 seconds (DAFF, 2007). Soft scalding leaves the epidermal layer intact, which is why it is commonly used for young broilers and turkeys, but still allows for relatively easy feather removal (Guerrero-Legarreta, 2010). Birds slaughtered for display should be scalded in this way to improve the appearance of the carcass, since water that is too hot will cause the outer layer of skin to loosen or be lost (Guerrero-Legarreta, 2010). Such a loss also results in the loss of some yellow pigment from the skin (Guerrero-Legarreta, 2010). Since soft scalding is done mainly on younger birds, this study focuses only on hard scalding.

According to the WRC (1989), scalding water quality and temperature are maintained by the flow of hot water and the corresponding overflow.

4.2.4 Plucking

Following the scalding operation, feathers are removed from the birds by defeathering machines equipped with rotating rubber fingers so that the bird's skin is not damaged (WRC, 2017). Water used in the defeathering machines should not exceed 20 °C to prevent any further damage to the epidermis (WRC, 2017). The required amount of water in pluckers should be between 0.25 litres and 0.5 litres per bird (WRC, 2017).

4.2.5 Hock cutting and washing

After defeathering, the birds' heads and feet are removed, and the carcasses are sprayed with water (sometimes chlorinated). The carcasses are cut open and the viscera pulled out for inspection (WRC, 1989). The carcass washer washes the carcass before evisceration. The carcass washer is maintained by adding potable water containing chemicals approved for the use of foodstuffs (WRC, 1989).

4.2.6 Evisceration

Evisceration takes place in a separate room from slaughtering, scalding, and defeathering. After passing inspection, the viscera are sorted into edible and inedible offal. Water is used to transport inedible offal away from the evisceration area for screening. Thus, the water is another potential source of high organic pollution loadings, as it contains significant levels of blood, fat and grease, tissue, and intestinal contents, which screening only removes partially (WRC, 1989).

4.2.7 Spray washing (final wash)

Spray washing of eviscerated birds is carried out for hygiene purposes and to remove loose particles (WRC, 1993). On mechanical lines, the carcasses go through an inside/outside washer with cold water containing a chemical approved for use on foodstuffs. The water washes the carcasses under mild pressure on the inside and the outside simultaneously. On manual lines, the carcass is usually washed with a shower-type sprayer (DAFF, 2007).

4.2.8 Primary carcass chilling

The birds' carcasses are chilled to below 10 °C to minimise microbiological contamination. The chilling can be done by either chilled air or chilled water (spin chiller). In some plants, the spin chiller is preceded by a pre-chiller.

The temperature of the water in the pre-chiller should be 18 °C. The dwell time should not exceed 10-15 minutes, depending on the size of the tank (WRC, 2017). Spin chillers operate on a make-up and overflow system to maintain water quality and temperature. This overflow contains significant levels of organic pollution (WRC, 1989).

In the spin chillers, the birds are immersed in aerated, chilled water of a maximum of 4 °C. The minimum preplacement rate is 1 litre of water for every bird. The carcass core temperature entering the chiller is about 38 °C. The deep bone temperature of carcasses leaving the spin chiller must be less than 7 °C. The overall dwell time should not exceed 30 minutes. The spin chiller must be drained and cleaned at the end of each shift, but where two shifts are worked per day, cleaning can take place at the end of the second shift (DAFF, 2007; WRC, 2017).

4.2.9 Air chilling

A pre-drying section can be used with an air temperature of ± 22 °C. The main purpose is to dry the carcass before it goes into the air chiller. A wet bird can sometimes form ice in the air chiller, and that is unacceptable. In the air chiller, cold air at ± 0 °C is blown over the carcasses at 0.75 metres per second. The deep bone temperature of these air-chilled carcasses should not exceed 7 °C. These air-chilled carcasses are used for fresh meat production (DAFF, 2007; WRC, 2017).

4.2.10 Chilling and freezing

The abattoir must provide adequate chillers and freezers for the final chilling, freezing, and storage of packed products (WRC, 2017). A chiller used for final chilling of poultry meat must be capable of providing uninterrupted cooling to reduce the core temperature of the meat to 4 °C within 12 hours. Meat, carcasses and portions being frozen may not be removed from the freezer before a core temperature of -12 °C has been reached (DAFF, 2007; WRC, 2017). Chilled poultry is cooled and stored at 4 °C and frozen poultry at -12 °C (WRC, 2017).

4.2.11 Plant and area wash-down

Plant and area wash-down in all processing areas is carried out routinely during and after each processing shift. Wash-down is a substantial factor in the water, effluent, and solid waste pattern at poultry abattoirs. In addition to the major processing plant items that are washed down, water is also used for sterilising equipment, hand wash basins, wash sprays for aprons and other protective clothing, shackle washers, tray washers, crate washers, and laundry purposes (WRC, 1993).

4.2.12 Ablution and washing facilities

According to the DAFF KZN (2015), personnel who handle foodstuffs must shower before assuming their duties, with water between 55 and 65 °C (Meyer, 2000-year; Meyer & Greyvenstein, 1991). Furthermore, personnel who handle foodstuffs wash their hands and forearms at a minimum water temperature of 40 °C. The personnel must do this after having used a toilet or when entering a working area (DAFF KZN, 2015).

4.3 Energy management opportunities in the poultry abattoir

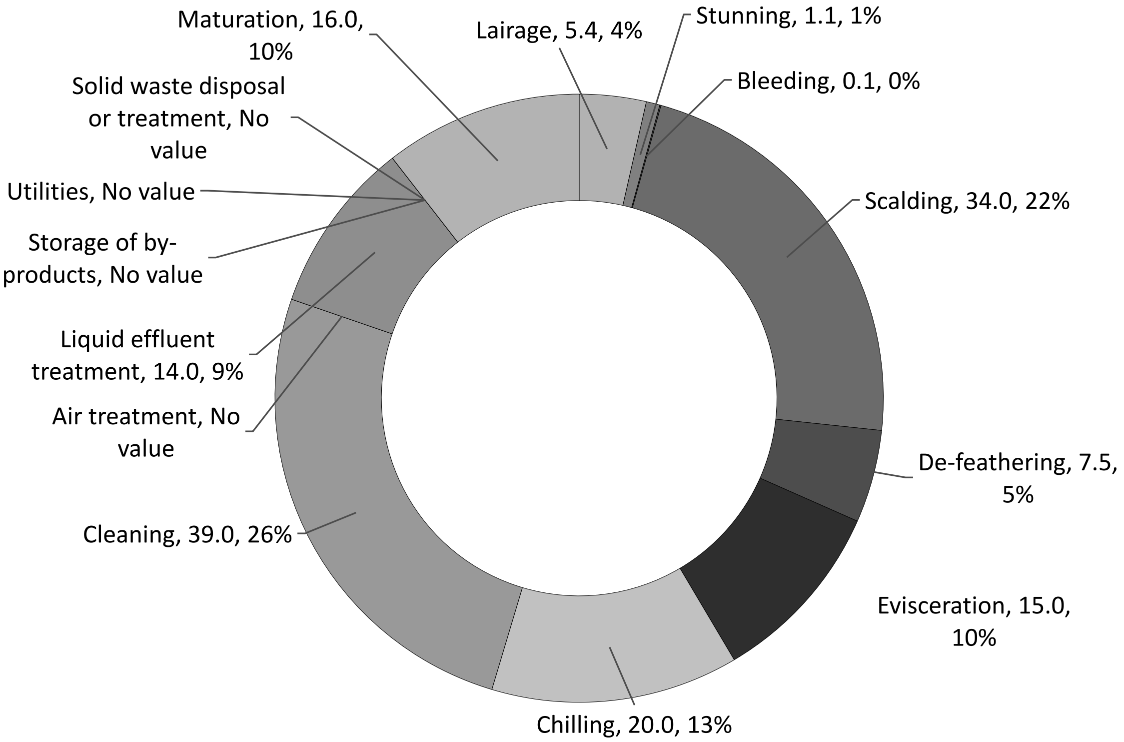


Figure 46: Energy consumption MJ/tonne for poultry abattoir. Source: Data from EIPPCB (2005)

To determine the energy management opportunities in poultry abattoirs, it is necessary to determine what the maximum energy users are. Figure 46 shows that, according to the EIPPCB (2005), the three sectors with the highest energy demand are cleaning, scalding, and chilling. These figures can differ vastly from site to site. For example, Jekaynfa (2007) conducted a study to investigate the energy use of three Nigerian poultry abattoirs over a year. The study found that the average energy use for scalding and defeathering was 44.01%, while washing and chilling was 15.78% and slaughtering was 16.97%. Thus, although the figures change from site to site, the data shows that the highest energy demand remains that of cleaning, scalding, and chilling.

4.4 Match operating temperatures of the CO_2 HP with that of the abattoir

To match a commercially available multi-function CO_2 HP to these processes, the respective operating temperatures and that of the HP must be known. Currently, there is a CO_2 HP available in SA that can provide hot water at both 65 °C and 90 °C and the chilled water as low as -9 °C, as illustrated in Figure 47.

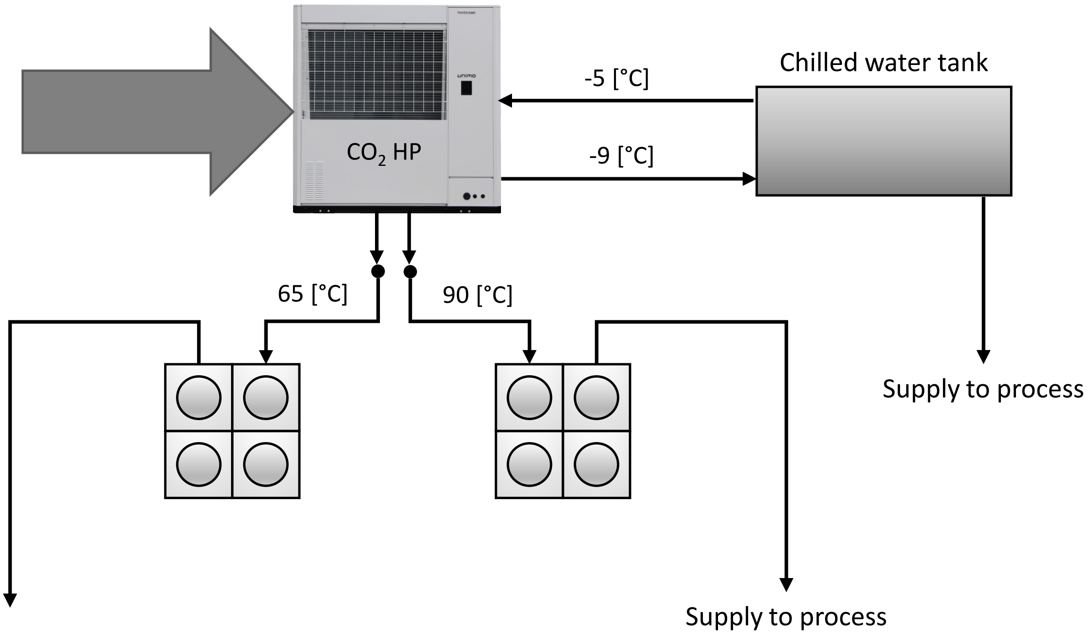


Figure 47: Suggested layout for a Unimo AWW CO_2 HP. Source: Mayekawa (2013a)

This CO_2 HP could thus be used to supply the thermal energy use for various processes. Table 17 shows a summary of the temperatures that coincide with that of the CO_2 HPs. The processes include sterilisation, cleaning, scalding, chilling, showering, and hot water for handwashing.

Table 17: Summary of essential temperatures in the abattoir. Source: DAFF (2007), Meyer (2000), Meyer and Greyvenstein (1991)

Activity	Process	Temperature °C		
		Chosen value	Upper limit	Lower limit
Sterilising	Sterilising of crates and hand equipment	82	82	
Process	Scalding tank water – hard		54	60
Process	Scalding tank water – soft	50	50	53
Wash-down	Water for rinsing/cleaning during the process	40	40	50
Wash-down	Hot water for handwashing	42	42	
Process	Water at the inlet to spin chiller	4	4	
Sanitation	Shower water	65	55	65

4.5 Summary

This chapter gave an overview of the poultry subdivision, abattoirs, and energy management opportunities. The information was then used to match the operating conditions of the poultry plant with that of the CO_2 HP.

The overview showed that the poultry subdivision and the broiler subdivision continue to dominate meat consumption, with an annual consumption of 27.76 kg per person or 59% of the total annual meat consumption. The subdivision generated a gross value of R38.6 billion in 2015/16, which was about 15.6% of the total gross value of agricultural products. The poultry meat subdivision in SA is dominated by two large producers, namely RCL and Astral Foods. Together, these two companies produce 46%. The other four medium-sized producers produce more than 50 million broilers per year, and collectively they supply 22% of the market. These top seven companies supply about 75% of the total South African poultry meat and 25% is supplied by hundreds of smallholder producers.

The section on the abattoirs gave a detailed overview of the most important processes. This information was then combined with that of the energy management opportunities and the operating conditions of the CO_2 HPs. The investigation revealed that CO_2 HPs can be integrated with the process of scalding and cleaning – which consists of floor and equipment washing, shower and handwash basins – sterilisation, and finally, chilled water. These three processes have also the highest energy demand of around 76% of the plant total energy demand.

In the next section, the poultry abattoir system model is discussed. This model is used to determine what is the potential impact of a CO_2 HP for poultry abattoirs.

Chapter 5. Poultry abattoir system simulation

5.1 Introduction

To evaluate the impact of the CO_2 HPs on the poultry abattoirs, the commercial available multi-function CO_2 HP system integration must be modelled, and the results compared with the two base cases, namely steam and electric boilers. The first step is to determine the steady-state mass flow, temperatures, pressures, and heat demand for the three systems. This information is used in Chapter 6 to match the thermal heat demand of the plant to that of the CO_2 HPs.

Figure 48 shows the overview for this chapter. Firstly, the three poultry system models are discussed. Secondly, the relevant theory is given, including the various assumptions and inputs, to solve the systems models. Thirdly, the various inputs and defined and finally, the simulation results are given.

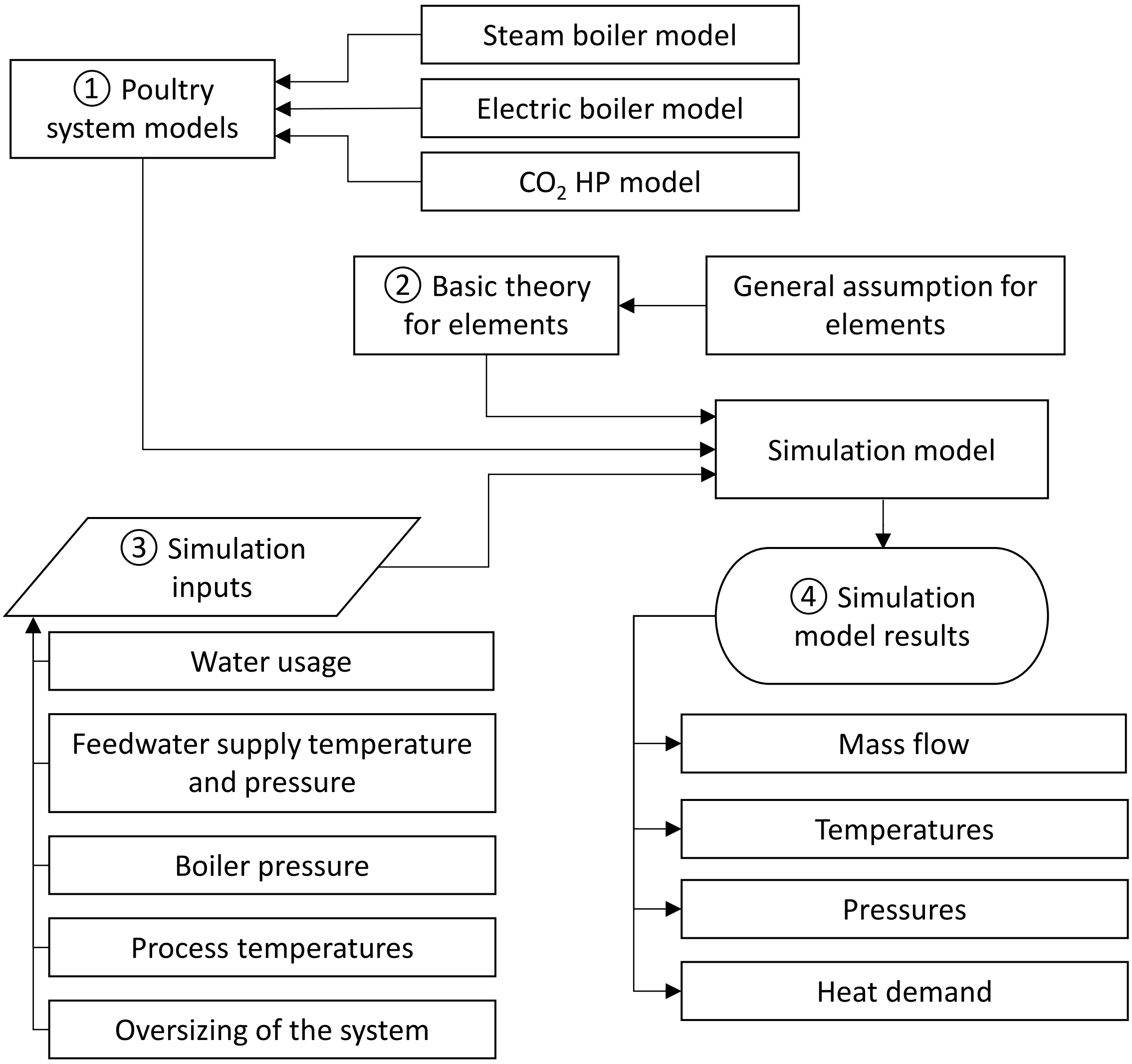


Figure 48: Overview of Chapter 5

5.2 Limitations

The limitations for this section of the work are as follows:

1. For this thesis, it is assumed that the CO_2 HPs and tanks will replace the current technology at the poultry abattoir. The comparison is not done for a new poultry abattoir installation where a decision needs to be made on what technology is the most cost effective and economical.
2. In the poultry abattoir, a chiller is used for the final chilling of the meat to a 4 °C core temperature within 12 hours. The chilled poultry is then stored at 4 °C. The cooling load and storage load of poultry is not included in this study due to the complexity on the sizing of the area and heat demand for the cooling. By including the cooling and storage load, the demand of the current chiller is reduced. The cooling will then be provided by the multi-function CO_2 HP. The impact would be positive for the CO_2 HP, the water is cooled at no extra cost. The impact of this needs then to be determined.

5.3 Poultry system models

To determine the potential of CO_2 HPs, the author needs to establish a base case. The system is based on a site visit to two abattoirs of the top seven poultry producers. The first base case is thus based on an actual poultry abattoir system layout and heating source. For this case, the process heat is provided by a steam boiler and the cooling by an ammonia chiller plant. For the second case, the process heat is provided by an electric boiler and the cooling again by an ammonia chiller plant. Finally, the proposed multi-function CO_2 HP is discussed.

Figure 49 shows the simplified layout of a hot water and chilled water distribution system for a typical poultry abattoir. Figure 49 shows that a single steam boiler supplies steam to a heat exchanger (HX) and two calorifiers at a higher and a lower temperature. The HX is used to heat the water for the scalding tanks, while the calorifiers supply hot water to the floor for equipment washing as well as the shower and handwash basins. Finally, the ammonia chiller is coupled to the spin chillers.

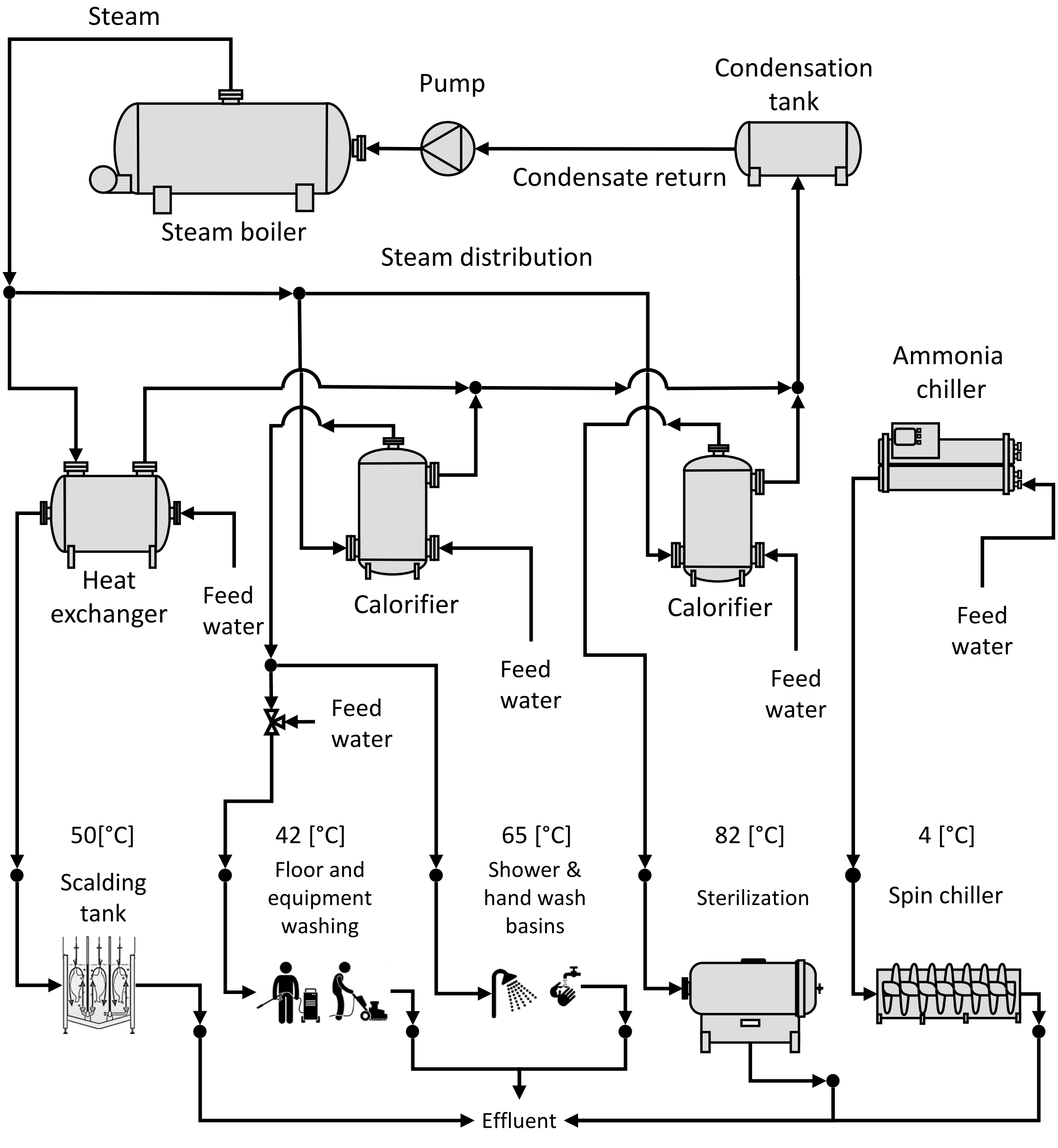


Figure 49: Typical poultry abattoir plant hot water layout using a steam boiler

As a part of the larger project, the Water Research Council (WRC) investigated the specific effluent volume and the energy use of poultry abattoirs (WRC, 2017). In total, 13 abattoirs, ranging from a small plant with a capacity of 78 000 birds per annum to large plants of 105 million birds per annum, were investigated (WRC, 2017). From the data, it was found that all abattoirs used coal for heating. Furthermore, from a conversation with Oosthuizen (2019) it was established that one HT abattoirs also use paraffin as an energy source for steam generation and hot water for scalding tanks. Irshad and Arun (2013) indicated that for a scalding tank, the water is heated by gas (LPG) and electricity. Although no examples of such plants could be found in SA, the author has included them to compete the picture.

Figure 50 shows the system layout for hot water supply via an electric system. For this scenario, the steam boiler is replaced with two electric calorifiers that operate at different temperature ranges. The two calorifiers operate at various temperatures to match them more closely with the temperatures of the process. The lower temperature tank is set at 65 °C to combat the impact of legionellae. According to the WHO (2007), legionellae is destroyed in hot water system at a temperature of 65 °C. SANS 893-2 (SABS, 2013) also indicates that the minimum temperature for a calorifier must be at least 60 °C. Consequently, a temperature of 65 °C was chosen to ensure that legionellae do not exist in the tanks.

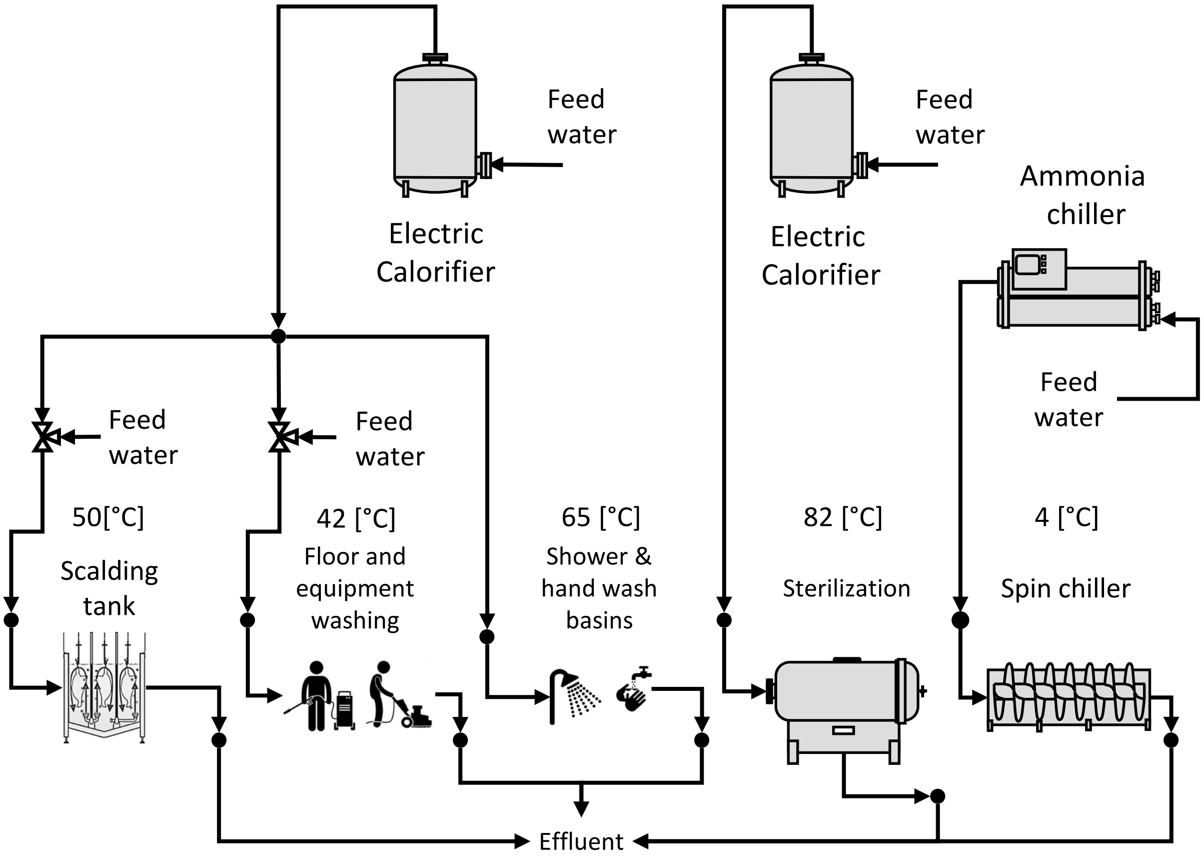


Figure 50: Typical poultry abattoir plant hot water layout using electric heating

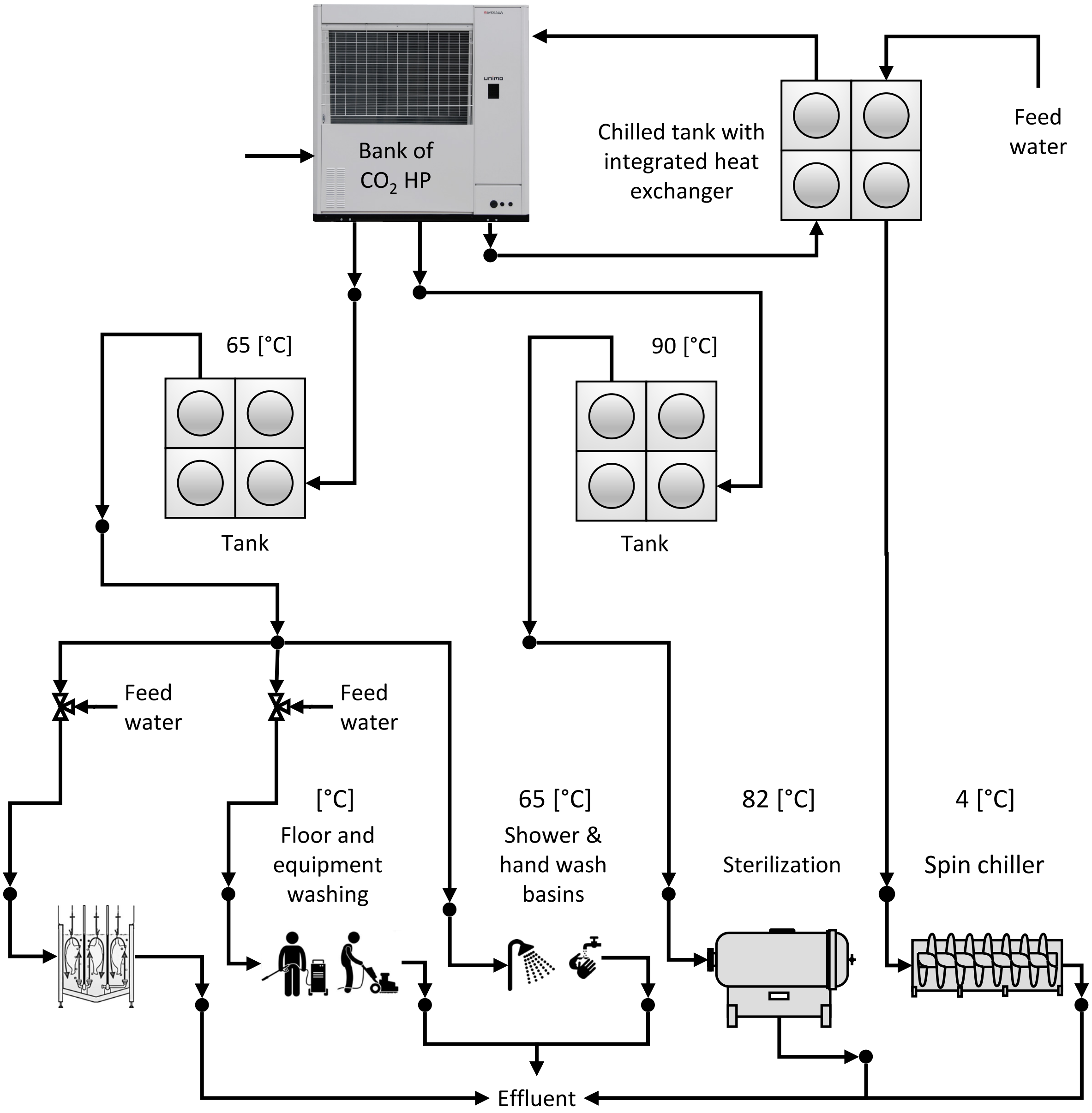


Figure 51: Proposed system layout with CO_2 HP

For the proposed layout (Figure 51), the boilers and chillers are replaced with a bank of Mayekawa multi-function air-water-water (AWW) CO_2 HPs. To simplify the diagram, the bank of CO_2 HPs are graphically represented as a single CO_2 HP. The CO_2 HP is a multi-function heat pump that delivers hot water at 65 °C and 90 °C respectively as well as chilled water down to -9 °C (Mayekawa, 2013a). The CO_2 HP bank can thus deliver at the same time both hot and chilled water (Mayekawa, 2013a). If no chilled water is required, the CO_2 HP generates only hot water using the air as a heat source (Mayekawa, 2013a). The system thus has no dedicated ammonia chiller because the CO_2 HP has a built-in chiller.

The system has no heat exchangers to preheat the feedwater from the effluent streams. According to the WRC (1989), scalding tanks that overflow have high organic and solid pollution loads. The high pollution is also found in the floor and equipment washing, shower and handwashing, and sterilisation. Water coming from the chiller have high amounts of ingesta, blood, fat, faecal material, and protein (Russel, 2013). Due to the high pollutant contents, there is a high probity of fouling; thus, the author excluded the use of intermediate heat exchangers that preheat the inlet water.

The next section discusses the general assumptions, theory and elements which are used for the simulation.

5.4 General assumption and theory for the various elements in the layout

This section provides the general assumptions and theory of the various elements of the proposed layouts. An element can be any type of thermal-fluid component such as a compressor, fan, pipe, pump turbine, or heat exchanger element.

Firstly, the general assumptions for the layout are discussed. Secondly, each element used in the simulation is briefly discussed, and an overview is given of the governing equations that are used. The simplified systems consist of the following elements:

- Pipes elements,
- junction elements,
- simple mixing valves,
- heat exchangers,
- storage vessels, heating and cooling elements, and
- pump elements.

5.4.1 General assumptions

The general assumptions for all the processes include the following Rousseau (2011):

1. The processes are at steady-state with steady flow.
2. The flow is one dimensional.
3. The height differences can be ignored between the various elements.
4. The components do not have any specific dimensions. Thus, the pipe diameter or storage tank area is not known at this stage.

The simulation of the various elements is based on three governing equations, which are the conservation of mass, the first law of thermodynamics, and the conservation of momentum. This section gives a brief overview of the equations.

The conservation of mass (the continuity equation) for a control volume is given by Rousseau (2011) as:

$$V\!\!\!\!-\,\frac{d\cancelto{0}{\rho}}{\cancel{dt}} = \sum \dot{m}_i - \sum \dot{m}_e \qquad (5),$$

$$\sum \dot{m}_i = \sum \dot{m}_e$$

where

$V\!\!\!\!-$	: Volume	[m]
ρ	: Density of the fluid	[kg/m]
$\dot{m}$	: Mass flow	[kg/s],

with the subscripts

i	: Inlet
e	: Outlet.

The first law of thermodynamics, also known as the conservation of energy for a finite control volume, is thus given by Rousseau (2011), and reduces to:

$$\dot{Q}_{CV} + \dot{W}_{CV} = \sum \dot{m}_e\left(h_{0e} + g\cancel{z_e}\right) - \sum \dot{m}_i\left(h_{0i} + g\cancel{z_i}\right) + V\!\!\!\!-\,\frac{d}{\cancel{dt}}\cancelto{0}{\left(\rho \cdot h_0 - p\right)} \qquad (6),$$

$$\dot{Q}_{CV} + \dot{W}_{CV} = \sum \dot{m}_e \cdot h_{0e} - \sum \dot{m}_i \cdot h_{0i}$$

where

g	: Gravity constant	[m/s^2]
h_0	: Stagnation enthalpy	[kJ/kg]
p	: Static pressure	[Pa]
$\dot{Q}_{CV}$	: Total rate of heat transfer to the fluid over the control volume	[kW]
$\dot{W}_{CV}$	: Total rate of work done on the fluid over the control volume	[kW]
z	: Elevation height	[m].

The conservation of momentum equation for an incompressible flow (water) is given by Rousseau (2011) and reduces to:

$$\rho L \frac{\partial \cancelto{0}{V}}{\cancel{\partial t}} + \left(p_{0e} - p_{0i}\right) + \rho g \cancelto{0}{\left(z_e - z_i\right)} + \Delta p_{0L} = 0 \qquad (7),$$

$$\left(p_{0e} - p_{0i}\right) = -\Delta p_{0L}$$

where

L	: Length of the control volume	[m]
V	: Velocity of the fluid	[m/s]

Δp_{0L} : Change in stagnation pressure over distance L [Pa].

t : Time [s].

The conservation of momentum equation for a compressible flow (steam) is given by Rousseau (2011) and reduces to:

$$\rho L \cancel{\frac{\partial V}{\partial t}}^{0} + \left(p_{0e} - p_{0i}\right) + \frac{1}{2}\rho V^2 \frac{1}{T_0}\left(T_{0e} - T_{0i}\right) + \rho g \cancel{\left(z_e - z_i\right)}^{0} + \Delta p_{0L} = 0 \qquad (8),$$

$$\frac{1}{2}\rho V^2 \frac{1}{T_0}\left(T_{0e} - T_{0i}\right) + \left(p_{0e} - p_{0i}\right) = -\Delta p_{0L}$$

where

T_0 : Stagnation temperature [K].

In the next section, the various elements are discussed in more detail.

5.4.2 Pipe element

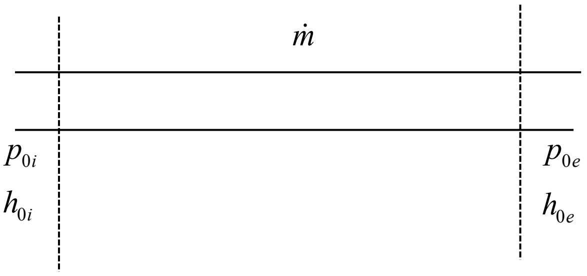


Figure 52: Simplified pipe

According to Rousseau (2011), the simplest way to estimate the pressure drop in a pipe is to write it as a fraction (α) of the average pressure level, namely:

$$\Delta p_{0L} = \alpha \frac{1}{2}\left(p_{0i} + p_{0e}\right) \qquad (9).$$

In the early design stages of the thermal system, the pressure loss for pipes or ducts is taken as zero (0). Thus:

$$\Delta p_{0L} = 0 \qquad (10).$$

$$p_{0i} = p_{0e}$$

Since there is only one inlet and outlet of the pipe, the continuity equation reduces to:

$$\dot{m}_i = \dot{m}_e = \dot{m} \qquad (11).$$

The conservation of energy equation used for pipe elements is given by Rousseau (2011):

$$\begin{gathered}\dot{Q}_{CV} + \cancel{\dot{W}_{CV}}^{0} = \sum \dot{m}_e \cdot h_{0e} - \sum \dot{m}_i \cdot h_{0i} \\ \dot{Q}_{CV} = \dot{m}\left(h_{0e} - h_{0i}\right)\end{gathered} \tag*{(12).}$$

In the early design stages of the thermal system, the heat gain for pipes or ducts is taken as zero (0). Thus:

$$\begin{gathered}\dot{Q}_{CV} = 0 \\ h_{0i} = h_{0e}\end{gathered} \tag*{(13).}$$

5.4.3 Junction (T-element)

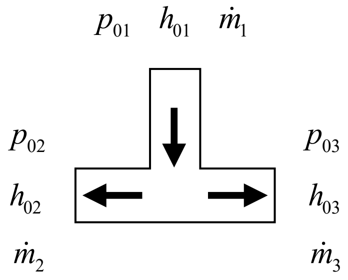


Figure 53: Simplified T-junction schematic

The pressure drop between point 1 and 2 is based on the principle of a simplified pipe element:

$$\Delta p_{0,12} = \alpha \frac{1}{2}\left(p_{01} + p_{02}\right) \tag*{(14)}$$

and

$$\Delta p_{0,13} = \alpha \frac{1}{2}\left(p_{01} + p_{03}\right) \tag*{(15).}$$

Furthermore, the pressure of point one is taken the same as the pressure of points two and three.

The conservation of mass (the continuity equation) is thus given by:

$$\begin{gathered}\sum \dot{m}_i = \sum \dot{m}_e \\ \dot{m}_1 = \dot{m}_2 + \dot{m}_3\end{gathered} \tag*{(16).}$$

The conservation of energy equation used for T-junction elements is given by:

$$\begin{gathered}\dot{Q}_{CV} + \cancel{\dot{W}_{CV}}^{0} = \sum \dot{m}_e \cdot h_{0e} - \sum \dot{m}_i \cdot h_{0i} \\ \dot{Q}_{CV} = \sum \dot{m}_e \cdot h_{0e} - \sum \dot{m}_i \cdot h_{0i}\end{gathered} \tag*{(17).}$$

In the early design stages of the thermal system, the heat gains of the T-junction are also then taken as zero. Thus:

$$\dot{Q}_{CV} = 0 \tag{18}$$
$$\dot{m}_1 \cdot h_{01} = \dot{m}_2 \cdot h_{02} + \dot{m}_3 \cdot h_{03}$$

5.4.4 A simplified mixing valve

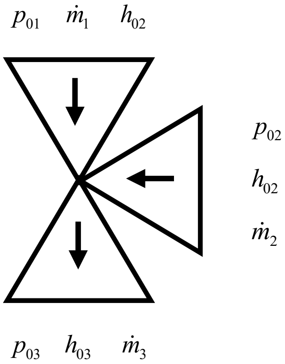


Figure 54: Simplified mixing valve schematic

The pressure drop between points 1 and 3 is based on the principle of a simplified pipe element:

$$\Delta p_{0,12} = \alpha \frac{1}{2}\left(p_{01} + p_{02}\right) \tag{19),}$$
$$\Delta p_{0,13} = \alpha \frac{1}{2}\left(p_{01} + p_{03}\right) \tag{20).}$$

Furthermore, the pressure of point two was taken the same as the pressure of point one.

The conservation of mass (the continuity equation) is thus given by:

$$\sum \dot{m}_i = \sum \dot{m}_e \tag{21).}$$
$$\dot{m}_3 = \dot{m}_1 + \dot{m}_2$$

The conservation of energy equation used for the mixing valve is given by:

$$\dot{Q}_{CV} + \cancel{\dot{W}_{CV}}^{0} = \sum \dot{m}_e \cdot h_{0e} - \sum \dot{m}_i \cdot h_{0i} \tag{22).}$$
$$\dot{Q}_{CV} = \sum \dot{m}_e \cdot h_{0e} - \sum \dot{m}_i \cdot h_{0i}$$

In the early design stages of the thermal system, the heat gains of the mixing valve were also taken as zero. Thus:

$$\dot{Q}_{CV} = 0 \tag{23).}$$

5.4.5 Heat exchangers

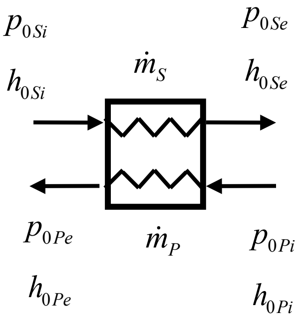


Figure 55: Simplified heat exchanger schematic

The pressure drop for the respective primary and secondary fluids is based on the principle of a simplified pipe element:

$$\Delta p_{0,12} = \alpha \frac{1}{2}\left(p_{01} + p_{02}\right) \tag{24}.$$

The simplest way to estimate the heat transfer duty for generic heat exchangers is to write it as a fraction of the maximum theoretically possible heat transfer $\dot{Q}_{\max}$:

$$\dot{Q} = \varepsilon \cdot \dot{Q}_{\max} \tag{25},$$

where

ε : Effectiveness of the heat exchanger [-].

For this thesis, it is assumed that the effectiveness for all heat exchangers is 0.9.

The maximum theoretically possible heat transfer between any two-fluid stream is given as:

$$\dot{Q}_{\max} = C_{\min} \Delta T_{\max} \tag{26},$$

where

$$\Delta T_{\max} = T_{Pi} - T_{Si} \tag{27}.$$

is the maximum possible temperature change that any of the two streams can undergo.

$$C_{\min} = \left[\dot{m} c_p\right]\Big|_{\min} \tag{28}$$

is known as the minimum heat capacity, which is equal to the minimum values of the mass flow rate times the specific heat capacity $\left(c_P\right)$ of either of the two-fluid streams.

5.4.6 Storage vessels, heating, and cooling elements

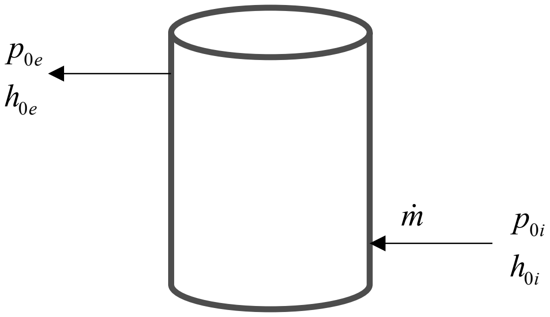


Figure 56: Simplified storage vessels, heating, and cooling elements

Storage vessels, heating, and cooling elements are all based on a basic pipe element as described by Rousseau (2011). The only difference is on heat transfer in conservation of energy. It is also assumed that the storage tanks are fully mixed. There is thus no stratification in the tank.

The simplest way to estimate the pressure drop in storage vessels, heating, and cooling elements is to write it as a fraction (α) of the average pressure level, namely:

$$\Delta p_{0L} = \alpha \frac{1}{2}\left(p_{0i} + p_{0e}\right) \tag{29}$$

In the early design stages of the thermal system, the pressure loss for storage vessels, heating, and cooling elements is taken as zero (0). Thus:

$$\begin{gathered} \Delta p_{0L} = 0 \\ p_{0i} = p_{0e} \end{gathered} \tag{30}$$

Since there is only one inlet and outlet for storage vessels, heating, and cooling elements, the continuity equation reduces to:

$$\dot{m}_i = \dot{m}_e = \dot{m} \tag{31}$$

The conservation of energy equation used for storage vessels, heating, and cooling elements is given by:

$$\begin{gathered} \dot{Q}_{CV} + \cancelto{0}{\dot{W}_{CV}} = \Sigma \dot{m}_e \cdot h_{0e} - \Sigma \dot{m}_i \cdot h_{0i} \\ \dot{Q}_{CV} = \dot{m}\left(h_{0e} - h_{0i}\right) \end{gathered} \tag{32}$$

In the early design stages of the thermal system, the heat gain for the storage tanks is taken as zero (0). Thus:

$$\begin{gathered} \dot{Q}_{CV} = 0 \\ h_{0i} = h_{0e} \end{gathered} \tag{33}$$

The heat gain or loss for heating and cooling elements is given by equation (32).

The amount of power used by a heating and cooling element is:

$$P = \left|\dot{Q}_{CV}\right| \Big/ COP \qquad (34),$$

where

P : Energy use of the heat pump or chiller [kW].

The amount of fuel used by a heating element (steam boiler) is:

$$\dot{m}_{fuel} = \frac{\dot{Q}_{CV}}{\eta_{Boil} \cdot CV_{fuel}} \qquad (35),$$

where

$\dot{m}_{fuel}$: Mass flow of fuel [kg/s],

η_{Boil} : Efficiency of the boiler [-],

CV_{fuel} : Calorific value of the fuel [kJ/kg].

5.4.7 Pump element

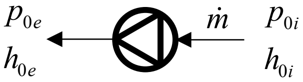


Figure 57: Simplified pump element

Since there is only one inlet and outlet of the pipe, the continuity equation reduces to:

$$\dot{m}_i = \dot{m}_e = \dot{m} \qquad (36).$$

The conservation of energy equation used for incompressible pump elements is given by Rousseau (2011):

$$P_P = \frac{\dot{m}}{\rho_i} \cdot \frac{1}{\eta_P} \left(p_{0e} - p_{0i} \right) \qquad (37),$$

where

P_P : Power use of the pump [W],

η_P : Isentropic efficiency of the pump [-].

5.5 Specific assumptions and inputs for the models

To determine the impact of CO_2 HPs in SA, the author must make various assumptions. The assumptions listed in this section of the work are needed to determine the steady-state energy use and mass flow of the steam boiler, electric calorifier, ammonia chiller, and multi-function CO_2 HP. These assumptions include:

1. water used in poultry plants,
2. the number of chickens processed by the abattoir,
3. feedwater supply temperature and pressure,
4. steam boiler operating pressure, and
5. oversizing of the system.

The next section gives details on the assumptions made for this study.

5.5.1 Water used in poultry plants

To establish norms for water intake and wastewater disposal, the WRC contracted VitaOne8 (Pty) Ltd to undertake the National Industrial Water and Wastewater Survey (NATSURV) of the poultry subdivision (WRC, 2017). Part of the research was conducted on the specific water intake per chicken for poultry abattoirs. In total, 15 abattoirs were investigated, which represents 56% of the number of birds slaughtered in 2015. From the data, it was observed that the chosen average specific water intake was 13.0 litres per bird with an associated uncertainty of 2.4 litres per bird. For detailed values, please refer to Table 41 in Appendix B.

WRC (1989) and WRC (1993) have reported on the water use in the various parts of the poultry abattoirs. To establish norms for water intake and wastewater disposal, the WRC undertook the NATSURV of the poultry subdivision in 1989 (WRC, 1989). As part of this study, an investigation was done on the breakdown of the water use in poultry abattoirs. Furthermore, as part of the guide for water and wastewater management in the poultry abattoir subdivision, the WRC conducted a second study on the breakdown of the water use in the poultry subdivision in 1993 (WRC, 1993). These two sources are combined in Table 18 to determine the specific inputs of the water usage.

Table 18: Percentage breakdown of water use in poultry abattoirs. Source: WRC (1989); WRC (1993)

Activity	Operation	Average	Uncertainty	1988	1992
Process	Hanging, stunning, bleeding	1.0%	0.1%	0.9%	1.2%
Process	Scalding	17.1%	0.1%	17.2%	17.1%
Process	Evisceration	33.0%	0.1%	33.1%	32.9%

Activity	Operation	Average	Uncer-tainty	1988	1992
Process	Spinning chilling	11.8%	0.1%	11.8%	11.8%
Utilities	Cooling towers and refrigeration	7.1%	0.1%	7.1%	7.1%
Utilities	Boilers	1.0%	0.1%	0.9%	1.2%
Wash-down	Floor and equipment washing	17.1%	0.1%	17.2%	17.1%
Wash-down	Crate washing	1.8%	0.1%	1.8%	1.8%
Wash-down	Truck washing	2.9%	0.1%	3.0%	2.9%
Other	By-products rendering	4.7%	0.1%	4.7%	4.7%
Other	Domestic (ablution, etc.)	2.4%	0.1%	2.4%	2.4%
TOTAL		**100.0%**			

By combining the values of the specific water intake per chicken (Table 19), the water use can be determined per operation. It is important to note that water used by the ablution for the showers and toilets is not separated. For this thesis, the author assumes that 50% of the water goes to the showers, while 50% goes to the toilets and hand washbasins.

Table 19: Breakdown of water use in poultry abattoirs. Source: WRC (1989); WRC (1993); WRC (2017);

Activity	Operation	Average [l/bird]	Uncertainty [l/bird]
Process	Hanging, stunning, bleeding	0.13	0.03
Process	Scalding	2.22	0.41
Process	Evisceration	4.29	0.79
Process	Spinning chilling	1.53	0.28
Utilities	Cooling towers and refrigeration	0.92	0.17
Utilities	Boilers	0.13	0.03
Wash-down	Floor and equipment washing	2.22	0.41
Wash-down	Crate washing	0.23	0.04
Wash-down	Truck washing	0.38	0.07
Other	By-products rendering	0.61	0.11
Other	Domestic (ablution, etc.)	0.31	0.06
TOTAL		**13.00**	

5.5.2 The number of birds processed per minute

The author must assume the number of chickens processed by a plant. For this, the number of chickens processed by the seven largest companies' various plants was investigated. This information is not readily available. Secondly, the author had to consider the processing speed of the mechanised line. The processing line speed can be as low as 500 birds per hour (8.3 birds per minute) and as high as 6 000 birds per hour (100 birds per minute) (Dutch poultry tech, 2015). From a conversation with Bruton (2019), it was established that JF equipment has upgraded a plant in SA to 9 000 birds per hour. Due to considerable variation in the processing speeds of poultry, it was decided to base the line speed on 100 birds per minute.

5.5.3 Feedwater supply temperature and pressure

Denys (2001) and Meyer and Greyvenstein (1991) assumed that the feedwater temperature is equal to the average ground temperature at a depth of 1.2 metres during any particular month. Consequently, Denys (2001) gave the average feedwater temperature per month for 27 locations in SA. The feedwater temperature would thus need to change for each location investigated in this thesis. This assumption would complicate the sizing of the tanks. From Denys (2001) data , it was determined that the maximum and minimum feedwater temperature for SA was 10.8 °C and 28.9 °C, respectively. Due to the major differences in the feedwater temperature, the average feedwater temperature is thus assumed as 10 °C with an associated uncertainty of 5 °C. The feedwater pressure is assumed to be 300 kPa.

5.5.4 Steam boiler operating pressure

From the site visit and a conversation with Oosthuizen (2019) and poultry plant visit, it was established that the operational pressure for the steam boiler was 900 kPa abs. An uncertainty of 50 kPa was chosen for the operational pressure.

5.5.5 Oversizing of the systems

For the boiler system, it was assumed that there are no heat losses for the pipes, boiler, and other elements. To compensate for the assumption, the total load for the boiler system, electric boiler, chiller, and CO_2 HP was assumed to be 10% greater than the design values, with the associated uncertainty of 5%.

5.6 Steady-state simulation results

This section shows the steady-state simulation results of the three scenarios that were simulated. The three scenarios were:

1. steam boiler cycle,
2. electric heating, and
3. CO_2 HP heating.

It should be noted that at this stage, the power use of the CO_2 HP cannot be shown. To determine the power use of the CO_2 HP, one needs to match the daily mass flow and heat demand of the plant to that of the CO_2 HP. The steady-state mass flow and heat demand of this section are needed to determine the COP. Therefore, only the mass flow and heat demand are presented at this stage for the CO_2 HP scenario.

The steady-state results are also shown as independent of the various climatic zones. The climatic zones only influence the mass flow and COP of the CO_2 HP and are dependent on the number of CO_2 HPs. The number of CO_2 HPs can only be determined from the steady-state results and are thus not possible at this point.

For the detailed simulation code, please refer to Appendix C.

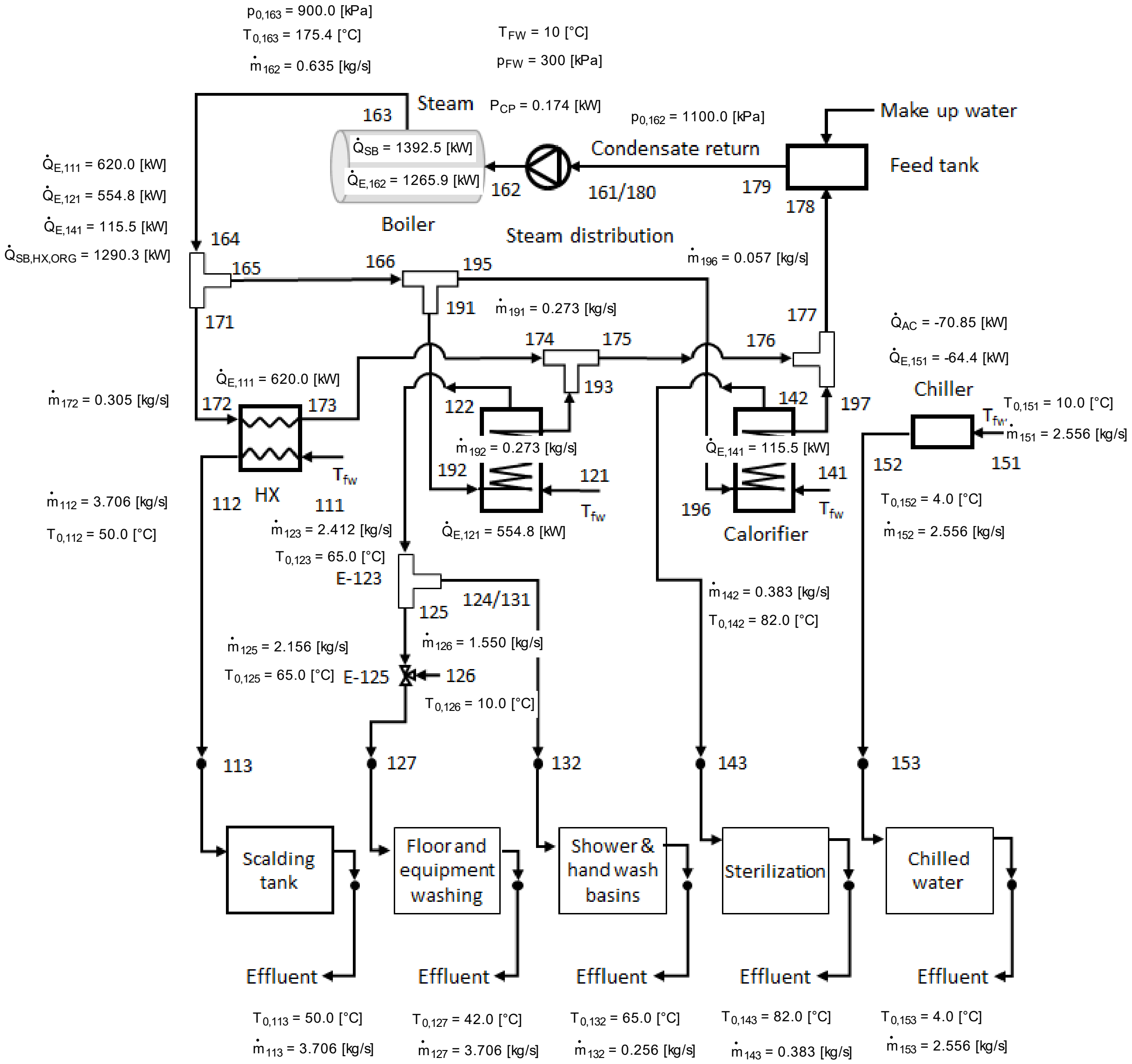


Figure 58: Simulated results for the steam boiler layout.

From Figure 58, one can see that the steam boiler needs to produce 0.635 kg/s of steam at a pressure of 900 kPa abs. The amount of energy needed to produce the steam is 1 265.9 kW. The steam mass flow through the heat exchanger is 0.305 kg/s and the thermal heat demand is 620 kW. For the calorifier that delivers water at 65 °C, the steam mass flow is 0.273 kg/s, with a thermal heat demand of 554.8 kW. The calorifier that which is used for the sterilisation thermal heat demand is 115.5 kW, with a steam mass flow of 0.057 kg/s. For the chiller, the thermal cooling demand is 64.4 kW.

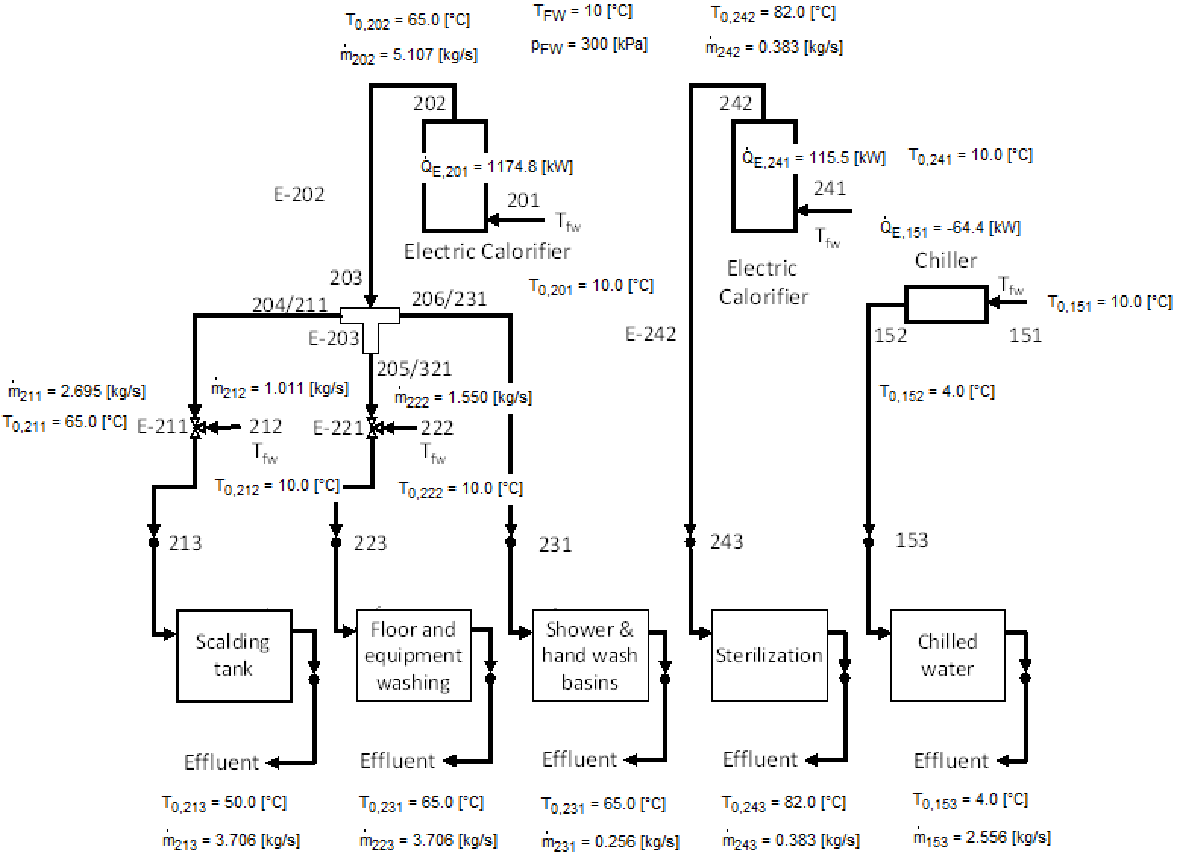


Figure 59: Simulated results for the electric boiler (calorifier) layout.

For electrical boiler layout (Figure 59), one can see that the electric calorifier has an outlet temperature of 65 °C, a mass flow of 5.107 kg/s, and the thermal heat demand is 1 174.8 kW. The electric calorifier with an outlet temperature of 90 °C has a thermal heat demand of 115.5 kW and a mass flow of 0.383 kg/s. The chiller thermal cooling load is the same as that for the steam boiler layout, which is 64.4 kW.

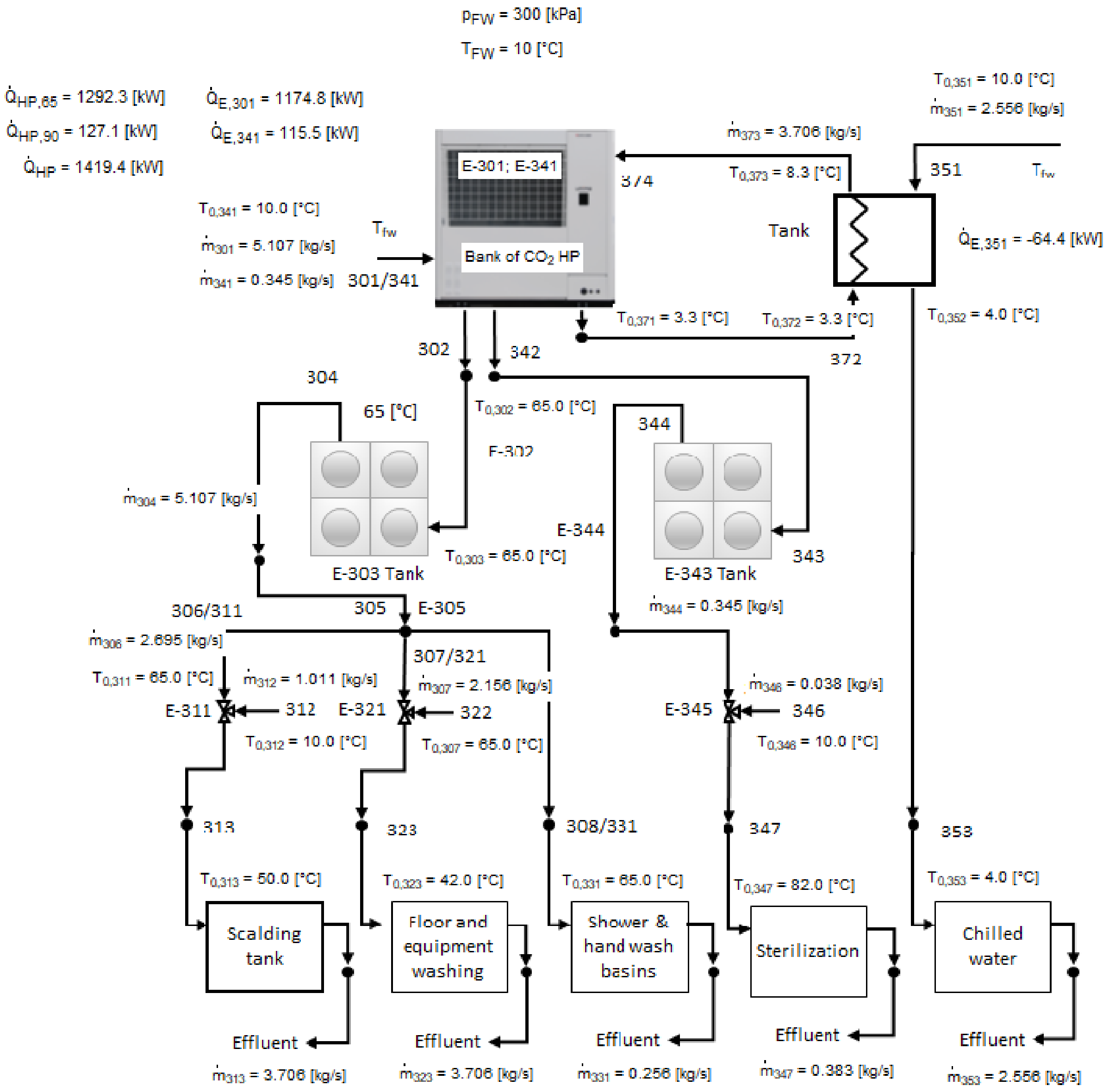


Figure 60: Simulated results for the multi-function CO_2 HP layout

From Figure 60, one can see that the total heating load for the bank of CO_2 HPs' total thermal load is 1 290.3 kW. The thermal load for the CO_2 HP at 65 °C is 1 174.8 kW with a mass flow of 5.107 kg/s. The thermal load for the 90 °C CO_2 HP is 115.5 kW, with a mass flow of 0.345 kg/s. The thermal heat demand of the 90 °C, is about ten times smaller than that of the 65 °C side. This is mainly due to the much smaller mass flow of the sterilisation stream. The cooling thermal demand is the same as that for the coal and electric boiler ammonia chiller, at 64.4 kW.

Various checks and balances were done in the simulation code. The checks and balances included ensuring that:

- the conservation of mass for the various components are adhered to,

- the conservation of energy for the various components are adhered to,
- the momentum equation for the various components are adhered to,
- the temperature reduces after a mixing valve,
- the temperature stays the same for the inlets and outlets of the piece,
- there are no negative mass flows, and
- the total heat demand for all the layouts are the same.

The detailed results can be seen in Appendix D.

5.7 Verification of the model

To verify the model an extra simulation was done using DWSIM. DWSIM is an open source chemical process simulator developed by Daniel Wagner (Medeiros) (DWSIM, 2021b). The software can a solver for both steady-state and dynamic modelling (DWSIM, 2021a). DWSIM has various steady state unit operators including pumps, compressors, expander, heater, cooler valves, pipe segment etc.(DWSIM, 2021a).

The detail results of the DHSIM simulation are given in Appendix E. To compare the result the author looked at the final energy values of the CO_2 HP, chillers, boilers, heat exchangers and boilers. The values are the most important results, as the energy use of the will be used in the next section.

Table 20: Comparison of the EES simulation and DWSIM results

System	Description	EES Value [kW]	DWSIM value [kW]	Percentage error
CO_2 HP	CO_2 HP chiller side	64.40	64.41	0.0%
	CO_2 HP at 65°C	1174.80	1174.82	0.0%
	CO_2 HP at 65°C	115.50	115.51	0.0%
Electric boiler	Chiller	64.40	64.41	0.0%
	Electric boiler at 65°C	1174.80	1174.82	0.0%
	Electric boiler at 90°C	115.50	115.40	0.1%
Steam boiler	Chiller	64.40	64.41	0.0%
	Boiler	1265.90	1268.80	0.2%
	HX at 50°C	620.00	619.93	0.0%
	HX at 65°C	554.80	554.84	0.0%
	HX at 82°C	115.50	115.40	0.1%
	Pump	0.174	0.174	0.0%

From Table 20 one can see that largest error was for the steam boiler of 0.2%. The absolute difference is 2.90 kW. The EES simulations is thus verified., and can be used to determine the impact of the CO_2 HP in poultry industry,

5.8 Summary

This chapter gave an overview of the system model. Three systems layouts were developed based on information gathered at an actual poultry abattoir. The first layout has a steam boiler at the primary energy source with an ammonia chiller for cooling. The second layout uses electricity for heating with an ammonia chiller for cooling. The third layout only uses a CO_2 HP for heating and cooling. The relevant theory was given to describe the models. Finally, the system's model results were presented. In the next chapter, the system's model results are used to match the daily mass flow and thermal heat demand of the plant to that of the CO_2 HPs. The combines results are then used to evaluate the potential of the CO_2 HP versus the two other base cases.

Chapter 6. Estimating the potential impact of CO_2 HPs in poultry abattoirs

6.1 Introduction

In the previous chapter, the steady-state models were simulated for the three case studies. In this chapter, the results are compared based on the monthly and annual energy use and greenhouse gas, total energy cost, and four financial indicators. With this information, a financial sensitivity analysis is done to determine the factors with the largest economic impact. Finally, an analysis is done to determine the environmental impact of 17 of the largest abattoirs that are converted from a coal boiler system to a CO_2 HP system. The overview of the chapter is shown in Figure 61.

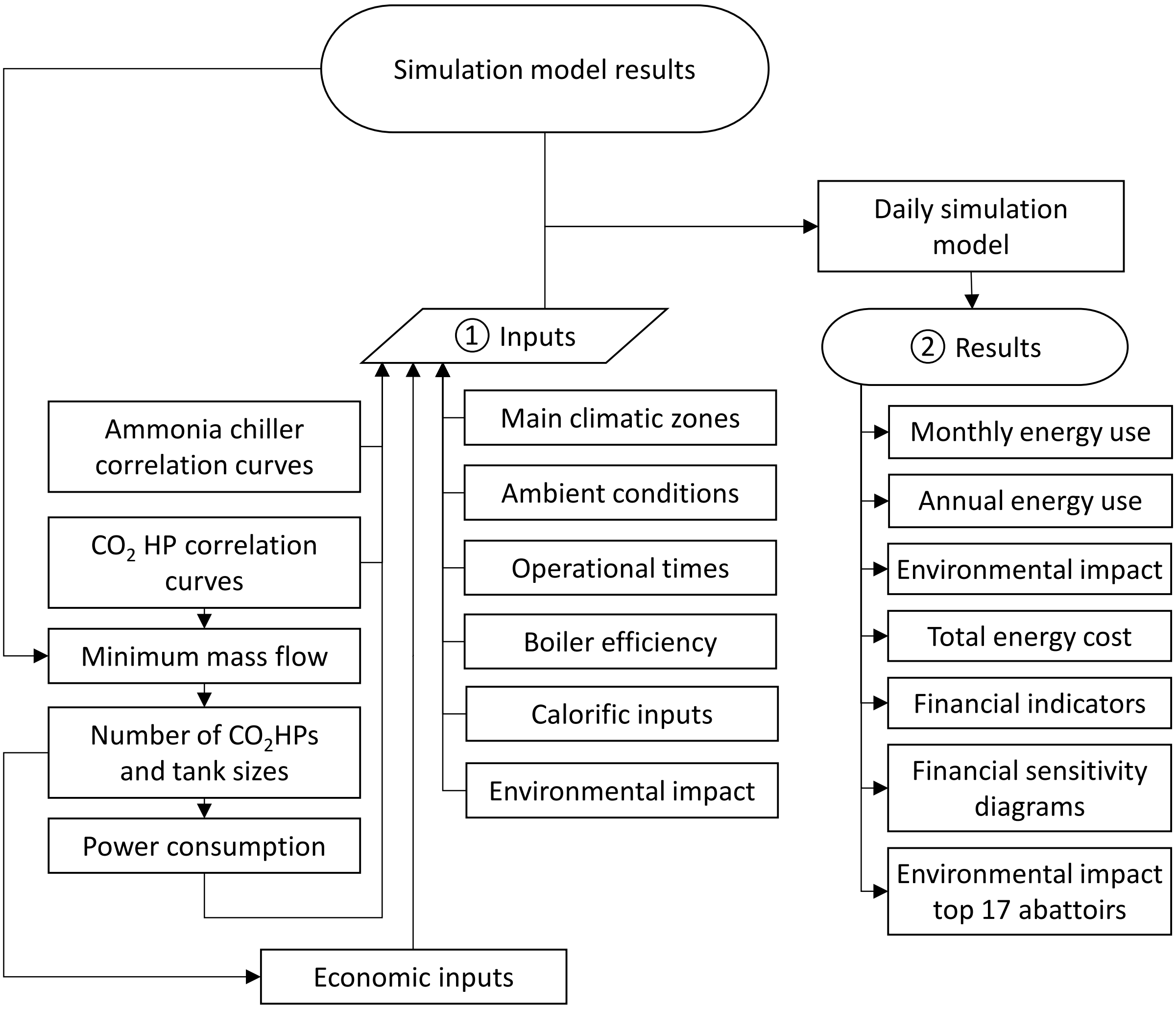


Figure 61: Overview of Chapter 6.

6.2 Inputs

6.2.1 Main climatic zones

The climatic zones are based on the SANS 204 (SABS, 2011a) and SANS 10400-XA SABS (2011b). The two standards recognise six main climatic regions in SA, as shown in Figure 62. The standards aim to establish the maximum energy demand and maximum energy consumption in the design of a particular building in the South African climate into the National Building Standards. In total, data for 141 towns in SA is available in the standard.

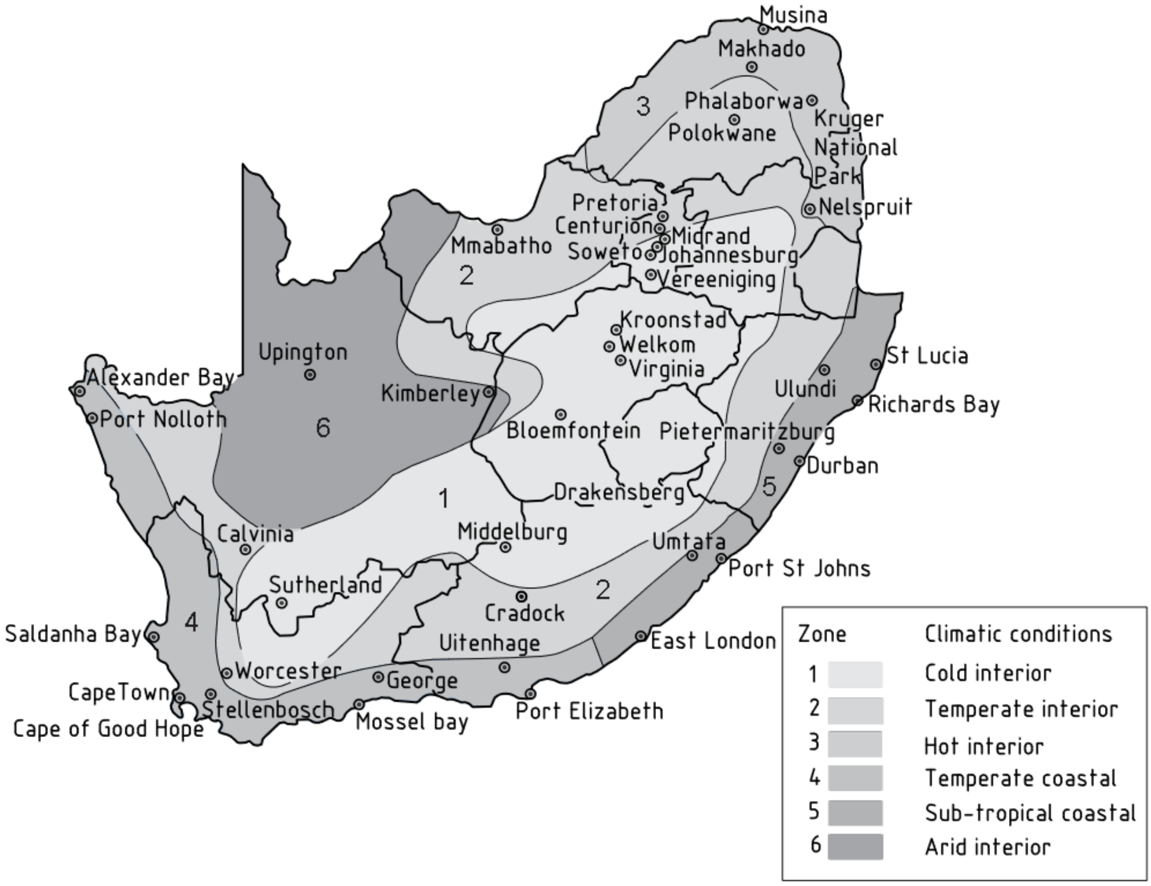


Figure 62: Climatic zones as defined by SANS 204 and SANS 10400-XA. Source: SABS (2011a); SABS (2011b)

These abattoirs were then divided into the various climatic zones. It should be noted that the SANS 204 (SABS, 2011a) and SANS 10400-XA SABS (2011b) lists 140 towns. The author had to extend this list by comparing the location of 86 towns with that of the two standards. The complete list of towns is given in 0.

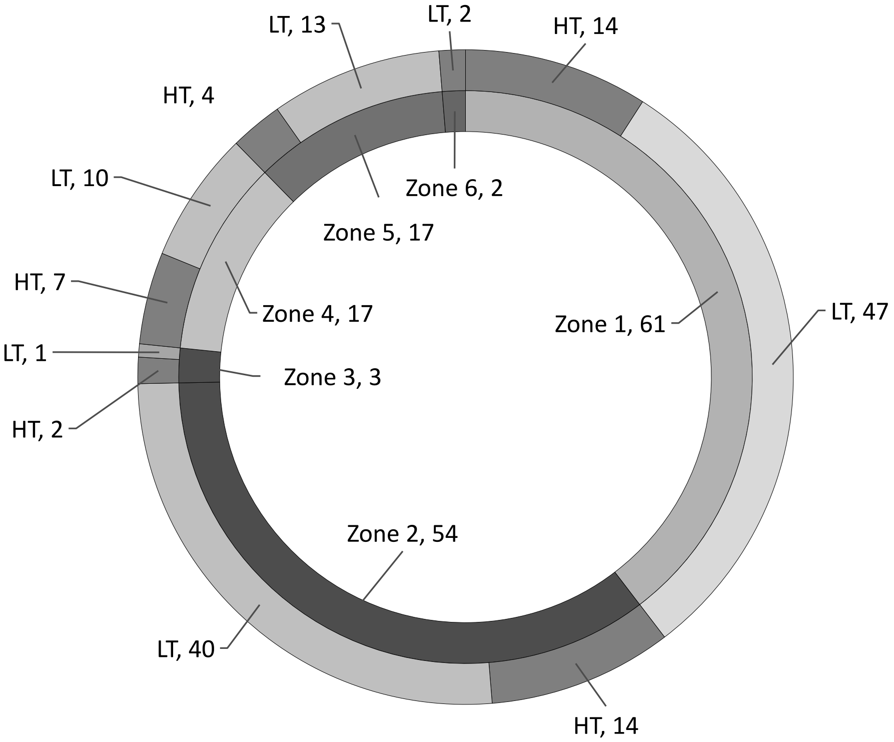


Figure 63: Division of the various poultry abattoirs into different climatic zones. DAFF (2018a); SABS (2011a); SABS (2011b)

According to Figure 63, 61 of the abattoirs are located in climatic zone 1 (cold interior) and 54 in climatic zone 2 (temperate interior). Climatic zone 4 (temperate coastal) and zone 5 (subtropical coastal) each has 17 abattoirs. The least number of abattoirs is for climatic zone 3 (hot interior) and zone 6 (arid interior), with each having two abattoirs.

6.2.2 Ambient conditions

For the weather data, the author obtained hourly weather data from Weather SA (2015) for 2015. In total, 19 towns were selected for the poultry abattoirs. The towns were selected as follows:

- All the cities that were listed by the major poultry supplies, as shown in Figure 44 (section 4.1), were included.
- Where fewer than three towns were in a climatic zone, at least three towns were included.
- For climatic zones that had only one town with an abattoir, additional towns were selected. These additional towns were selected by hand, near the original towns to represent the climatic zone better.

Table 21 shows the weather stations selected for the input. For each of the climatic zones, the hourly average and uncertainty were determined using the data for the towns of the specific climatic zone.

Table 21: Weathers stations for the various climatic zones of SA. Source: DAFF (2018a); SABS (2011a); SABS (2011b); Weather SA (2015)

Climatic zone	Number of abattoirs for zone	Weather station locations	Number of HT abattoirs	Number of low-throughput abattoirs
1	61	Bloemfontein	1	4
		Johannesburg	0	4
		Potchefstroom	3	0
		Randfontein	0	5
		Springs	2	1
		Vereeniging	0	2
2	53	Hartebeespoort	1	0
		Mafikeng	1	3
		Pretoria	1	6
		Tzaneen	2	0
3	2	Nelspruit	2	0
		Kruger Park International Airport	0	0
		Graskop	0	0
4	17	Cape Town	2	0
		Malmesbury	1	0
		Port Elizabeth	0	2
5	17	Durban	2	2
		Margate	2	2
		Mthatha	0	1
		Pietermaritzburg	0	1
6	2	Upington	0	2
		Prieska	0	0
		Kathu	0	0
TOTAL	153		20	35

6.2.3 Operational times

The author conducted a site visit of a HT abattoir to determine the typical operating hours of an abattoir. From the site visit and a conversation with Oosthuizen (2019), it was established that the operation of the HT poultry abattoir is divided into three typical production days. These typical days are given in Table 22. As seen in Table 22, Bruton (2019) and Oosthuizen (2019) indicated that operations of HT abattoirs typically comprise double shifts for weekdays. On Saturdays, the production is reduced to one shift, and on Sundays, no chickens are slaughtered.

Table 22: Typical working days for a local abattoir. Source: Oosthuizen (2019); Bruton (2019)

Description	Number of shifts	Days
Full production	Two	Monday to Friday
Half production	One	Saturdays, Easter Sunday, New Year's Day
No production	None	Sundays, Christmas, and Easter Friday

Oosthuizen (2019) indicated that the auxiliary systems (chilled water and steam boiler) have to start earlier, as shown in Table 23. However, all the start times were taken as the same because the auxiliary systems need to preheat and precool the same amount of water irrespective of the number of chickens slaughtered on a day. The similar start times were chosen to ensure the chilled water and hot water tanks are on temperature before the shift starts. It is assumed that for an electric boiler, the same operational times are used as that of the steam boiler.

Table 23: Detail operation of a poultry abattoir. Source: Oosthuizen (2019)

Description	Full production		Half production	
	Time	Hours per day	Time	Hours per day
Steam boiler	02:00 – 24:00	22	02:00 – 14:30	12 ½
Chilled water	06:30 – 23:30	17	06:00 – 14:30	8 ½
Slaughter of chicken	06:00 – 23:00	17	06:00 – 14:00	8 ½

6.2.4 Boiler efficiency

The various boiler efficiencies are assumed to be equal to the work done in section 3.2.4. The values are repeated in Table 24 for ease of reference.

Table 24: Typical efficiency for boilers

Boiler	Chosen value	Uncertainty
Coal	77%	13%
Oil (Paraffin)	73%	7%
Natural Gas (LPG)	77%	13%
Electricity	88%	12%

6.2.5 The calorific value of the various energy sources

To determine the energy used by the various types of boilers, the calorific values are also required, and for liquid fuel, the density of the fluid is required. The Digest of South African Energy Statistics for 2009 (DoE SA, 2009), the Energy Price Report of 2018 (DoE SA, 2018), Steyn and Minnitt (2010), the IPCC (2006), and Carbon Tax Act 15 (2019) have reported on the calorific values of various energy sources. Only the IPCC (2006) indicated lower and upper values for the net calorific values of the various fuels. The Digest of South African Energy Statistics for 2009 (DoE SA, 2009) and the Energy Price Report of 2018 (DoE SA, 2018) gave the same values for the various energy sources. Table 25 shows the combined values of the various sources. For detailed values of the various sources, refer to Appendix C.

Table 25: Calorific value for the various fuel sources. Source: DoE SA (2018); Steyn and Minnitt (2010), IPCC (2006); and Carbon Tax Act 15 (2019);

Carrier	**Coal (Various) [MJ/kg]**	**LPG [MJ/kg]**	**Paraffin [MJ/l]**
Calorific value	25.56	48.44	34.10
Uncertainty	2.83	2.72	4.60

The next section discusses the various environmental impacts of the energy sources.

6.2.6 Environmental impact of the energy sources

As part of its annual report, Eskom publishes the environmental impact of generating electricity. The indices include coal use, water use, ash produced, CO_2, SO_x and NO_x emissions. Table 26 shows the environmental impact of electricity. The author took an average of ten years from 2008/09 until 2018/19 for a more generalised value. For detailed values, please refer to Appendix M.2.

Table 26: Environmental implications of using or saving electricity. Source: Data from Eskom (2016)

Description	**Unit**	**Average**	**Uncertainty**
CO_2 emissions	[kg/kWh]	0.97	0.02
Sox (SO_4) emissions	[g/kWh]	8.00	0.25
N_2O emissions	[g/kWh]	0.01	0.00
NO_x emissions	[g/kWh]	4.09	0.08
Particulate emissions	[g/kWh]	0.32	0.04
Water use	[l/kWh]	1.37	0.04
Ash produced	[g/kWh]	151.38	4.34

The 2006 IPCC Guidelines for National Greenhouse Gas Inventories assists countries in compiling complete, national inventories of greenhouse gases (IPCC, 2006). The guideline has been structured so that any country, regardless of experience or resources, should be able to produce reliable estimates of their emissions and the removal of these gases (IPCC, 2006). The guideline is used by the South African National Greenhouse Gas (N GHG) emission reporting regulations for the monitoring, reporting, and verification of greenhouse gas emissions by industry (SA N GHG, 2016). Table 27 shows the CO_2, CH_4 and N_2O values with its associated uncertainties. For coal, another bituminous coal was chosen as the reference value as it has the closest calorific value to that of South African coal. Eskom does not publish the values on CH_4 and N_2O. Thus, these values were taken from Table 27 for coal. The same values were used by Zhou *et al.* (2009) to determine the regional emission factors for the power sector in Southern Africa. The CO_2 emissions value was verified against the published value of Eskom. The error was smaller than 0.02%, thus indicating that the values for NO_2 and SO_4 can be trusted.

Furthermore, the IPCC (2006) gives an upper and lower value for the various emissions. The difference between the default emissions factor and the upper and lower limit is not always the same. Therefore, the uncertainty was determined by using the standard deviation equation with the data from the upper and lower limits. It should be noted that the standard deviation is sometimes larger than the difference between the default value and the upper and lower limits. The value was thus truncated at the smallest difference. For detailed calculations, please refer to Appendix M.

Table 27: Default emissions factor for stationary combustion in the energy industries : Source: IPCC (2006)

Emissions	**Description**	**Unit**	**Eskom Coal (Sub-bituminous coal)**	**Coal (Other bituminous coal)**	**LPG**	**Paraffin**
CO_2	Default	[kg/TJ]	96100	94600	63100	71900
	Uncertainty	[kg/TJ]	2943	4164	1500	1100
CH_4	Default	[kg/TJ]	1.00	1.00	1.00	3.00
	Uncertainty	[kg/TJ]	0.70	0.70	0.70	2.00
N_2O	Default	[kg/TJ]	1.50	1.50	0.10	0.60
	Uncertainty	[kg/TJ]	1.00	1.00	0.07	0.40

6.2.7 The chiller correlation curves

In this thesis, the author assumes that a York chiller is used in the poultry plants. York chillers are sold in SA, and they publish data sheets with the COP cooling. However, York (2016) data tables show only a COP that depends on the machine size and model. No detail is given on the change in COP with the operating conditions.

Consequently, a curve fit was done using the cooling capacity as an input. Equation (38) is used:

$$COP_C = 0.004 \cdot \dot{Q}_C + 2.5015 \tag{38}$$,

where

COP_C : Coefficient of performance of the chiller [-]

and

$\dot{Q}_C$: Cooling capacity of the chiller [kW].

Figure 64 shows the accuracy of the predicted curve fit. Figure 64 demonstrates that the two largest errors are 10% and 13%. The coefficient of determination (R^2) of the curve fit is only 0.51. If the largest error is removed, the R^2 increases to 0.88. Therefore, this data point seems to be an outlier. However, the author decided to take the data as is. An uncertainty of 3.9% was taken, which is based on the standard deviation of the error.

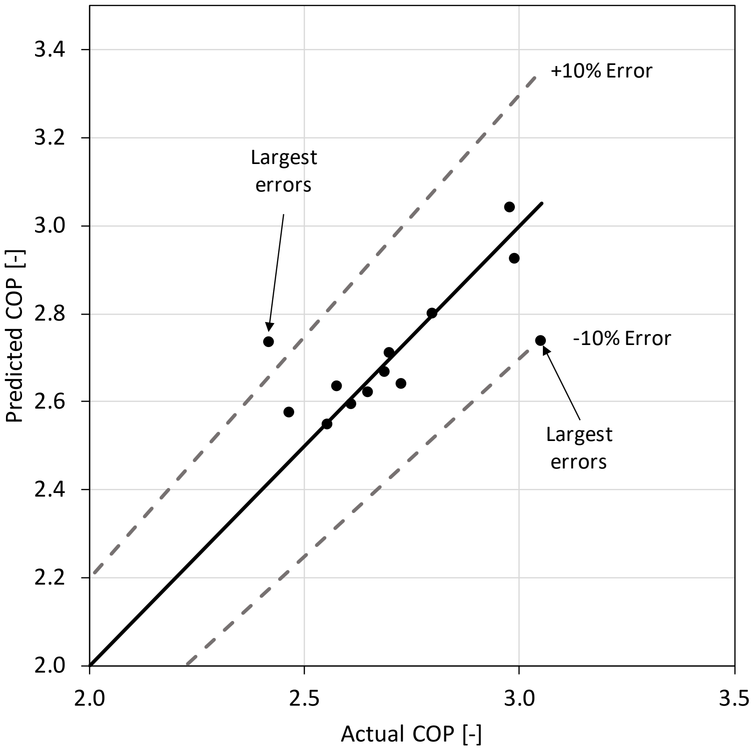


Figure 64: Chiller COP. Source: Data from York (2016)

6.2.8 The proposed COP heating curve for the CO_2 HP

For this thesis, the Mayekawa AWW CO_2 HP has been used as the basis for the simulations. To simulate the CO_2 HP completely, the COP for heating and cooling as well as the mass flow of the cooling and heating are required. The data sheets of the Mayekawa AWW CO_2 HP provide limited data. The data sheets show only three data points for a 65 °C hot water outlet operating under the water-water as well as three data points for the air-water conditions. No detail is given on the 90 °C conditions. The South African supplier of Mayekawa also indicated that this was the only data available. Consequently, the Mayekawa air-water (Mayekawa, 2013a) and water-water (Mayekawa, 2013b) data sheets were combined and calibrated to simulate the combined AWW CO_2 HP. The three HPs have similar values for the various operational modes.

The calibration of the Mayekawa AWW CO_2 HP was divided into two parts. For the first part, the Mayekawa water-water mode (Mayekawa, 2013a) and water-water (Mayekawa, 2013b) was calibrated to the six values of the Mayekawa (2013a).

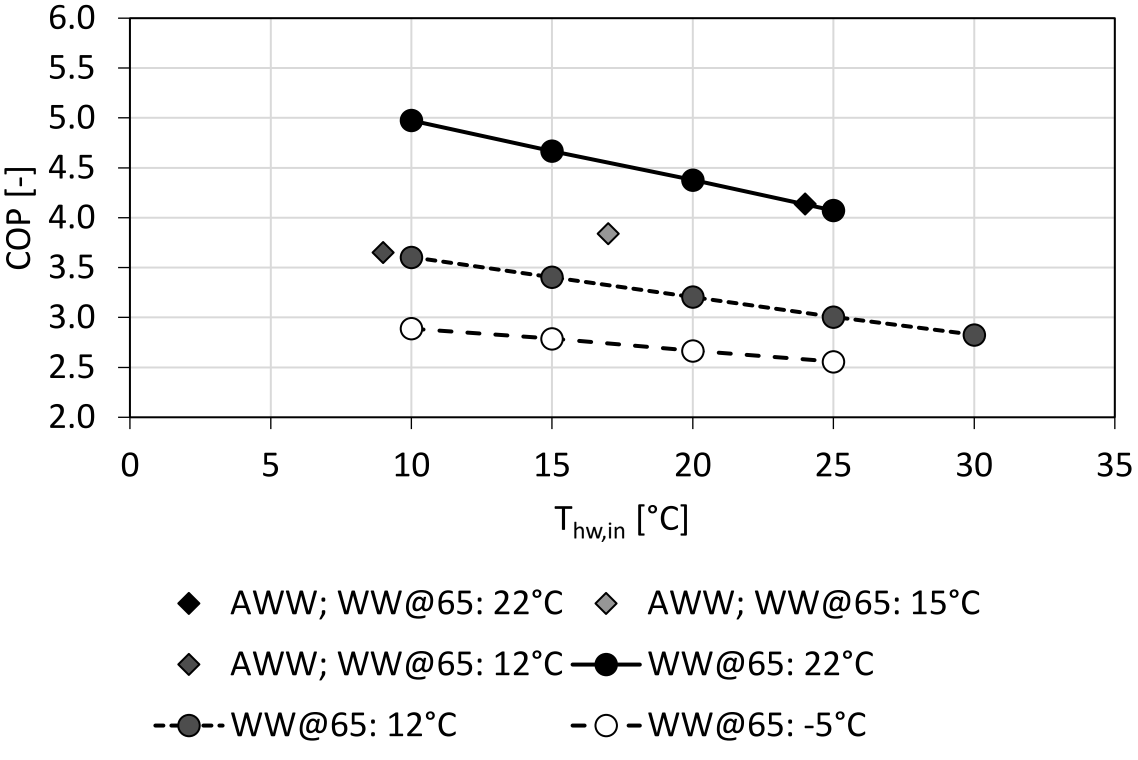


Figure 65: COP data of the AWW and WW CO_2 HP.

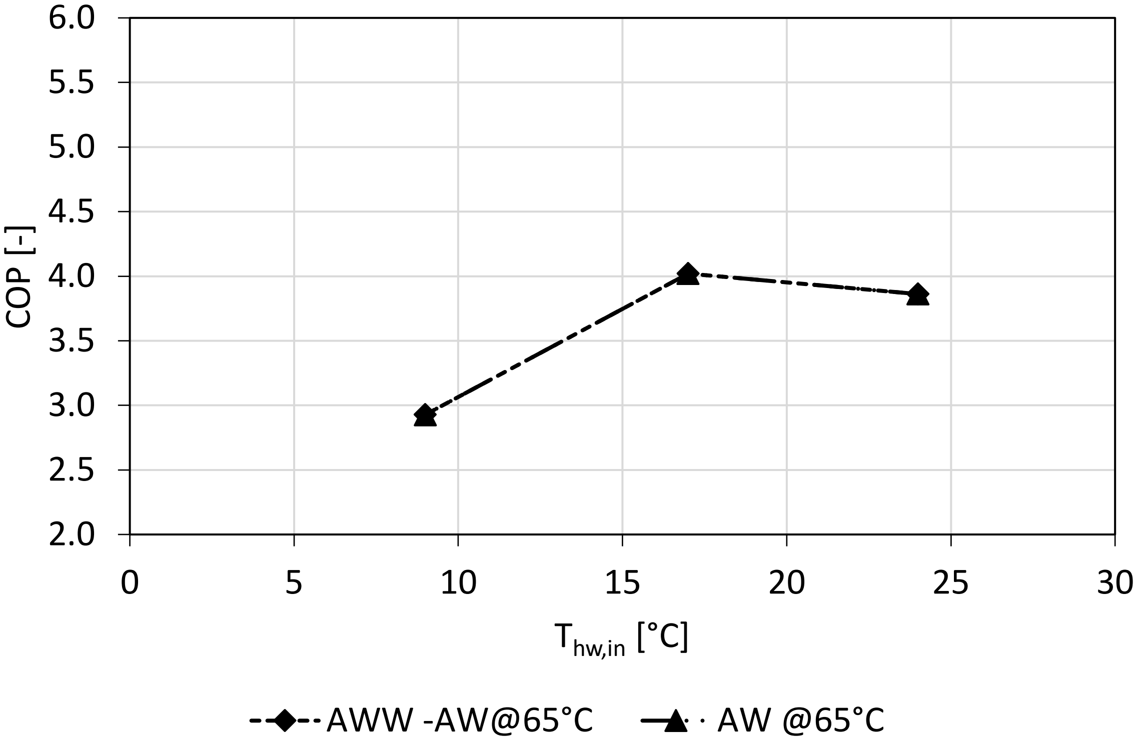


Figure 66: COP data of the air-water-water and air-water CO_2 HP.

From Figure 65 one can see for the that two of the available points from the Mayekawa AWW CO_2 HP in the water-water mode intersect the lines of the Mayekawa WW CO_2 HP. For the points where there was no data available, the points were kept as is. Figure 66 shows the AWW at 65°C hot water outlet temperature corresponds with the calibrated air-water data points. For more detail on the calibration of the HPs, please refer to Appendix G.

The maximum and minimum heating and cooling capacities for multi-function CO_2 HPs are given in Table 28. From Table 28 one can see the maximum COP heating is 5.0 for the water-water case with an exit temperature of 60 °C. The minimum COP heating is 2.4 for the water-water case with an exit temperature of 90 °C. The detailed heating capacity, cooling capacity and COP of the CO_2 HP can be seen in Appendix G.

Table 28: Heating and cooling capacity of a single CO_2 HP. Source: Adapted from Mayekawa (2013a) and Mayekawa (2013b)

Hot water temperature	**Mode**	**Description**	**Unit**	**Maximum value**	**Minimum value**
65 °C	Water-water	Heating capacity	[kW]	105.6	46.3
		Cooling capacity	[kW]	88.7	29.7
		Power	[kW]	21.2	18.1

Hot water temperature	Mode	Description	Unit	Maximum value	Minimum value
		COP heating	[-]	5.0	2.6
	Air-water	Heating capacity	[kW]	84.6	58.8
		Power	[kW]	21.9	16.1
		COP heating	[-]	3.8	3.7
90 °C	Water-water	Heating capacity	[kW]	97.7	44.8
		Cooling capacity	[kW]	72.6	28.2
		Power	[kW]	27.5	18.3
		COP heating	[-]	3.5	2.4
	Air-water	Heating capacity	[kW]	84.6	59.8
		Power	[kW]	21.9	19
		COP heating	[-]	3.8	3.1

For the characterisation of the CO_2 HP, the operation of the CO_2 HP must be divided into the water-water and air-water modes. The water-water mode curve fits are dependent on the chilled water inlet temperature and the difference between the water outlet and inlet temperature. For the air-water mode, the curve fits are dependent on the air inlet enthalpy and the difference between the water outlet and inlet temperature.

For the COP of the water-water mode, no single curve fit could be found with a sufficient R^2 for heating for the 65 °C and 90 °C scenarios. Consequently, the curve fit was divided into two scenarios, namely the hot water exit temperatures of 65 °C and 90 °C, respectively. For the air-water mode, a single equation could be found. The program code for determining the various coefficients can be found in Appendix G.3. The various equations used for the COP characterisation of the CO_2 HP are thus:

$$\begin{aligned} COP_{WW,65^\circ C} &= 261.6003861 - 1.848984040 \cdot T_{CW,IN} - 0.358349201 \cdot \Delta T_{65^\circ C} \qquad (39), \\ &+ 0.001331656 \cdot T_{CW,IN} \cdot \Delta T_{65^\circ C} + 0.003288783 \cdot T_{CW,IN}{}^2 - 0.000223722 \cdot \Delta T_{65^\circ C}{}^2 \end{aligned}$$

$$\begin{aligned} COP_{WW,90^\circ C} &= -3.067109594 + 0.001305523 \cdot T_{CW,IN} + 0.048913979 \cdot \Delta T_{90^\circ C} \qquad (40), \\ &+ 0.000059997 \cdot T_{CW,IN} \cdot \Delta T_{90^\circ C} + 0.0000333 \cdot T_{CW,IN}{}^2 - 0.000313278 \cdot \Delta T_{90^\circ C}{}^2 \end{aligned}$$

$$\begin{aligned} COP_{AW,H} &= 9.665155071 + 0.086586692 \cdot h_{AIR,IN} - 0.244249377 \cdot \Delta T_{HW} \qquad (41), \\ &+ 0.000838824 \cdot h_{AIR,IN} \cdot \Delta T_{HW} - 0.001555800 \cdot h_{AIR,IN}{}^2 + 0.001547257 \cdot \Delta T_{HW}{}^2, \end{aligned}$$

where

COP : Coefficient of performance of the CO_2 HP [-]

$T_{CW,IN}$: Cold-water inlet temperature [K]

ΔT_{HW} : Temperature difference between the outlet and inlet hot water [K]

$\Delta T_{65°C}$: Temperature difference between the hot water temperature at 65 °C and the inlet [K]

$\Delta T_{90°C}$: Temperature difference between the hot water temperature at 90 °C and the inlet [K]

$h_{AIR,IN}$: Enthalpy of the inlet air [kJ/kg]

and with the subscripts of the COP as

$WW, 65°C$: Water-water mode, for heating with a water exit temperature of 65 °C;
$WW, 90°C$: Water-water mode, for heating with a water exit temperature of 90 °C;
AW, H : Air-water CO_2 HP, for heating with a water exit temperature at 65 °C and 90 °C.

The R^2 for of each of the curve fits is as follows:

$$R^2{}_{WW,65°C} = 0.999$$

$$R^2{}_{WW,90°C} = 0.998$$

$$R^2{}_{AW,H} = 0.951$$

Figure 67 shows the accuracy of the prediction for COP heating for all the data simulated. Furthermore, Figure 67 shows that none of the 38 data points had an error higher than 10%. The largest error for the COP heating was 9%. An uncertainty of 2.8%, based on the standard deviation of all the data points, was taken for the COP heating.

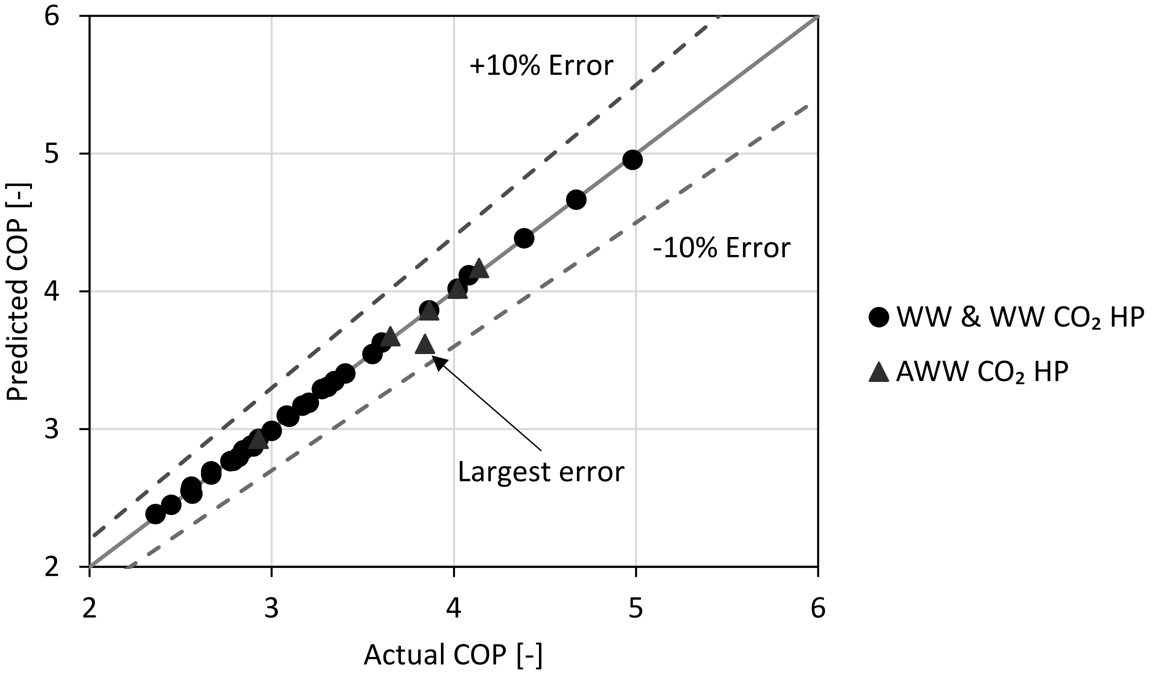


Figure 67. Predicted versus the actual COP for the water-water and air-water scenarios

6.2.9 The proposed CO_2 HP correlation curves for the mass flow

The CO_2 HP used in this thesis can supply both hot and chilled water. For the hot water mass flow, the same technique was used as that for the COP correlation curves. Thus, in total, three equations are needed to characterise the hot water mass flow. For the chilled water mass, the temperatures of the water are below 4 °C, and a brine solution is thus used. No single curve could be found for the chilled brine-water mass flow at a hot water mass flow of 65 °C and 90 °C. Consequently, two separate equations were used. The program code for determining the various coefficients can be found in Appendix G.3.

The equations used for the characterisation of the brine-chilled water mass flow are:

$$\dot{m}_{BCW,65°C} = 280.077595555 - 2.024501287 \cdot T_{CW,IN} - 0.205644270 \cdot \Delta T_{65°C} \quad (42),$$
$$+0.000875999 \cdot T_{CW,IN} \cdot \Delta T_{65°C} + 0.003670167 \cdot T_{CW,IN}{}^{2} - 0.000060192 \cdot \Delta T_{65°C}{}^{2}$$

$$\dot{m}_{BCW,90°C} = 14.203533409 - 0.135230576 \cdot T_{CW,IN} - 0.034600292 \cdot \Delta T_{HW,90°C} \quad (43).$$
$$+0.00083227 \cdot T_{CW,IN} \cdot \Delta T_{HW,90°C} - 0.00037470 \cdot T_{CW,IN}{}^{2} - 0.00064269 \cdot \Delta T_{HW,90°C}{}^{2}$$

The equations used for the characterisation of the hot water-water mass flow are:

$$\dot{m}_{WW,65°C} = 6.277291106 - 0.054942670 \cdot T_{CW,IN} + 0.023676995 \cdot \Delta T_{65°C} \quad (44),$$
$$-0.000138246 \cdot T_{CW,IN} \cdot \Delta T_{65°C} + 0.000126596 \cdot T_{CW,IN}{}^{2} + 0.000104762 \cdot \Delta T_{65°C}{}^{2}$$

$$\dot{m}_{WW,90°C} = -6.372892491 + 0.039226332 \cdot T_{CW,IN} + 0.010993048 \cdot \Delta T_{90°C} \quad (45),$$
$$-0.000047751 \cdot T_{CW,IN} \cdot \Delta T_{90°C} - 0.000053834 \cdot T_{CW,IN}{}^{2} + 0.000004091 \cdot \Delta T_{90°C}{}^{2}$$

$$\dot{m}_{AW,H} = 0.711774662 + 0.005779350 \cdot T_{CW,IN} - 0.011324028 \cdot \Delta T_{HW} \quad (46),$$
$$-0.000044519 \cdot T_{CW,IN} \cdot \Delta T_{HW} - 0.000023653 \cdot T_{CW,IN}{}^{2} + 0.000057852 \cdot \Delta T_{HW}{}^{2},$$

where

$\dot{m}$: Water mass flow for a single CO_2 HP [kg/s],

with the subscripts

$BCW,65°C$: Brine-chilled water when the hot water exit temperature is 65 °C,
$BCW,90°C$: Brine-chilled water when the hot water exit temperature is 90 °C.

The R^2 for of each of the curve fits is as follows:

$$R^{2}{}_{BCW,65°C} = 1.000$$
$$R^{2}{}_{BCW,90°C} = 0.985$$
$$R^{2}{}_{WW,65°C} = 1.000$$
$$R^{2}{}_{WW,90°C} = 1.000$$
$$R^{2}{}_{AW,H} = 1.000$$
$$R^{2}{}_{AWW,H} = 0.997.$$

Figure 68 (a) and (b) show the accuracy of the prediction for chilled brine mass flow and hot water mass flow for all the simulated data points. From Figure 68 (a) and (b), one can see that only two of the 38 data points had an error larger than 10%. The largest percentage error is for the brine chilled mass flow, which is 10.1%. The largest error for the hot water mass flow is 3.0%. For both cases, the largest error is for the lowest mass flows. The uncertainty is based on the standard deviation of the error for the chilled brine mass flow and hot water mass flow. Consequently, an uncertainty of 2.1% was taken for the chilled brine mass flow and 1.1% for the hot water mass flow.

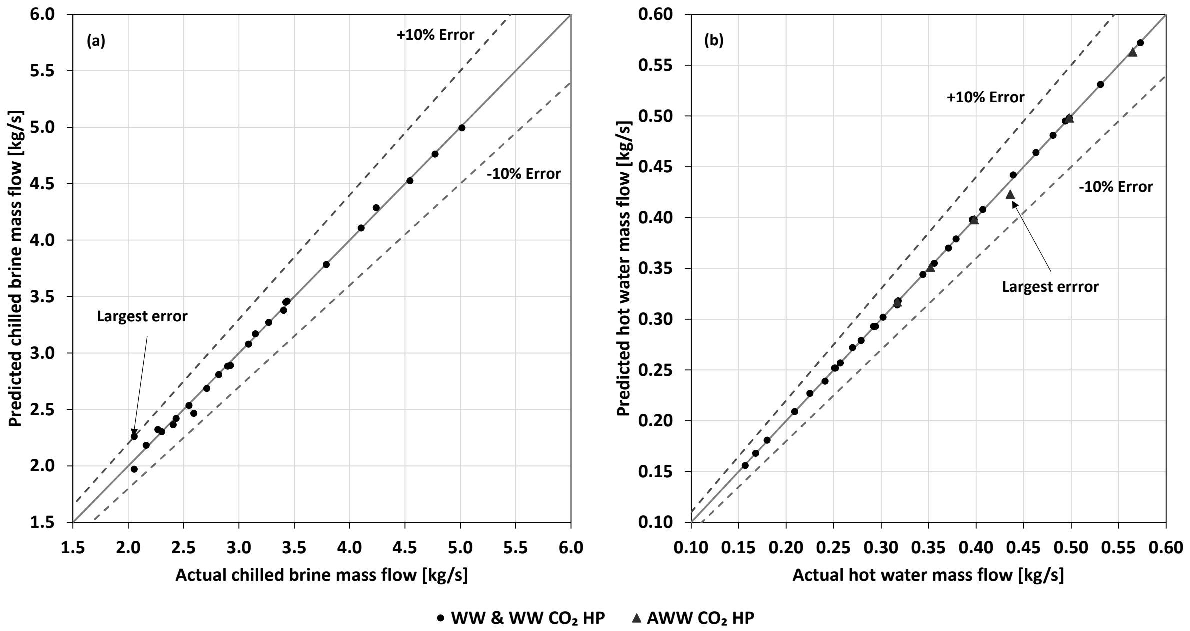


Figure 68. Predicted versus the actual mass flow for the chilled brine scenario (a) and hot water mass flow (b)

With the characterisation of the CO_2 HP completed, the next step is to determine the tank sizes and operating philosophy of the CO_2 HP. The calculation is needed to determine how many hours a day the CO_2 HP needs to operate.

6.2.10 The number of CO_2 HPs and the daily power consumption of the CO_2 HPs

This section aims to determine the number of CO_2 HPs, power consumption of the CO_2 HPs, and sizes of the various tanks. For this, the CO_2 HP correlation curves of section 6.2.9 are used to determine the minimum mass flow for SA in various climatic zones (section 6.2.1). From the minimum mass flow, the number of CO_2 HPs and their daily power consumption can be determined. Finally, the minimum mass flow is also used to determine the size of the various tanks.

6.2.10.1 Minimum mass flow of a CO_2 HP

The first step of determining standard tank sizes and number of CO_2 HPs is to determine the minimum mass flow of the CO_2 HP. It is assumed that no back-up chiller or electrical resistive heater is needed to cool and heat the water. Thus, in the worst-case scenario, the CO_2 HP should still deliver the amount of water needed. The CO_2 HP mass flow is dependent on the ambient conditions, the chilled water inlet temperature, and the temperature difference between the hot water inlet and outlet.

The author conducted a matrix of simulations for each climatic zone to determine the minimum mass flow. The feedwater supply temperature was changed from 30 °C to 10 °C with a steps size of 5 °C. The maximum and minimum values are based on the data from Denys (2001). Denys (2001) indicated that the minimum and maximum feedwater temperature for SA in 2001 was 10.8 °C and 28.9 °C respectively. The feedwater temperatures were rounded to 10 °C and 30 °C to simplify the calculation.

The chilled water inlet temperature was changed from -5 °C to 30 °C with a step size of 5 °C. The minimum chilled water temperature is based on the lowest temperature from the datasheets of the CO_2 HP (Mayekawa, 2013b). The maximum value is based on the data from Denys (2001).

Table 29 shows the minimum mass flows for the various temperature modes. For the detailed simulation results, please refer to Appendix G.

Table 29: Minimum mass flow for a single multi-function CO_2 HP

Chilled water [kg/s]	**Hot water at 65 °C [kg/s]**	**Hot water at 90 °C [kg/s]**
2.00	0.21	0.13

6.2.10.2 Number of CO_2 HPs

To determine the number of CO_2 HPs, the plant's operational details are required. No detail on hourly data was available to model the water demand accurately. Consequently, the author assumed, for this thesis, that the demand profile for the tank evens out for the day. Thus, although the demand profile changes for the day, the average value is taken for the operating hours.

Furthermore, the author combined the minimum mass flow per CO_2 HP with the simulation results, as presented in section 5.6. To determine the number of CO_2 HPs, it is assumed that the total hot water supplied at a temperature is equal to the total hot water demand at that temperature for the day. Thus, for the hot water at 65 °C:

$$\sum \dot{m}_{65°C,DMD/day} = \sum \dot{m}_{65°C,SUP/day} \tag{47.}$$

$$\dot{m}_{65°C,DMD/hr} \cdot hr_{65°C,DMD/day} = N_{HP}\begin{pmatrix} \dot{m}_{WW,65°C,SUP/hr} \cdot hr_{WW,65°C,SUP/day} \\ +\dot{m}_{AW,65°C,SUP/hr} \cdot hr_{AW,65°C,SUP/day} \end{pmatrix}$$

For the hot water at 90 °C:

$$\sum \dot{m}_{90°C,DMD/day} = \sum \dot{m}_{90°C,SUP/day} \tag{48.}$$

$$\dot{m}_{90°C,DMD/hr} \cdot hr_{90°C,DMD/day} = N_{HP}\begin{pmatrix} \dot{m}_{WW,90°C,SUP/hr} \cdot hr_{WW,90°C,SUP/day} \\ +\dot{m}_{AW,90°C,SUP/hr} \cdot hr_{AW,90°C,SUP/day} \end{pmatrix}$$

For the chilled water:

$$\sum \dot{m}_{CW,DMD/day} = \sum \dot{m}_{CW,SUP/day} \quad (49).$$

$$\dot{m}_{CW,DMD/hr} \cdot hr_{CW,DMD/day} = N_{HP} \begin{pmatrix} \dot{m}_{CW,65°C,SUP/hr} \cdot hr_{WW,65°C,SUP/day} \\ + \dot{m}_{CW,90°C,SUP/hr} \cdot hr_{WW,90°C,SUP/day} \end{pmatrix}$$

The author assumed that the CO_2 HPs which supply water at 90 °C runs only in the air-water mode, thus:

$$hr_{WW,90°C,SUP/day} = 0 \quad (50).$$

Finally, the total hours for the plant are:

$$\begin{aligned} hr_{HP,TOT,SUP/day} &= hr_{WW,65°C,SUP/day} + hr_{AW,65°C,SUP/day} \\ &\quad + hr_{WW,90°C,SUP/day} + hr_{AW,90°C,SUP/day} \end{aligned} \quad (51),$$

where

N_{HP}	: Number of CO_2 HP	[-]
hr	: Number of hours the CO_2 HP runs	[hr]
$hr_{HP,TOT,SUP/day}$	: Total number of hours the CO_2 HP runs per day to supply the hot water	[hr]

with the subscripts:

$65°C, DMD/day$: Demand per day at a temperature of 65 °C
$65°C, SUP/day$: Supply per day at a temperature of 65 °C
$65°C, DMD/hr$: Demand per hour at a temperature of 65 °C

$90°C, DMD/day$: Demand per day at a temperature of 90 °C
$90°C, SUP/day$: Supply per day at a temperature of 90 °C
$90°C, DMD/hr$: Demand per hour at a temperature of 90 °C

To determine the number of CO_2 HPs, the minimum mass flow, as defined in section 6.2.10.1, was used. Secondly, it is assumed that the CO_2 HP works a maximum of 22 hours a day, $(hr_{HP,TOT,SUP/day} = 22)$. The value is based on the maximum number of operational hours of the steam boiler as in section 6.2.3. From these assumptions, it was determined that a total of 20 CO_2 HPs is needed.

The total installed power requirement for the CO_2 HP is 535 kW. The maximum total heating and cooling capacity for the CO_2 HPs is thus 2 394 kW and 2 070 kW. However, the total power, heating, and cooling capacity of the bank of CO_2 HPs is less, as it is dependent on the cooling water temperature and weather conditions.

6.2.10.3 Daily power consumption of the CO_2 HP

To determine the CO_2 HP daily power consumption, the number of hours the HP runs in each mode must be determined.

The total energy demand per day of the CO_2 HP is given by Equation (52):

$$\begin{aligned}\sum P_{tot/day} &= P_{WW,65°C/day} + P_{WW,90°C/day} + P_{AW,H/day} \\ &= P_{WW,65°C/hr} \cdot hr_{WW,65°C,SUP} + P_{WW,90°C/hr} \cdot hr_{WW,90°C,SUP} + P_{AW,H/hr} \cdot hr_{AW,H,SUP}\end{aligned} \quad (52),$$

where

$\sum P_{tot/day}$	: Total energy use of the CO_2 HP for the day	[kWh/day]
P	: Energy use of the CO_2 HP	[kWh/day] ,

To determine the energy amount for each mode, the following equations are used:

$$\begin{aligned}P_{WW,65°C} &= \dot{Q}_{WW,65°C} \big/ COP_{WW,65°C} \\ &= \frac{N_{HP} \cdot \dot{m}_{WW,65°C,SUP/hr} \cdot c_p \cdot \left(T_{65°C} - T_{FW}\right)}{COP_{WW,65°C}}\end{aligned} \quad (53)$$

$$P_{WW,90°C} = \frac{\dot{m}_{WW,90°C,SUP/hr} \cdot c_p \cdot \left(T_{90°C} - T_{FW}\right)}{COP_{WW,90°C}} \quad (54)$$

$$P_{AW,H} = \frac{\dot{m}_{AW,H,SUP/hr} \cdot c_p \cdot \left(T_{90°C} - T_{FW}\right)}{COP_{AW,H}} \quad (55),$$

where

COP	: Coefficient of performance determine for the CO_2 HP in section 6.2.8
$\dot{m}$	: Mass flow of the CO_2 HP determined in section 6.2.8.

To determine the number of hours the CO_2 HP runs in each mode, equations (47) to (50) together with the actual mass flow and the weather data are used as inputs. From these equations, the total energy use of the plant can then be determined. The energy use is determined for every day of the year and summed to determine the total energy use of the plant for the year.

6.2.11 Tank sizes

For this thesis, the chilled water tank and two hot water tanks need to be sized. The chilled water tank size is based on the spin chiller fill volume. Before the plant starts, the various spin chiller tanks need to be filled with chilled water. Consequently, the buffer tank is sized as 1.1 times larger than the size of the spin chiller tanks[10]. Thus, the chilled water tank size was assumed as 19 500 litres.

The chilled water tanks need to be cooled down before the operation of the day can take place. During this time, the CO_2 HP also produces hot water. Thus, the 65-°C water tank needs to be sized accordingly. To determine the time to cool the chilled water, it is assumed that the tank is fully mixed and thus there is no stratification. From equation (56) and Kalogirou (2014), the temperature of the tank can be determined:

$$T_{s+\Delta t} = T_s + \frac{1}{\left(M \cdot c_p\right)_s}\left[Q_i - Q_e - Q_{tl}\right] \cdot \Delta t \qquad (56),$$

where

$T_{s+\Delta t}$	: New storage tank temperature after time interval Δt	[K]
T_s	: Storage tank temperature	[K]
M	: Mass of the storage capacity	[kg]
Q_i	: Rate of energy delivered to the storage tank	[kW]
Q_e	: Rate of energy removed from the storage tank	[kW]
Q_{tl}	: Rate of energy loss from the storage tank	[kW]
Δt	: time step	[min].

The following assumptions were made:

- The heat loss for the tank is zero.
- The mass flow of the chilled water from the CO_2 HP through the HX is constant.
- Although the mass flow changes depending on chilled water temperature, the mass flow was taken as the lowest possible mass flow, as determined in section 6.2.10.1.
- Tanks are sized according to standard tank sizes on the market. For detailed tank sizes, please refer to Appendix J.

For the hot water tank sizes at 65 °C, the author has also looked at the maximum demand for the hot water. According to Oosthuizen (2019), deep cleaning of the plant happens at night when the abattoir is not operational. Furthermore, the DAFF KZN (2015) indicates that personnel who handle foodstuffs must shower before assuming their duties. Therefore, the demand for hot water is sized on a one-hour hot water demand for floor and equipment washing as well as for the showers and hand wash

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[10] Based on a six spin chiller that can handle 1 000 birds per hour per spin chiller (Meyn, 2013).

basins. Thus, the hot water tank sizes at 65 °C was assumed as 15 000 litres. The large size is due to uncertainty on the hot water demand during the night shift.

The 90-°C hot water is used for sterilisation of equipment and the crates. Sterilisation happens when the birds are slaughtered. Thus, the sterilisation mass flow has a has a smaller uncertainty. Therefore, a half-hour buffer would be sufficient, and the hot water tank sizes at 90 °C was assumed as 1 000 litres.

With these assumptions, the author determined that the various times to cool down the water to 65 °C is about 45 minutes. For detailed calculations, please refer to Appendix I. Table 30 shows the various tank sizes. The tank sizes were adjusted to standard sizes as available in the market. For a list of standard tank sizes, please refer to Appendix J.

Table 30: Tank sizes

Description	**Chilled water**	**Hot water at 65 °C**	**Hot water at 90 °C**
Estimated water demand [tonne]	18.1	14.2	0.7
Size of tanks [tonne]	19.5	15.0	1.0
Estimated running time of the CO_2 HPs [hour]	0.75	1	1

Once the number of CO_2 HPs, the energy used by the CO_2 HPs, and the sizes of the various tanks are determined, the operational cost for the various options investigated must be determined. The next section discusses the various values needed to determine the energy cost.

6.2.12 Energy cost of the energy sources

6.2.12.1 Cost of the coal, LPG, and paraffin

According to DoE SA (2016b), the illuminating paraffin price is based on a coastal and inland region. No specific detail could be found on which towns are in which region. Consequently, the maximum price was chosen as a representative value for SA.

LPG is a liquefied and mixed gaseous hydrocarbon. Although there are many variations of LPG, it is primarily made up of propane and butane, which are compressed into liquid form for ease of transport, storage, and handling. Industrial customers use LPG for heating purposes where a readily controlled temperature is needed (DoE SA, 2016b).

Quantec data (2019a, 2019b, 2019c) publishes the monthly local price of bituminous coal, LPG, and paraffin in SA, which is shown in Table 31. Unfortunately, the price for the individual grades of coal is not given. For the detailed monthly prices, please refer to Appendix L.

Table 31: Price of coal, LPG, and paraffin. Source: Quantec data (2019a, 2019b, 2019c)

Description	Value	Uncertainty	Unit
Coal	510.12	19.26	R/tonne (VAT included)
LPG	29.00	1.31	R/kg (VAT included)
Paraffin	10.59	0.55	R/litre (VAT included)

6.2.12.2 Cost of electricity

A data analysis of the National Energy Regulator of South Africa (NERSA, 2017) found that SA has two main electricity billing systems for industrial sites. Firstly, the energy and demand charge system, which works on the principle of the total active energy used (kWh) and the maximum demand during the month. For some municipalities, the energy charge is also divided between peak, standard, and off-peak times. Secondly, the time-of-use billing system, which works on a seasonal time-of-use differentiated by an active energy used structure. There are, in general, three time-of-use periods, namely peak, standard, and off-peak.

Not all abattoirs in SA use the same billing structure. For example, the Chicken World Poultry abattoir situated in Mthatha, which lies in the King Sabata Dalindyebo local municipality, does not have a time-of-use tariff billing option (NERSA, 2017). On the other hand, the Sovereign Foods abattoir that is located within the Nelson Mandela local municipality has a time-of-use tariff billing option (NERSA, 2017).

The author decided to simplify the investigation so that all abattoirs investigated are based on the Local Authorities Business rate from Eskom. The Eskom tariff structure for local authorities is effective from 1 July of the year to 30 June of the following year. Thus, a combination of the tariff structure of 2018/2019 and 2019/2020 was used. It is assumed that the chicken abattoir already uses electricity on its facility. Therefore, the network capacity charge and the service and administration charge are excluded from the costing structure. Table 32 shows the applicable tariffs and periods that are used.

Table 32: Business rate for the local authority. Source: Eskom (2014)

Description	Months	Tariff [c/kWh] (VAT included)
2018/2019 rates	Jan-June	132.05
2019/2020 rates	July-December	156.12

Finally, the economic inputs are shown in the next section.

6.2.13 Economic inputs

In this section, the inputs are given for the financial analysis. The inputs include the inflation rate, expected life of the CO_2 HP, tax rate, and the CO_2 HP and storage tank costs used.

6.2.13.1 Inflation rates

The various inflation rates for SA change from year to year. The average value of the inflation rates were taken for ten years. The value is chosen to eliminate short term uncertainties of the various inflation rates. For some of the sources, ten years of data is not available. For these sources, the maximum number of years available was used. For details on the specific yearly values, please refer to Appendix L.

Table 33: Inflation values. Source: South African Reserve bank (2020), Statistics South Africa (2019b), Quantec data (2019a), Quantec data (2019b), DoE SA (2018), DoE SA (2016b)

Description	**Value**
Prime lending rate	9.6%
General inflation rate	5.2%
Electric inflation rate	14.2%
Coal inflation rate	10.1%
LPG inflation rate	4.5%
Paraffin inflation rate	7.8%

6.2.13.2 Financial assumptions

For the financial calculations, various assumptions concerning the CO_2 HP and depreciation period need to be made. Table 34 shows the various values together with the source.

Table 34: Inflation values and discount rates. Source: SAIPA (2019), SARS (2020)

Description	**Value**	**Source**
Expected live of an HP	20 years	SAIPA (2019)
Corporate tax rate	28%	SARS (2020)
Depreciation period	5	SAIPA (2019)
Depreciation rate year one	40%	SAIPA (2019)
The depreciation rate for the remaining years	20%	SAIPA (2019)

6.2.13.3 Carbon-based tax

According to SARS (2019), carbon-based tax is a response to climate change. The tax is aimed at reducing greenhouse gas emissions in a cost effective, sustainable, and affordable manner. The Carbon Tax Act came into effect on 1 June 2019 (SARS, 2019). Carbon tax comprises two phases.

During the first phase, significant tax-free emission is allowed, ranging from 60% to 95% (Treasury, 2019). The introduction of carbon tax will also not have any impact on the price of electricity for the first phase (Treasury, 2019). A review of the impact of the tax will be conducted before the second phase (Treasury, 2019). After the review, future changes to the tax-free thresholds and rates will follow.

The author investigated a scenario where the carbon tax was not phased in and was thus calculated at R120/tonne of CO_2 (Carbon Tax Act 15). Thus, no discounts were included due to sequestration, allowance of industrial processes, trade exposure, and carbon budget allowances.

The amount of carbon emissions is calculated with (Treasury, 2019):

$$\mathrm{CO_2Tax} = \left[\left(\mathrm{C} \cdot 1\right) + \left(\mathrm{Me} \cdot 23\right) + \left(\mathrm{N} \cdot 296\right)\right] \cdot \mathrm{CV} \cdot \mathrm{m} \cdot \mathrm{CO_2Tax}/tonne \quad (57),$$

where

$\mathrm{CO_2Tax}$	: Total tax amount payable	[R]
C	: Carbon dioxide emissions of a fuel type determined	[kg CO_2/TJ]
Me	: Methane emissions of a fuel type	[kg CH_4/TJ]
N	: Nitrous Oxide emissions of a fuel type	[kg NO_2/TJ]
CV	: Default calorific value	[TJ / tonne]
m	: Mass of fuel used	[tonne]
$\mathrm{CO_2Tax}/tonne$	: Tax amount payable per tonne	[R/tonne].

The emission values for the various combustible fuels are specified in the Act (Carbon Tax Act 15, 2019). It seems that the emission values are rounded values provided by the (IPCC, 2006). Therefore, the values determined in section 6.2.6 are used in this study. However, the calorific values of the various fuels differ in the Carbon Tax Act 15 (2019) from those in section 6.2.6. The values of section 6.2.6 are averages from various sources and are thus used for the current tax calculation.

6.2.13.4 CO_2 HPs and storage tank cost

The CO_2 HPs and storage tank cost for this thesis is based on actual quotes for the CO_2 HPs and tanks. The total purchasing cost of the equipment is given in Table 35.

Table 35: Total purchase cost of equipment Source: HTE (2020), Mayekawa South Africa (2019)

Description	Detailed description	Number	Cost per item (VAT included)	Total cost (VAT included)
CW tank	HTE 10 000 litre tank with build in heat exchanger	2	R185 062	R370 124
Hot water tank at 65 °C	HTE 10 000-litre tank	2	R238 937	R477 875
Hot water tank at 90 °C	HTE 20 000-litre tank	1	R74 457	R74 457
CO_2 HP	Mayekawa Unimo AWW CO_2 HP	20	R1 495 000	R29 900 000
Total cost				**R30 822 455**

To determine the total installation cost, equipment erection, piping and other costs must be included. These costs are based on the costing factors for fluids as given by Sinnott (2005). The total plant installation cost is given by Equation (58):

$$\mathrm{PIC} = \mathrm{PCE} \cdot \left(1 + f_1 + f_2 + f_3 + f_4 + f_5 + f_6 + f_7 + f_8 + f_9\right), \tag{58}$$

where

PIC	: Total plant installation cost	[R]
PCE	: Total physical equipment cost	[R]
$f_1 = 0.40$	: Equipment erection cost factor	[-]
$f_2 = 0.70$	: Piping cost factor	[-]
$f_3 = 0.20$	: Instrumentation cost factor	[-]
$f_4 = 0.10$	: Electrical cost factor	[-]
$f_5 = 0.15$	: Buildings cost factor	[-]
$f_6 = 0.50$	: Utilities cost factor	[-]
$f_7 = 0.15$	: Storages cost factor	[-]
$f_8 = 0.05$	: Site development cost factor	[-]
$f_9 = 0.05$	: Ancillary buildings	[-].

The author decided to include the following cost factors for the cost estimation of the plant:

- Equipment erection cost factor,
- piping cost factor,
- instrumentation cost factor,
- electrical cost factor, and
- site development cost factor.

The total cost factor including the original equipment is thus 2.45.

Table 36: Total cost of the plant

Original equipment price (VAT included)	Cost factors	Final equipment prices (VAT included)
R30 822 455	2.45	R75 515 016

From Table 36, one can see that the total cost of the plant it thus around R75.5 million, VAT included. The next section reveals the results for the various scenarios.

6.3 Comparing the results of CO_2 HPs to that of the steam boiler and electric boiler

This section provides the results of the CO_2 HPs compared to the steam boiler and electric boiler as shown in section 5.6. Firstly, the CO_2 HPs' monthly energy use is shown for all the six climate zones as described in section 6.2.1. Secondly, the energy use is shown for the steam and electric boiler compared with the CO_2 HPs in the various zones. Thirdly, the environmental impacts of the various scenarios investigated are compared. This is followed by a discussion of the total running cost and the financial indicators. Finally, a financial sensitivity analysis is given of the results.

6.3.1 Monthly energy use of the CO_2 HPs

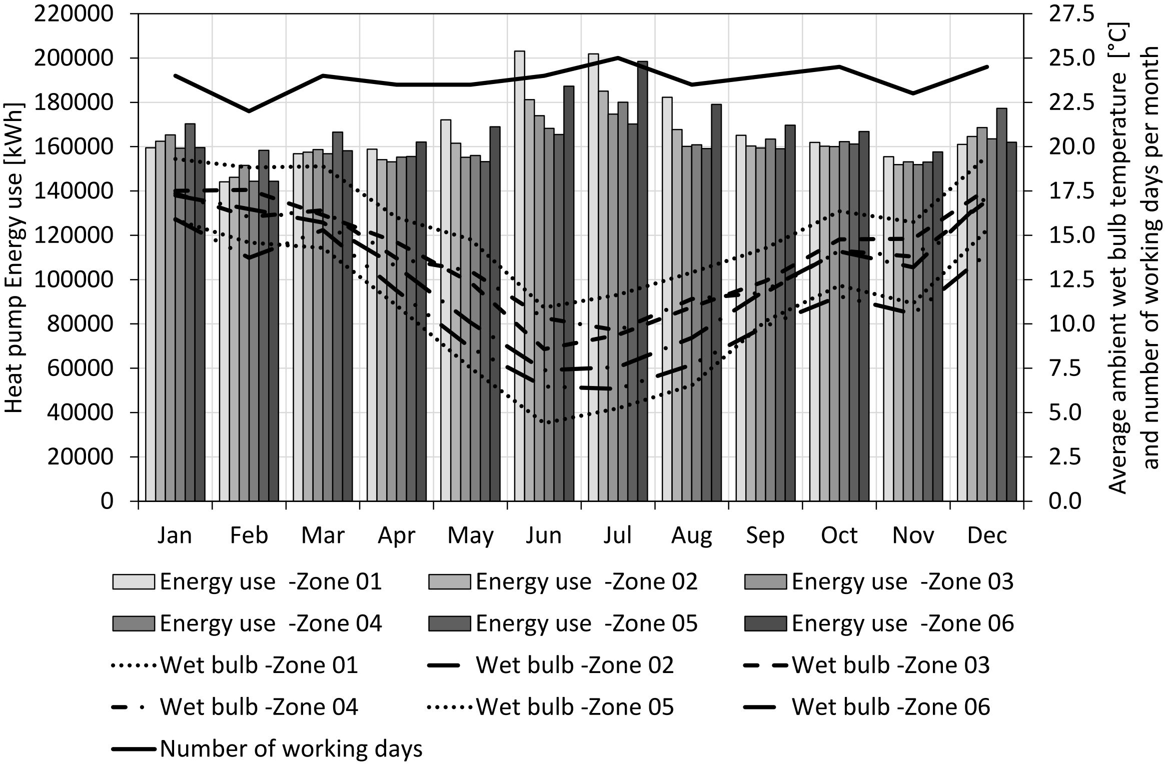


Figure 69: Combined CO_2 HPs' monthly energy use for the various zones

As indicated in Figure 69, there is a small difference between the monthly energy for the CO_2 HPs. The HPs' monthly energy follows the number of working days very closely. The differences between the various zones' monthly energy use are mainly a result of the changes in the wet-bulb temperature. For example, for the winter months from May to August, the wet-bulb temperature for zone 1 is lower compared to zone 6. The lower wet-bulb temperature causes the higher energy use of zone 1 of 25 470 kWh, which is 3.5% more than for zone 6. The results show that the wet-bulb temperature has a smaller impact on the energy use.

6.3.2 Annual energy use

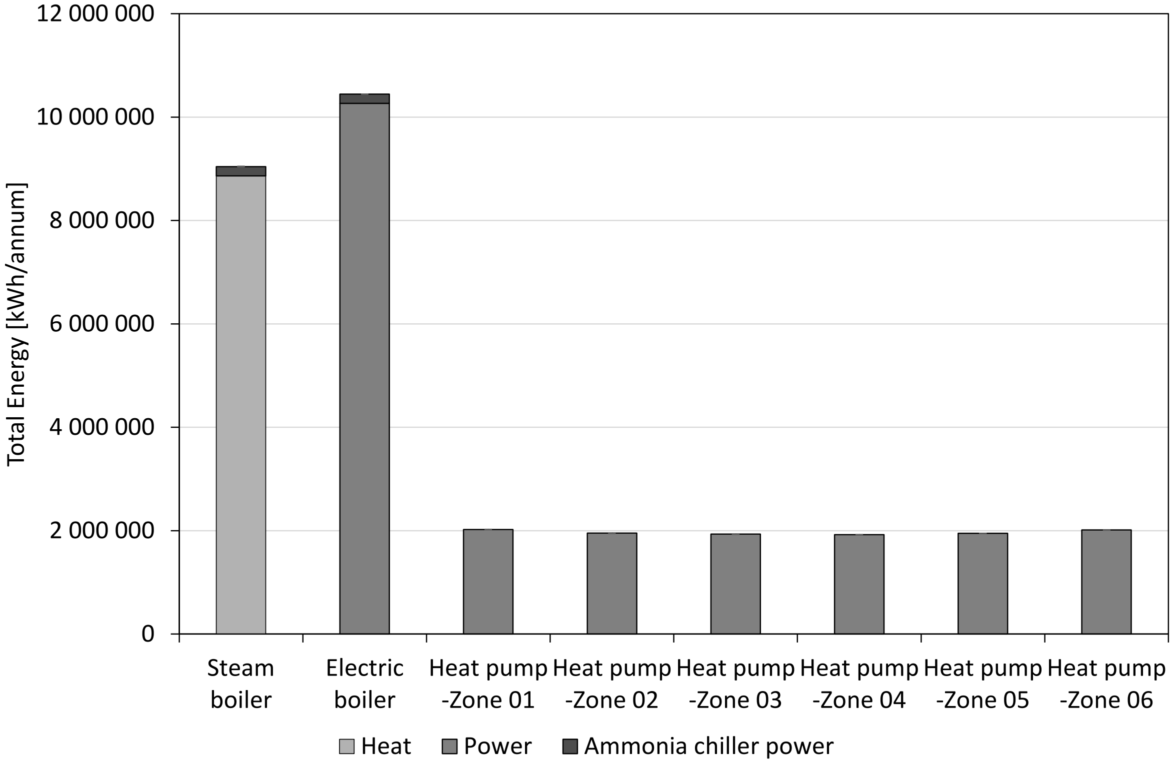


Figure 70: Comparison of energy use for the CO_2 HPs.

Figure 70 illustrates that for the CO_2 HPs, the energy use per annum is 4.5 times smaller than that of the steam boiler and 5.2 smaller than that of the electric boiler. Of the six climatic zones, zone 4 (temperate coastal) had the lowest energy use, while zone 1 (cold interior) had the highest energy use. The difference between zone 1 (cold interior) and zone 4 (temperate coastal) is 100 034 kWh, which is less than 5% of the total energy. The energy use of zone 1 (cold interior) was slightly higher than that of zone 6 (arid interior), with an increase of 7 911 [kWh] or 0.4%. The same trend can be seen for the energy use of zone 4 (temperate coastal), which was 11 647 [kWh] or 0.6% higher than that of zone 3 (hot interior).

The main reason for the difference in energy use is the higher wet-bulb temperature of the air, which caused a higher enthalpy and consequently a higher COP. The impact of the higher COP is a lower total energy use and thus lower emissions value. The trend can be seen in the emissions, annual cost, as well as straight payback. Thus, the author only included the average values for the six zones for the following graphs.

The influence of the ammonia chiller was less than 2.1 % and 1.8% of the total energy use for the steam and electric boiler, respectively. According to the DAFF (2007), the meat cutting and wrapping, packing, dispatching and the red offal sorting area must be kept at 12 °C. However, this was not included in the calculation of the ammonia chiller. The cooling of these areas would thus increase the load on the ammonia chiller. By including the environmental cooling in the simulation, the savings can be increased.

6.3.3 Greenhouse gas emissions

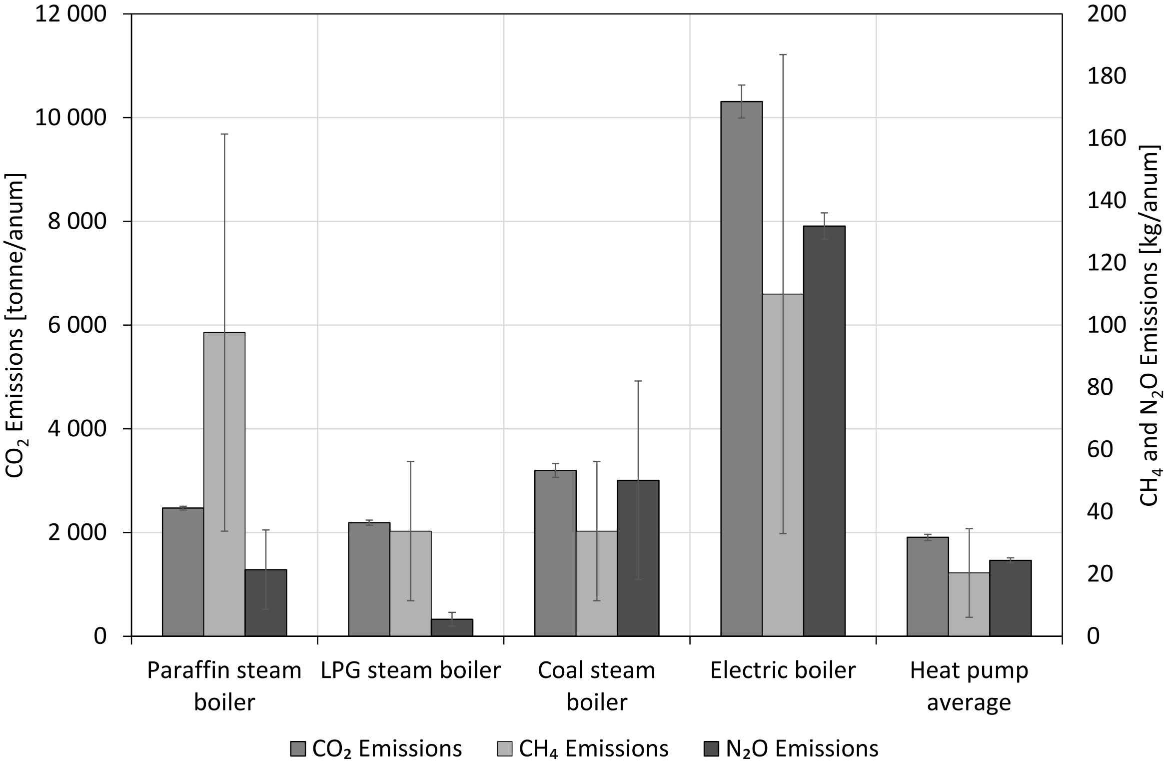


Figure 71: Comparison of greenhouse gas emissions for the various technologies.

As seen in Figure 71, the CO_2 HPs have the lowest CO_2 emissions of all the technologies. The electric boiler emissions and the coal steam boiler emissions are 5.4 and 1.7 times higher than the average emissions of the CO_2 HPs, respectively. The values for the LPG and paraffin boilers are much smaller, at 1.1 and 1.3 times, respectively. The CO_2 emissions for the HPs in the various zones did not differ that much, with a value of 97 tonnes per annum between the maximum and minimum. The uncertainties of the CO_2 emissions are minimal due to the small uncertainty of CO_2 emissions per TJ.

For the CH_4 emissions, the CO_2 HPs has the lowest emissions. The paraffin, steam and electric boilers have the highest emissions, which are 4.8 and 5.4 times higher than that of the CO_2 HPs, respectively. The LPG and coal boiler emissions are both 1.7 times higher than that of the average CO_2 HP emissions. The uncertainty for the CH_4 emissions for the paraffin, LPG, and coal boiler is around 66%. The uncertainty for both the electric boiler and the CO_2 HPs was 70%. This high uncertainty is due to the considerable uncertainty of the CH_4 emissions per TJ.

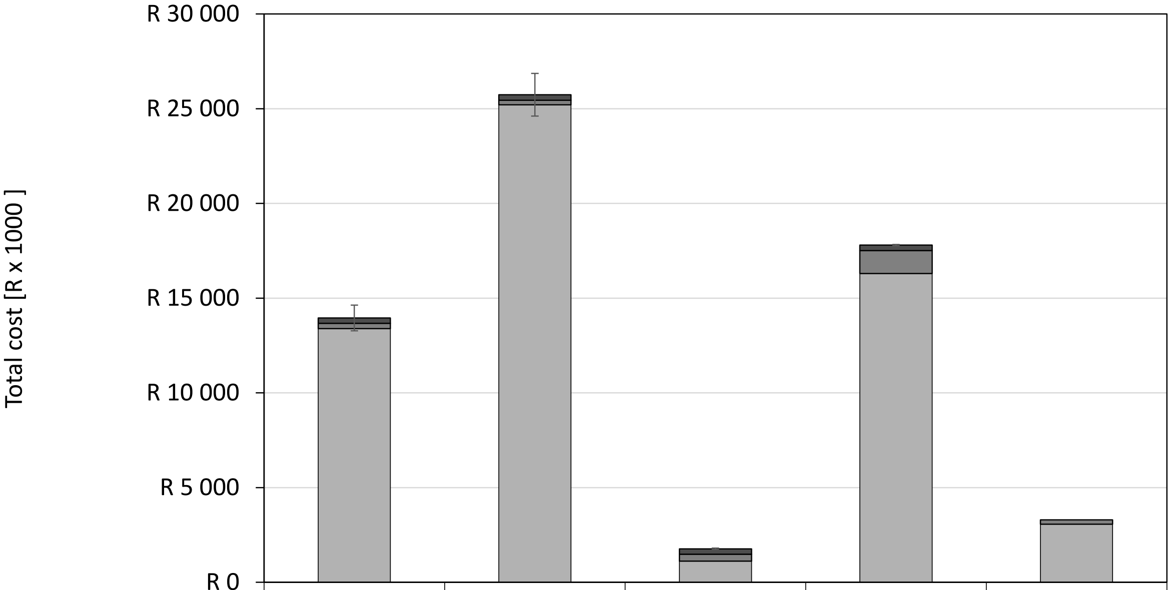
Finally, the N_2O emissions are the lowest for the LPG boiler at 0.2 times that of the CO_2 HPs. The low value is because of the low emissions of N_2O per TJ for paraffin. The average N_2O emissions of the paraffin boiler were 0.9 times that of the CO_2 HPs, but the coal and electric boiler emissions were 2.1 and 5.4 times more that of the CO_2 HPs, respectively. The paraffin boiler had the similar N_2O emissions as that of the CO_2 HPs. The uncertainty for the N_2O emissions is the highest for the coal, LPG and paraffin boiler, at 65%, 66% and 66% respectively. The uncertainty is due to the considerable uncertainty of the CH_4 for these fuels. The uncertainty for the electric boiler and CO_2 HPs were for the CO_2, CH_4 and N_2O emissions, which was 3.2%.

Table 37: Comparison of the environmental statistics for electric boilers and CO_2 HPs

	Coal [tonne]	Ash [tonne]	Water [kl]	NOx [tonne]	SOx [tonne]	Particle [tonne]
Electric boiler	5463.3 ±52.4	1550.7 ±34.8	14415.5 ±522.4	42.2 ±1	84.6 ±2.7	3.3 ±0.4
Heat pump - Average	1028.1 ±9.9	291.8 ±6.5	2712.7 ±98.3	7.9 ±0.2	15.9 ±0.5	0.6 ±0.1
Savings	4435.2 ±42.5	1258.9 ±28.3	11702.8 ±424.1	34.3 ±0.8	68.7 ±2.2	2.7 ±0.3

Table 37 shows the comparison of the environmental statistics for the electric boiler and CO_2 HPs for the various zones. In general, the CO_2 HPs resulted in a considerable saving in the environmental statistics, which was 81%.

6.3.4 Total energy cost



	Paraffin steam boiler	LPG steam boiler	Coal steam boiler	Electric boiler	Heat pump average
■ Ammonia chiller cost	R 284	R 284	R 284	R 284	R-
▩ CO2 Tax	R 276	R 242	R 364	R1 216	R 230
□ Energy cost	R13 391	R25 205	R1 116	R16 296	R3 067

Figure 72: Total cost of the various types of heat technologies excluding CO_2 tax

From Figure 72 can be seen that the CO_2 HP's annual energy cost is on average R 3 066 533 ± 7 480. The maximum difference between the zones is R 156 053. Furthermore, the CO_2 HPs energy cost is 7.7 times lower than that of the LPG, 4.2 times lower than that of paraffin, and 5.3 times lower than that of an electric boiler. The main reason for the CO_2 HPs being so much cheaper than the electric boilers is that the average COP of the CO_2 HPs is between 2 and 5.5.

In general, CO_2 HPs are 2.2 times more expensive to run than coal. The main reason for this is the high cost of electricity. In comparison, coal costs 2.0 c/MJ while electricity costs 36.7 c/MJ. Thus, at the current cost for coal and electricity, the CO_2 HPs cannot compete financially with coal. The cost of the ammonia chiller per annum is only a small fraction, at around R 284 346 ± 849 per annum.

Thus, the total annual cost for coal is much cheaper than of the CO_2 HPs. However, coal comes with other long-term environmental challenges, forcing people to move away from it. In that case an CO_2 HPs is a better solution than any of the other types of boilers.

6.3.5 Financial indicators

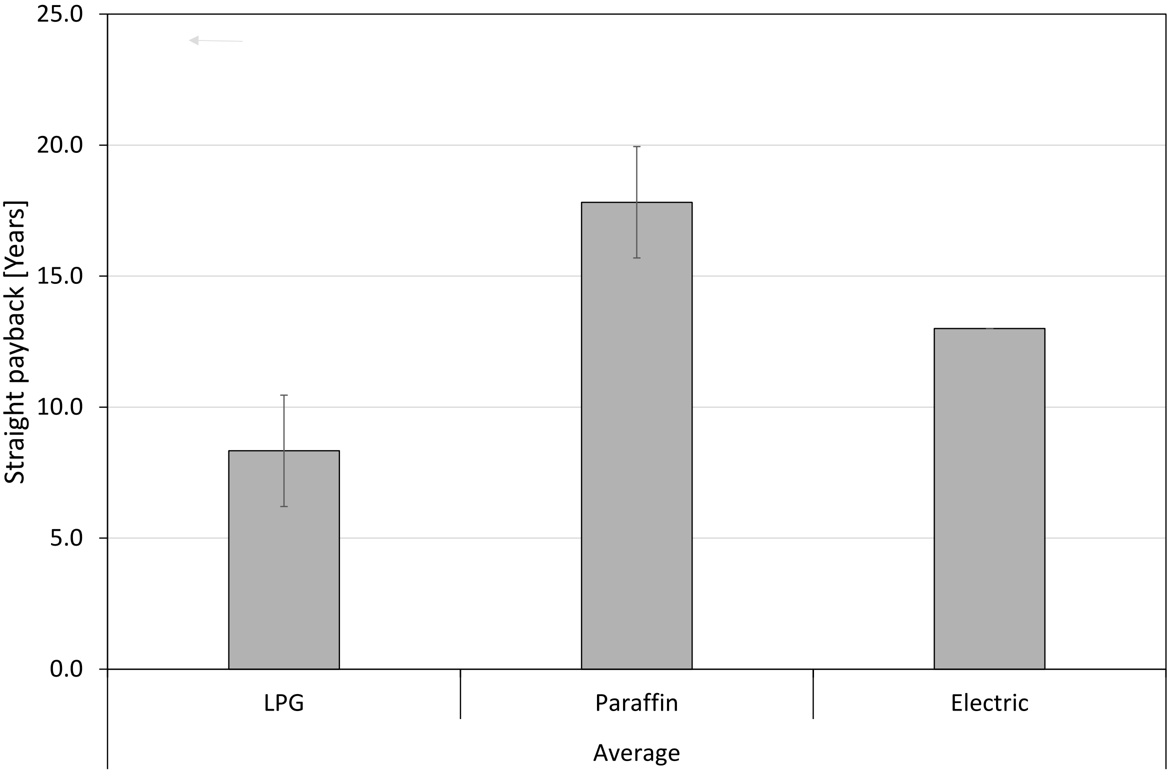


Figure 73: Comparison of the average :CO_2 HP's straight payback compared to LPG, paraffin and electrical boiler.

Figure 73 shows the straight payback for CO_2 HPs compared to LPG, paraffin, and electrical boiler. The payback is only based on the total installation cost and energy cost. Thus, the corporate tax and depreciation costs are not included in the calculations. The figure also indicates that the straight payback for the CO_2 HPs compared to the LPG and the electric boiler is around 8.3 and 13.0 years, respectively. The straight back period for the CO_2 HPs compared to the paraffin boiler, was high at 17.8 years. Depending on the company criteria, CO_2 HPs could be financially viable for LPG and electric options. The coal boiler was excluded because it has a lower energy cost than that of CO_2 HPs.

Table 38: Financial indicators of CO_2 HPs versus paraffin, LPG, and electric boilers.

Description	**CO_2 HPs vs Paraffin boiler**	**CO_2 HPs vs Electric boiler**	**CO_2 HPs vs LPG boiler**
Net present value (NPV) (5 years) [R X 1 000]	-R4 245	R14 341	R25 988
Internal rate of return (IRR) (5 years)	-2.3%	7.1%	13.1%
Return of investment (ROI)	4.2%	11.5%	15.6%
Straight payback (SP) (years)	2.5	2.4	2.4

Table 38 shows the financial indicators for the comparison of CO_2 HPs versus the paraffin, LPG, and electric boiler. Table 38 reveals that the CO_2 HPs compared to the paraffin boiler is not an economically viable option, as the NPV and IRR are both negative, and the ROI is below the prime lending rate. The CO_2 HPs are economically viable when compared to the LPG boiler and electric boiler. Both options have an ROI higher than the prime lending rate. Overall, CO_2 HPs versus the LPG boiler is the best option when one considers the economic merit.

In the next section, a sensitivity analysis is done on the CO_2 HPs versus the three case scenarios investigated.

6.3.6 Financial sensitivity diagrams

In this section, a sensitivity analysis is done for CO_2 HPs versus the paraffin boiler, electric boiler, and LPG boiler. Many of the input parameters used in the financial model have a certain degree of uncertainty. Sensitivity diagrams are done to investigate the factors that have the largest influence on the four financial indices investigated. The sensitivity diagrams of financial model parameters represent an important step in the modelling process in order to obtain credible results and valuable information, as well as to increase the confidence in the model results. The sensitivity diagrams could thus potentially address the barrier not only on the uncertainty of future energy prices, but also the other factors investigated. The sensitivity of seven factors is investigated for four financial indices. The seven sensitivity factors are:

1. capital layout cost,
2. CO_2 tax,
3. general inflation,
4. energy inflation of specific fuel source,
5. electric inflation,
6. prime lending rate, and
7. tax rate.

The four indices are:

1. IRR,
2. NPV,
3. ROI, and
4. SP.

In the next few sections, the sensitivity diagrams are shown and discussed. Finally, a summary is given on which sensitivity factors have the largest impact on all the scenarios investigated.

6.3.6.1 Sensitivity diagrams for the CO₂ HPs versus electric boiler

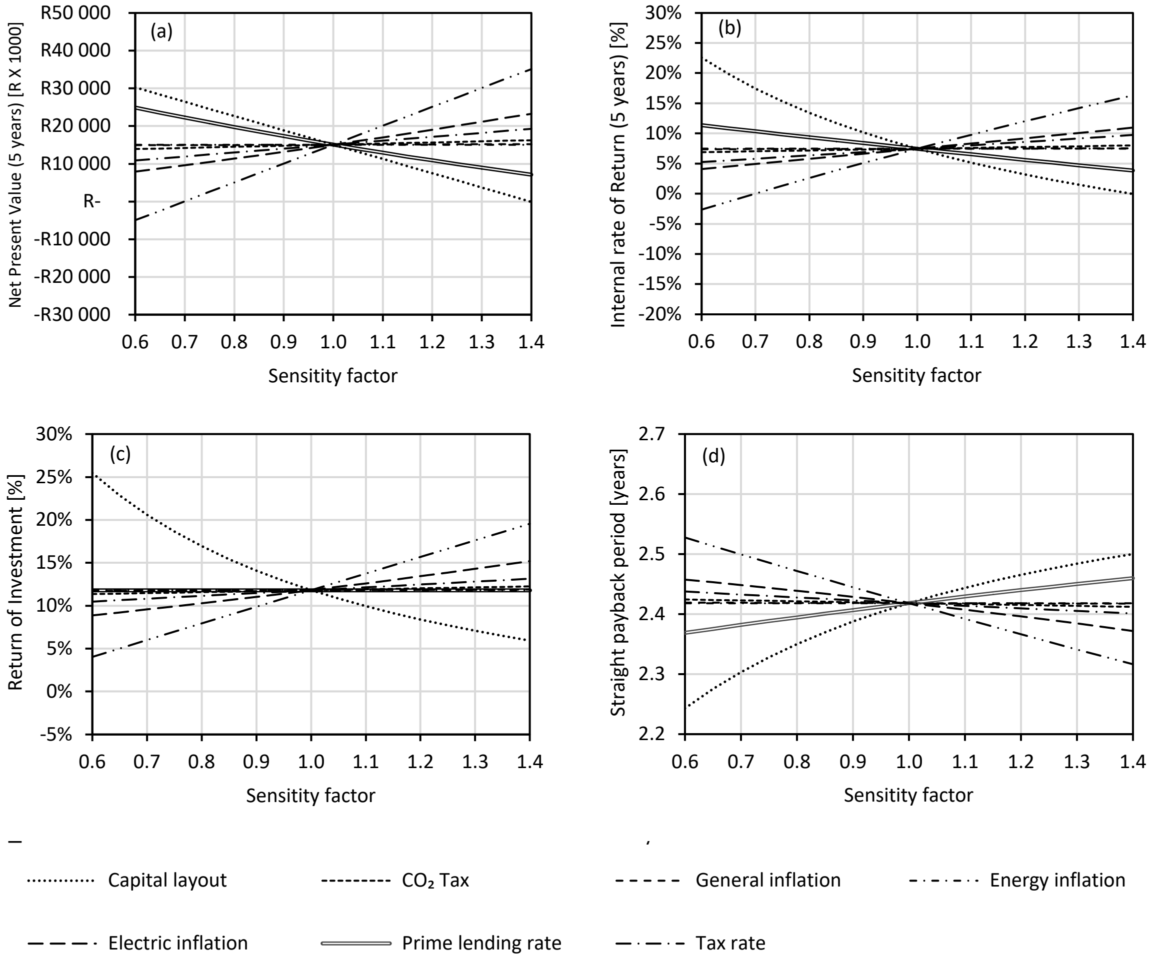


Figure 74: Sensitivity diagram for CO_2 HP savings compared with the electric boiler for NPV (a), IRR (b), ROI (c), and SP (d)

Figure 74 shows the sensitivity diagram for CO_2 HP savings compared with the electric boiler for the eight factors investigated. From Figure 74, one can see that for the NPV, IRR and ROI, the different indices changed substantially due to the change in the sensitivity factor. However, the change for the SP period was small. The SP did not change much because of the influence of the depreciation rate. For the first year, the depreciation rate is 40%, while in the second year, it is 20%. The impact of the high depreciation rate is that SP is less than three years, and the rest of the factors investigated have a small impact on the SP. The depreciation rate is a fixed value that is determined by the South African tax laws (SAIPA, 2019). The depreciation factor and SP are thus not discussed further in the sensitivity analysis.

Figure 74 shows the four factors with the largest impact on the indices investigated, which are the capital layout cost, electricity inflation per annum, prime lending rate, and corporate tax rate. The factors with the least influence are general inflation, energy inflation, and boiler energy cost.

If the capital layout cost SF is reduced to 0.9 (by 10%), the NPV increases by R 3 789 000 (25%) (Figure 74 (a)), the IRR decreases by 2.7% (Figure 74 (b)), and the ROI decreases by 2.3%. The capital layout cost can be improved with the economy of scale in the manufacturing of the CO_2 HPs. On the other hand, a more accurate estimation of the installation cost can increase or decrease the capital layout cost. A more accurate estimation of the installation cost is thus needed.

If the sensitivity factor (SF) of the electric inflation increases to 1.1 (by 10%), the NPV reduces by R 1 922 000 (13%) (Figure 74 (a)) and the IRR and ROI decrease by 0.9% (Figure 74 (b) and (c)). In the last 10 years, electric inflation has increased by more than 10%, or six times. The highest increase was in 2010/2011, when the electricity price increased by 27% for the industrial sector[11]. Furthermore, the electric inflation is an external factor that the industry has little control over. Thus, the electric inflation is a high-risk factor in the financial analysis for CO_2 HPs versus electric boilers.

If the prime lending SF increases to 1.1 (by 10%), the NPV decreases by R 2 224 000 or 15%, the IRR decreases by 0.9%, and ROI does not change. The prime lending rate has increased by more than 10% only once in the last 10 years and has decreased four times in the same period. The average prime lending rate increase for the last ten years was -1%[12]. The prime lending rate is thus a risk that should be managed.

If the corporate tax rate SF increases to 1.1 (by 10%), the NPV reduces by R 1 073 000 or 8%, the IRR decreases by 0.6%, and the ROI decreases by 0.3%. In the last 10 years, the corporate tax rate has decreased from 34.55% to 28% and was constant for the last seven years (KPMG, 2020). All the other factors investigated have a smaller impact on the various indices investigated.

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[11] Please see Table 66 in Appendix O for the electricity inflation for the last ten years

[12] Please see Table 61 in Appendix O for the prime lending rate increase for the last ten years

6.3.6.2 *Sensitivity diagrams for the CO_2 HPs versus paraffin boiler*

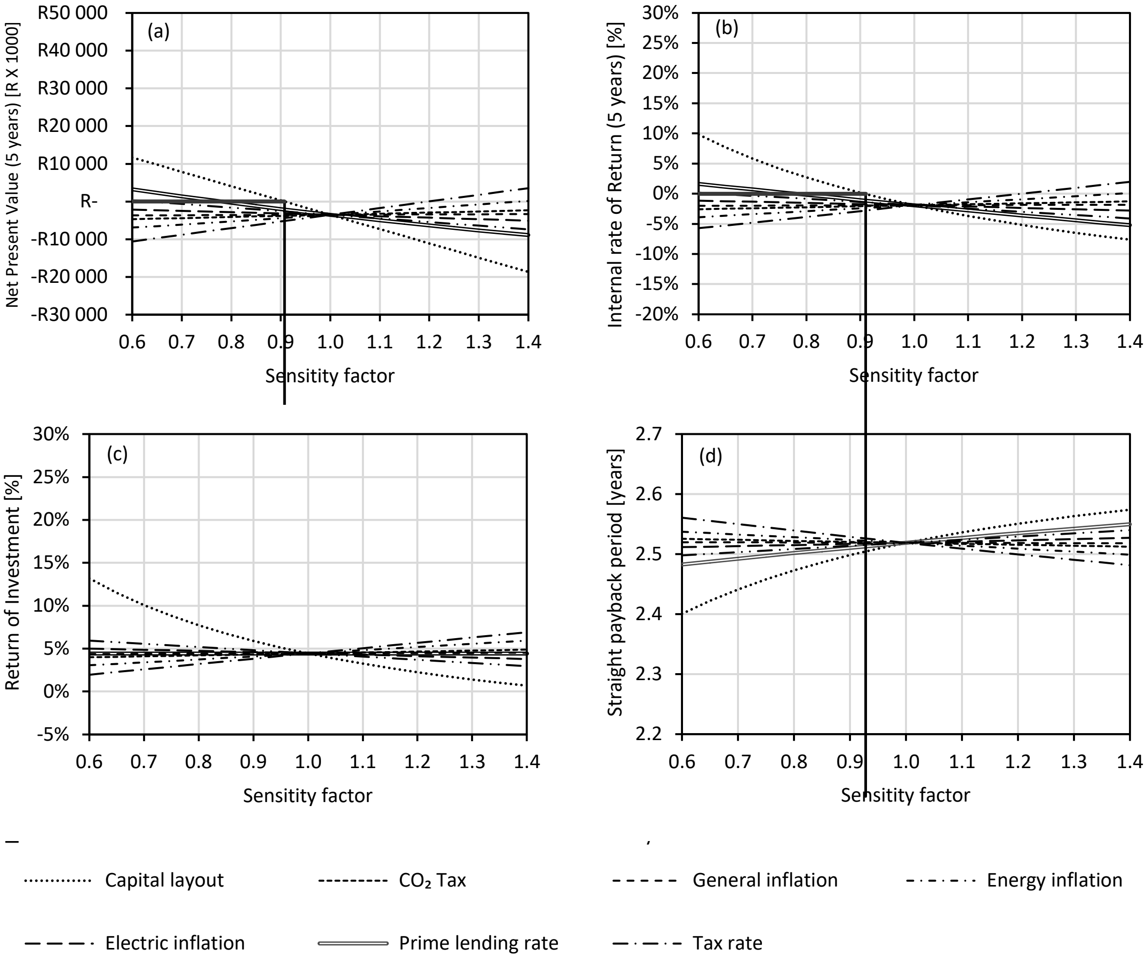

Figure 75: Sensitivity diagram for CO_2 HP savings compared with the paraffin boiler for NPV (a), IRR (b), ROI (c), and SP (d)

From Figure 75, one can see that the four factors with the largest impact on the indices investigated are the capital layout cost, corporate tax rate, energy (paraffin) inflation and the prime lending rate. The indices with the smallest impact are electric inflation, CO_2 tax, and general inflation.

With a decrease in the capital layout, the various indices show improvement. For example, if the capital layout SF decreases to 0.91, or 91%, of the current capital cost, the NPV and IRR will be above zero (Figure 75 (a) and (b)). The capital layout cost must decrease to 0.45, or 45%, of the current capital cost to give an ROI equal to the prime lending rate of 9.6%. Thus, the capital cost must reduce considerably, which seems to be unlikely.

If the tax rate SF decreases to 0.9 (by 10%), the NPV, IRR and ROI improve. As previously mentioned, corporate tax in the last seven years has been constant, and thus it is not discussed further. With an increase in boiler energy inflation cost, thus paraffin inflation cost, the various indices' performances also decrease. For example, if the boiler energy inflation SF increases to 1.1, the NPV decreases by R 893 000, or by 21%, the IRR decreases by 0.5%, and the ROI increases by 0.4%. In the last 10 years, the paraffin inflation has increased by more than 10%, or six times[13]. The paraffin inflation is an external factor and thus cannot be controlled by industry.

If the prime lending rate SF increases by 10%, the NPV decreases by R 1 431000, or 34%, the IRR increases by 0.8%, and the ROI does not change at all. The electricity cost per annum on the indices has the sixth-largest impact. As previously mentioned, the prime lending rate is a risk that should be managed.

6.3.6.3 Sensitivity diagrams for the CO_2 HPs versus LPG boiler

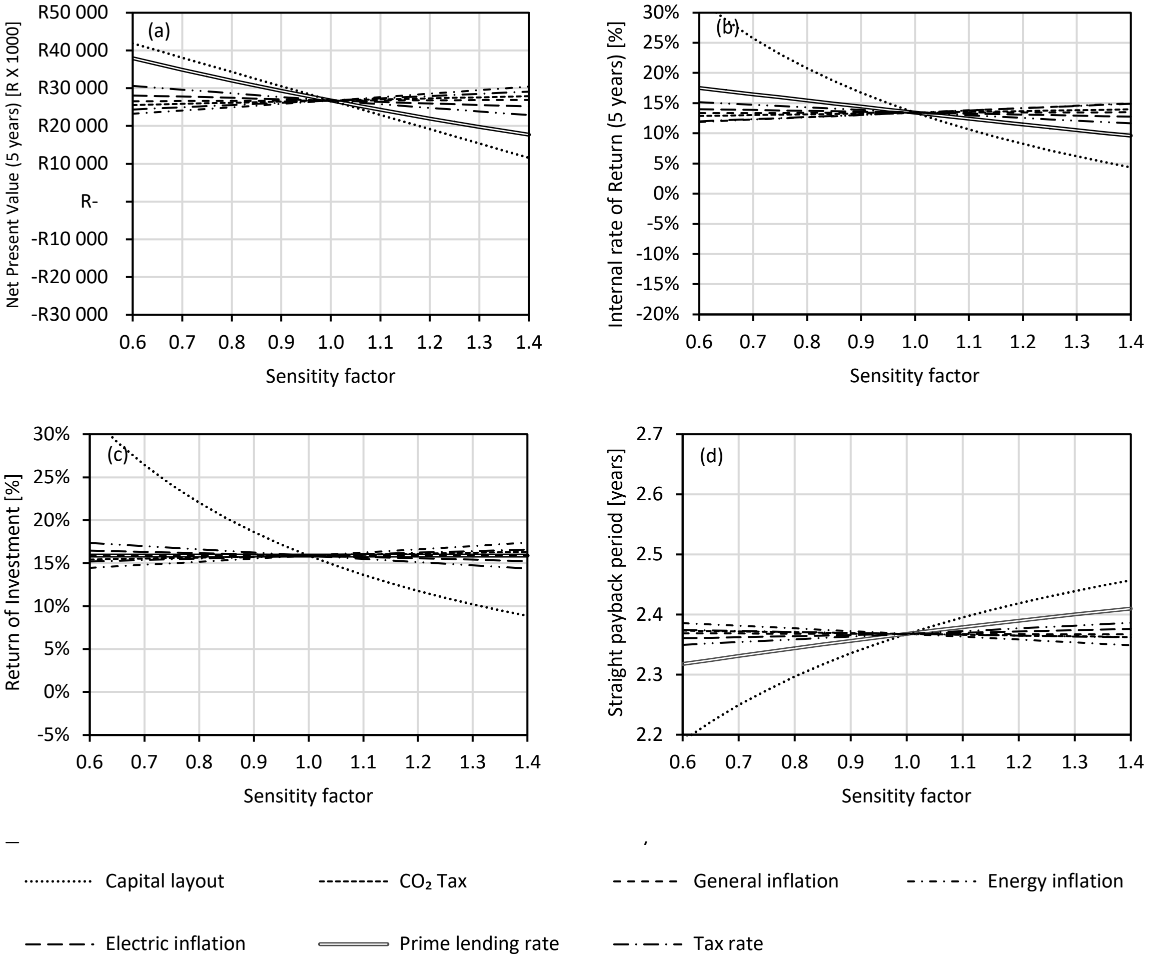

Figure 76: Sensitivity diagram forCO_2 HP savings compared to LPG boiler for NPV (a), IRR (b), ROI (c), and SP (d)

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[13] Please see Table 65 in Appendix O for the inflation increase of paraffin for the last ten years

From Figure 76, one can see that the capital layout cost, corporate tax rate, prime lending rate, energy (LPG inflation) rate, and boiler energy cost have the largest impact on all the indices shown. The general inflation has the smallest impact.

If the capital layout cost SF decreases by 10%, the NPV increases by R 3 789 000, or 14%, the IRR increases by 2.8%, and the ROI decreases by 2.2%. If the capital layout decreases by 4%, the IRR is still above the prime lending rate (Figure 76 (b)). The capital layout cost SF can be increased to 1.11 for the ROI and still be above the prime lending rate (Figure 76 (c)).

The prime lending rate and energy inflation (LPG inflation) have a smaller impact on the indices investigated. For example, if the prime lending rate SF increases to 1.1, the NPV decreases by R 2 417 000, or 9.3%, the IRR decreases by 1.0%, and the ROI does not change at all. If the LPG inflation SF increases to 1.1, the NPV decreases by R 906 000, or 3.5%, the IRR increases by 0.4%, and the ROI increases by 0.4%. Thus, these factors are not such a significant leverage for the economics of CO_2 HPs compared to LPG.

In conclusion, the CO_2 HPs compared with the LPG boiler is the best in terms of the economic factors investigated. If there is such a poultry abattoir in SA that operates on LPG gas, it would be worthwhile to implement a CO_2 HP at the location.

6.3.6.4 *Factors that have overall the highest impact on all scenarios*

A frequency diagram is drawn to determine which of the factors investigated had the biggest impact on all the indices investigated.

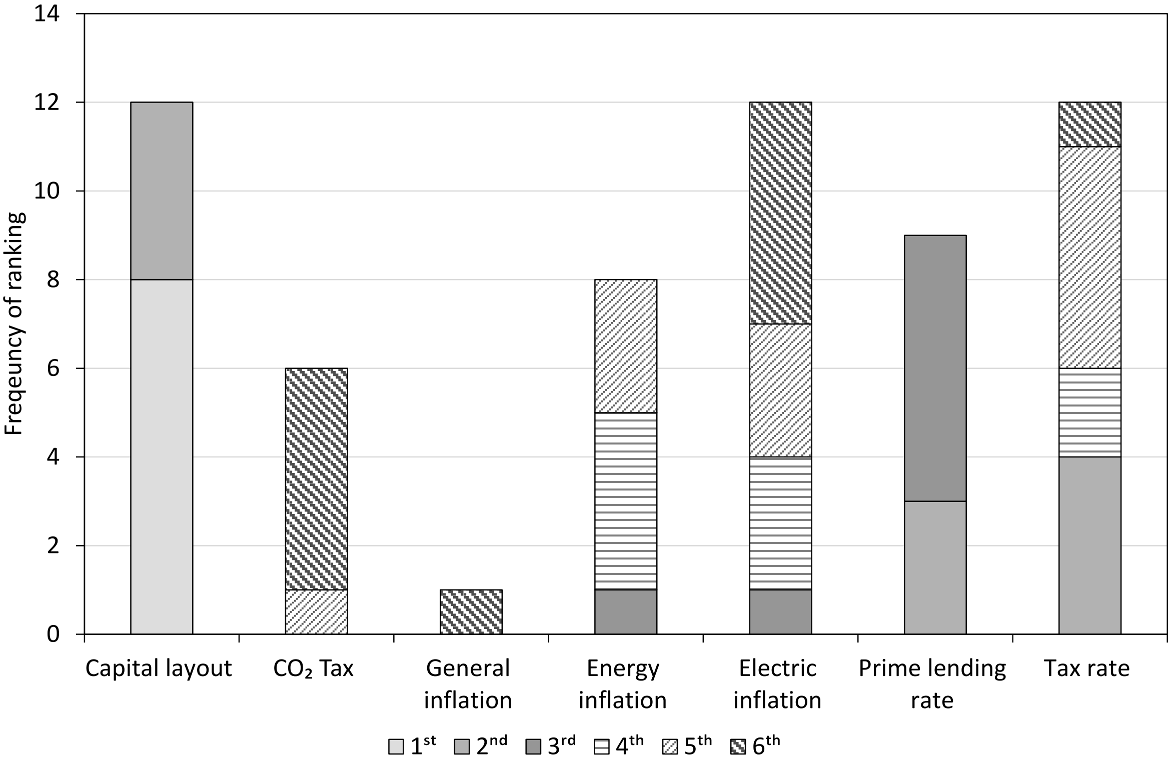

Figure 77: Frequency diagram of the highest technical potential for CO_2 HPs

Figure 77 illustrates that the capital layout cost had the first- and second-highest frequencies of all the factors investigated. By decreasing the capital cost, all the indices for all the cases improved. The capital cost for CO_2 HPs should thus decrease dramatically. As previously mentioned, the CO_2 HPs' price can decrease with economies of scale. On the other hand, it is crucial that a more accurate estimation of the installation cost be done, as it can influence the economics in both directions.

The prime lending rate had the second- and third-highest frequencies of all the factors investigated. A lower prime lending rate influences all the indices positively. Given its strong influence on all the indices, the prime lending rate is thus a variable that needs to be managed.

Up to now, the impact of a single abattoir with a fixed number of birds per second has been investigated. In the investigation, CO_2 HPs were compared with coal, LPG, paraffin, and electric boilers for six different zones in SA. In the next section, an investigation is done to determine the potential environmental impact in the event that CO_2 HPs were implemented in 75% of abattoirs in SA.

6.4 Environmental impact on SA

In 2016, the Johannesburg Stock Exchange (JSE) indicated that all JSE-listed companies are required to apply and disclose the codes of the King IV Report on Corporate Governance (JSE, 2017). As part of the King IV, corporate governance (Institute of Directors Southern Africa, 2016) companies should oversee and monitor their impact on the environment (point 14. D). Currently, five of the seven largest poultry producers are listed on the JSE. Together, the five producers slaughter approximately 64% of all the poultry in SA (DAFF, 2017).

The focus of this section is to determine the impact of the CO_2 HPs on the environment. From a study done by the WRC (2017) on 15 chicken abattoirs, it was found that all the 15 abattoirs investigated use coal as a heating source. Thus, although CO_2 HPs do not make sense economically when compared with coal steam boilers, an investigation was launched to determine the environmental impact of replacing coal boilers with CO_2 HPs for SA. The author made the following assumptions to determine the impact of CO_2 HPs on SA.

- Only the top seven producers were investigated. Together, the seven top producers represent approximately 75% of SA's poultry production (DAFF, 2017). The details of the locations of the various abattoirs were available for each plant.
- The operational times (Section 6.2.3) for the abattoirs were assumed to be the same for all the plants investigated.
- The number of CO_2 HPs was determined for each site, based on whether one CO_2 HP could supply water for 5.0 birds per minute.
- All the sites use coal as its primary heat source.

The top seven producers' sites were divided into two categories, namely actual and estimated. As seen in Table 39, Astral sites and the Sovereign sites (Site 16 and 17) were classified as actual. Only Astral indicated the average bird per week per location. For the Sovereign sites, the data was based on statistics from the SAPA (2017). For all the estimated sites, the average bird per week per producer was obtained from SAPA (2017), but no information on the average number of birds per week was available for the specific site. The birds per week were thus estimated based on a percentage per province, news articles, and data from reports (Gogela *et al.*, 2017). For detailed calculations, please refer to Appendix O. The actual data and estimated data represent approximately 33% and 42% of the total of South African poultry subdivision data, respectively.

Table 39: Input data of the top seven producers.

Site no	Town	Producer	Zone	Number of CO_2 HPs	Birds\min	Average Birds per week	Type of data
1	Olifantsfontein	Astral	1	40	198	1109510	Actual
2	Durban	Astral	5	6	27	153210	Actual
3	Standerton	Astral	1	57	283	1588090	Actual
4	Cape Town	Astral	4	50	247	1385810	Actual
5	Bloemfontein	CBH	1	5	25	141220	Estimated
6	Tigane	CBH	1	22	108	603400	Estimated
7	Mafikeng	CBH	2	22	108	603400	Estimated
8	Springs	Daybreak	1	18	86	481430	Estimated
9	Springs	Daybreak	1	18	86	481430	Estimated
10	Potchefstroom	Fouries poultry	1	36	178	999460	Estimated
11	Potchefstroom	Fouries poultry	1	6	28	155980	Estimated
12	Durban	RCL	5	45	223	1253440	Estimated
13	Tzaneen	RCL	2	13	64	360990	Estimated
14	Rustenburg	RCL	2	84	420	2356470	Estimated
15	Worcester	RCL	2	24	116	650880	Estimated
16	Uitenhage	Rocklands - Sovereignfoods	4	35	172	962870	Actual
17	Hartbeespoort	Tydstroom - Sovereignfoods	2	42	206	1155440	Actual

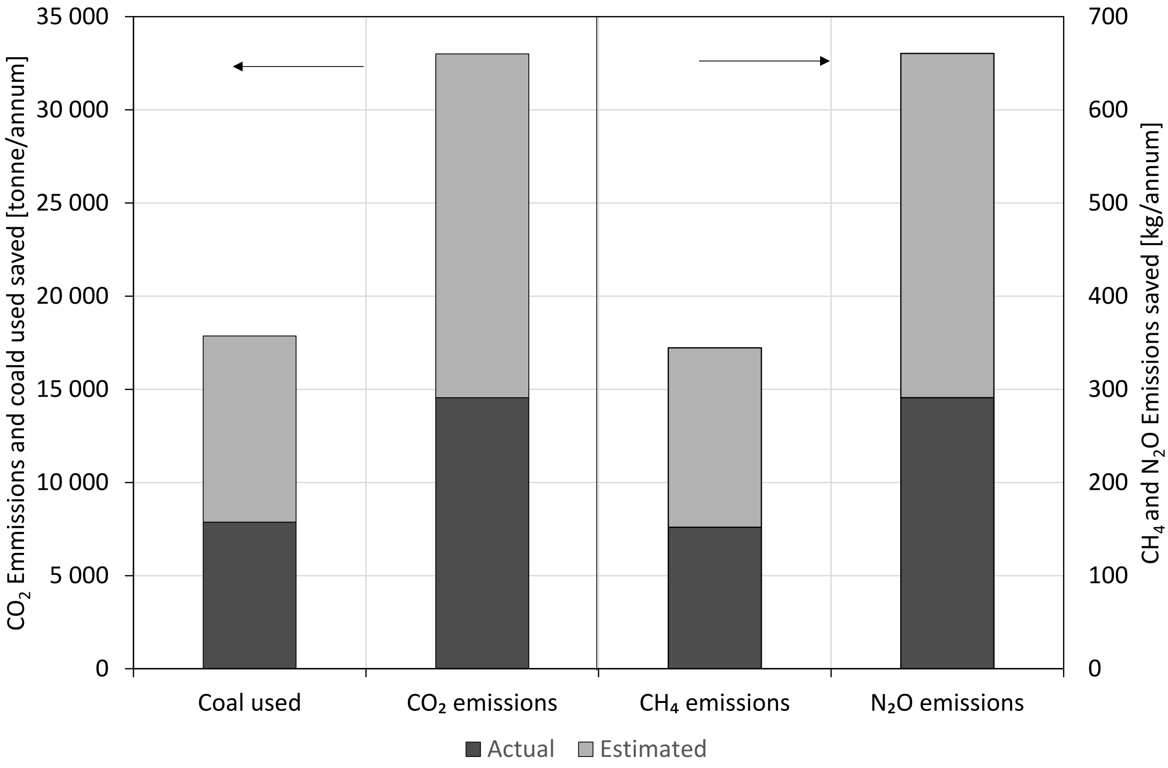

Figure 78: Estimated environmental saving for the seven largest producers in SA

Figure 78 shows the estimated environmental saving for the coal uses, CO_2, CH_4, and N_2O emissions. Overall, CO_2 HPs can save 45% of the total coal used and CO_2, and N_2O emissions, while the CH_4 emissions are reduced by 55%. The CH_4 emissions are higher because Eskom does not report on the CH_4 emissions, and so the value was estimated from the IPCC (2006).

Figure 78 demonstrates that the estimated total coal savings is approximately 17 863 tonnes/annum. The coal savings is defined as the difference between the coal that is used by the boiler and the coal that is used to generate the electricity. The coal savings equates to approximately 585 double 40 m^3 twin bin trailer loads.[14] The CO_2 savings are approximately 37 671 tonnes/annum; this equates to approximately 7 500 hectares of Portulacaria Afra (spekboom) sequestration per year.[15]

In conclusion, if the seven largest poultry producers in SA implement CO_2 HPs, they can reduce the total coal used by 45%. This reduction is substantial and well above the industrial target of 16% set by the post-2015 National Energy Efficiency Strategy (DoE SA, 2016c).

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[14] Calculation based on data from (Afrit, 2020)

[15] Calculation based on data from (Cowling & Mills, 2014).

6.5 Summary

From the simulations, it was found that CO_2 HPs used, on average, at least five times less energy than the steam boilers and 5.3 times less than the electric boilers. The simulation also showed that, of the six climatic zones, zone 4 (temperal coastal) had the lowest energy use, while zone 1 (cold interior) had the highest energy use. The difference in maximum and minimum energy use for the CO_2 HPs was less than 4.9% of the total energy use. The main reason for this is the higher wet-bulb temperature of the air, which caused a higher enthalpy and consequently a higher COP. The energy use of the ammonia chiller was below 2% of the total energy use. The cooling of the cutting, packing, and dispatching areas was not included in the calculations.

The average CO_2 HPs emissions were 2.5 times less than that of the paraffin steam boiler, 1.1 less than the LPG steam boiler, two times less than a coal boiler, and 5.8 less than an electric boiler. CO_2 HPs emissions were thus much lower than that of the coal, paraffin, and electric boilers. The emissions of the LPG were only 10% more than of the LPG steam boiler on average. Thus, in general, the CO_2 HPs emits fewer greenhouse gases than coal, LPG, paraffin, and electricity.

The total energy cost to run the CO_2 HPs, is 2.3 times more than a coal steam boiler. The main reason for this is the high cost of electricity. In comparison, coal costs 2.0 c/MJ, while electricity cost 36.7 c/MJ. The CO_2 HPs are 7.7 times cheaper than LPG, 4.2 times cheaper than paraffin, and 5.3 times cheaper than an electric boiler. CO_2 HPs is so much cheaper than electric boilers because of the high COP of around 4. CO_2 HPs are thus more expensive to run than the coal steam boilers but are less expensive to run than paraffin, LPG steam boilers, and electric boilers.

The economic investigation showed that the CO_2 HPs compared with the paraffin boiler is not a financially viable option. The NPV and IRR were both negative. However, the CO_2 HPs compared with the electric and LPG boiler are both economically viable. The best option is replacing the LPG boiler with a CO_2 HP, as this option has the highest NPV, IRR, and ROI. CO_2 HP compared with the LPG boiler therefore not only has the potential to save energy but is also a financially viable option.

The sensitivity investigation shows that the electricity and boiler energy costs have the largest impact on the NPV (five years), IRR (five years), ROI, and SP. The electricity and boiler energy costs are external costs with the industry having little influence on them. The capital cost has the third-largest impact on the four indices investigated. With a reduction in capital cost, the four indices investigated all performed better. The capital cost can be decreased with economies of scale.

An investigation was done on the impact of CO_2 HP for 75% of the South African poultry subdivision. For the investigation, it was assumed that all the abattoirs used coal as its primary fuel source. Although coal does not make economic sense, it was found that CO_2 HP could potentially reduce the total coal used and the CO_2 and N_2O emissions by 45%. The CH_4 emissions could be reduced by 55%. The reduction is well above the 16% target set for the industrial sector by the National Efficiency Strategy.

Chapter 7. Summary and recommendation

7.1 Summary and implications of the results

This thesis contributes to the research body by determining where CO_2 HPs can be implemented in the South African industry. The first main objective of this thesis was to conduct a literature review on the industrial sectors that have the highest potential for the implementation of CO_2 HPs. From the literature, it was found that the food and beverage division has the highest theoretical potential, as well as the highest number of installed CO_2 HPs.

In relation to the first research objective, the theoretical potential for the use of CO_2 HPs with an operating temperature of below 100 °C was determined for SA. The investigation was done for various industrial divisions in SA. Based on IEA (2016) data, the approximate heat demand for SA is 219.5 ±71.93 PJ/annum, or 18.8% of the total energy demand for the industrial sector. The non-specified industrial division has the by far largest theoretical electric potential for heat below 100 °C, with a share of 89.0% (40.5 PJ/annum). The mining (excluding fuels) and quarrying division has the second-largest share of nearly 6.8% (3.1 PJ/annum). The rest of the divisions altogether make up about the rest of the 4.2% (1.9 PJ/annum).

The food, beverage, and tobacco division's heat demand below 100 °C is only 0.8% (1.8 PJ/annum). However, if one assumes the data from Knaack *et al.* (2019) to be correct, the theoretical potential is 9.2 PJ/annum, or 4.8 times larger. If one assumes the SATIM (ERC, 2013) data to be accurate, then the heat demand below 100 °C for the food, beverage, and tobacco divisions is 20.75 PJ/annum or 10.9 times larger.

Next, the author conducted an investigation to determine which is the most suited division to implement CO_2 HPs. The investigation looked at the percentage GVA, the percentage of the total heat demand below 100 °C, and the percentage of processes that are below 100 °C. The author found that the food, beverages and tobacco division has the highest potential for CO_2 HPs in SA. To find the most suited food, beverage, and tobacco division, the author looked at the number of companies in the division, typical temperature ranges of their various processes, and the energy used per kilogram of processed product. The investigation found that poultry abattoirs have the highest in terms of these qualifiers and are thus most suited for the implementation of CO_2 HP. The second-best option was for the processing of milk and milk-related products. The integration of CO_2 HPs in poultry abattoirs were thus investigated further.

To determine the best option for integrating a CO_2 HPs, the author conducted a site visit to a local poultry abattoir. From the visit and the literature, the author determined that the CO_2 HP operating conditions match the various processing steps of the poultry abattoir. These include soft scalding, flow and equipment washing, sterilisation, chilling, and showering. According to the EIPPCB (2005), these processing steps make up about 61% of the energy used in poultry abattoirs.

Consequently, the author wrote a simulation that integrated a CO_2 HP in a poultry abattoir. The simulation was verified with DWSIM software. The largest percentage error was 0.2%. Therefore, the model is verified and can be used for further analysis. Four different scenarios were compared with each other, namely CO_2 HP versus coal, paraffin, LPG steam boilers, and electric boilers. The simulation indicated that, on average, the CO_2 HP uses 4.6 times less energy than that of the coal, paraffin, and LPG steam boiler and 5.3 less than that of the electric boiler. For the six climatic zones, zone 4 (temperate coastal) has the lowest energy use, while zone 1 (cold interior) has the highest energy use. The difference between zone 4 and zone 1 is less than 5% (100 034 kWh) of the total energy. It is important to note that the energy use of zone 01 (Cold interior) and zone 06 (Arid interior) is similar, with a difference of only 7 911 kWh or 0.4%. The same can be seen for zone 04 (Temperature coastal) and zone 03 (Hot interior), with a difference of 11 647 kWh or 0.6%.

If one compares the greenhouse emissions, the electric boiler had the highest CO_2 emissions at 5.8 times higher than that of the average CO_2 HP. The coal steam boilers had 1.8 times more CO_2 emissions than the average of CO_2 HP. The values for the LPG and paraffin boilers were much smaller, at 1.2 and 1.4 times, respectively.

The simulation showed that, in general, for the CO_2 HP, the combined CO_2, CH_4, and N_2O emissions were 0.9 less than that of the LPG steam boiler, 2.5 times less than that of the paraffin steam boiler, two times less than that of the coal boiler, and 5.4 less than that of the electric boiler. The CO_2 HP emissions were thus much lower than that of the coal, paraffin, and electric boilers. The average emissions of the CO_2 HP were only 10% more than that of the LPG steam boiler on average. The CO_2 HP thus emitted fewer greenhouse gases than the other technologies.

The result showed that the running cost of CO_2 HP is significantly higher than that of coal steam boilers. The cost of electricity is approximately 18 times more expensive than that of coal. Thus, with the current cost of electricity, CO_2 HPs are too expensive to run compared to a coal system. In comparison with electric, paraffin and LPG steam boilers, CO_2 HPs are 5.3 times, 7.7 and 4.2 times less expensive to run.

A barrier to the implementation of CO_2 HPs is the uncertainty of energy prices. Thus, a sensitivity investigation was done to determine the impact of energy prices, inflation, capital layout cost, and tax rates. The sensitivity investigation found that the electricity, boiler energy cost, and capital cost have the three largest impacts on the NPV (five years), IRR (five years), ROI, and SP. The electricity and boiler energy costs are external factors, with the division having little impact on the price. However, the capital cost can be reduced by a more accurate estimation of the installation cost or economies of scale.

Although CO_2 HPs do not necessarily make sense financially currently when compared with coal steam boilers, they can impact on greenhouse gas emissions. An investigation was done on the environmental impact of approximately 75% of the abattoir sector of SA. The investigation found that the coal usage, CO_2, and N_2O emissions can be reduced by at least 45%. The CH_4 emissions can be reduced by 55%. The reduction is well above the 16% target set for the industrial sector by the National Efficiency Strategy.

7.2 Recommendation and future work

Based on the results of this study the following was identified as areas that need further attention.

1. The IEA HPT published the findings of Annex 48 (Industrial Heat Pumps, Second Phase) February 4, 2021 (IEA HPC, 2021). The objective of Annex 48 was to create a tool for decisions makers to use more IHPs for the larger scale market in industrial applications (IEA HPC, 2021). In total 342 examples of IHP were give (IEA HPC Annex 48, 2021). The findings could strengthen the work done by NWU and reports need thus to be analysed for further work.
2. From the theoretical heat demand below 100 °C in SA, it was found that the food, beverage and tobacco division's potential for implementing CO_2 HPs was very low. The values from Knaack *et al.* (2019) and SATIM (ERC, 2013) were 10.2 times and 11.5 times more than that values based on the IEA (2017a). It is recommended that the theoretical potential should be updated with the SATIM data. To use the SATIM data, the most recent values must be updated.
3. Currently the Mayekawa AWW CO_2 HP data is only available for a hot water temperature of 65°C. Laboratory and field test need to be done to determine the operating conditions of the CO_2 HP.
4. The poultry abattoir must provide a chiller for the final chilling of the meat to a 4-°C core temperature within 12 hours. The chilled poultry is then stored at 4 °C. The cooling load and storage load were not included in this study due to the complexity on the sizing of the area and the heat demand for the cooling. However, if one includes the cooling and storage load, the cooling demand of the multi-function CO_2 HP chiller is increased. The additional cooling load of the chiller will not increase the energy use of the CO_2 HP dramatically. The additional ammonia chiller that is needed for the chilling and storage should thus not be needed. This would have a positive impact on the financials assessment and could make CO_2 HP more economically viable.
5. For the financial analysis, the author assumed that the CO_2 HPs replaces the current technology. An investigation needs to be done for when a new plant is constructed. The economics will look

notably different for the scenario where the capital costs of all the technologies are compared.

6. Further, investigation needs to be done on other processes that use hot water below 100 °C. The focus of the investigation should be on opportunities in the food, beverage, and tobacco division. The introduction of CO_2 HPs into this field is considered easy because the temperature required in the process is below 100 °C (HPTCJ, 2010). The investigation showed that a possible division for further research would be the processing of milk and manufacturing of milk-related products.
7. For CO_2 HPs to have a larger impact in the industrial market, the cost of the CO_2 HP needs to be reduced. The cost can be reduced with economies of scale. One way to increase the implementation of CO_2 HPs in SA is with the establishment of a South African IHP association. Such an association would aim to address the barriers of the application of IHPs in industry. The association's aim should be to drive:
   - the promotion of information on the successful application of IHPs in industry

     Currently, only one example could be found in the literature of an implemented HP in industry for SA. Thus, the promotion of the successful application of IHPs in the industry will address this barrier. The showcases should highlight scoping and successfully implemented projects. The aim of the showcases would be to address various barriers to the implementation of IHPs, including a lack of information, uncertainty of future energy prices, and long payback periods. The showcases should further aim to establish customer confidence in IHPs.
   - the establishment of an IHP labelling programme

     The South African IHP association should drive the certifications of the IHPs. The labelling programme should ensure that more certified products enter the market. The aim of the labelling program should be to address the barrier of poor equipment quality and build customer confidence in more reliable IHPs.

     To ensure the quality of the IHPs, IHPs should undergo rigorous testing by independent laboratories. For example, the IHP motor will have to adhere to SANS 60335-2-89 (household and similar electrical appliances - Safety Part 2-89: Particular requirements for commercial refrigerating appliances with an incorporated or remote refrigerant unit or compressor) and SANS 60335-2-34 (household and similar electrical appliances - Safety Part 2-34: Particular requirements for motor-compressors) (SANS, 2015a, 2015b).
   - training and certification of installers, sales representatives, and technicians

     SA has made various efforts to increase the training of plumbers that install residential and commercial HPs and certify their work. For example, the Institute of Plumbing South Africa (PIRB) (2015) rolled out a qualification in the installation of HPs. Secondly, according to the Plumbing Industry Registration Board (PIRB, 2020), a plumbing certificate of compliance must be issued for most plumbing work, including the installation, relocation, or replacement of any HP water heating system. The programme should be extended to the industrial sector, thereby addressing the identified barrier of the lack of skilled installers.

- legislation.

  The association should drive the legislation of IHPs in SA. According to Goetzler *et al.* (2009), the Korean ground source IHP market has shown tremendous growth since 2001. This growth has been fuelled by legislation passed in 2005 by the Korean government that required new public buildings to incorporate alternative and renewable energy sources. Currently, SA has the 12 L tax-saving initiative. However, the initiative only rewards electric energy savings (SARS, 2017). The initiative should be extended to other forms of thermal energy, for example, coal, LPG, and paraffin.
- Advise the government on the establishment of energy statistic department

  To determine the theoretical heat-demand of SA, the author needed to base the values on international data. It is recommended that the association advise the SA government to establish an energy statistic department. The function of this department is to gather data on the heat demand of industry at various temperatures.

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Appendix A Overview of processes in different industrial divisions structured by typical temperature ranges.

Table 40: Overview of processes in different industrial divisions structured by typical temperature ranges below 100 °C. Source: Wolf *et al.* (2012), Wolf *et al.* (2014), IEA HPC Annex 35 (2014), Schweiger *et al.* (1999), Kalogirou (2003), Arpagaus *et al.* (2018), Lauterbach *et al.* (2012), and Lauterbach *et al.* (2011); FoodBev SETA (2011)

Temperature [°C]

SECTOR NAME	PROCESS	40		50		60		70		80		90		100	RANGE [°C]
Several sectors	Preheating	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨		20 - 100
	Warm water	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨		10 - 100
	Washing	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨				30 - 90
	Washing/cleaning	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨				30 - 90
Food, beverages & tobacco	Blanching					▨	▨	▨	▨	▨	▨	▨			60 - 95
	Bottle washing					▨	▨	▨	▨	▨	▨				60 - 90
	Boiler feed water	▨	▨	▨											20 - 55
	Brewing		▨	▨	▨	▨	▨	▨	▨	▨	▨				45 - 90
	Cleaning					▨	▨	▨	▨	▨	▨				60 - 90
	Cooling									▨	▨	▨			80 - 95
	Preheating														30 - 40
	Scalding		▨	▨	▨	▨	▨	▨	▨	▨	▨				45 - 90
	Smoking	▨	▨	▨	▨	▨	▨	▨	▨						20 - 83
	Tempering	▨	▨	▨	▨	▨	▨	▨	▨						40 - 80
	Wash water	▨	▨	▨	▨	▨									35 - 65
	Washing	▨	▨	▨	▨	▨	▨	▨	▨						35 - 80
	Wort boiling														100 - 100
	Concentration					▨	▨	▨	▨						60 - 80
Food	Cooling														-18 - 20
	Distillation	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨		40 - 100
	Washing	▨	▨	▨	▨										30 - 60
	Substance concentration					▨	▨								60 - 70
	Preheating of substances	▨	▨	▨	▨										20 - 60
	Cleaning the facility	▨	▨	▨	▨	▨	▨								30 - 70
Prcng. & prsvng. of meat, fish, fruit & vegtables	Bleaching					▨	▨	▨	▨	▨	▨				60 - 90
	Cooking					▨	▨	▨	▨	▨	▨	▨			60 - 98
	Scalding												▨		95 - 100
	Bleaching					▨	▨	▨	▨	▨	▨				60 - 90
	Pasteurization					▨	▨	▨	▨						60 - 80
	Pasteurization					▨	▨	▨	▨						60 - 80
Prcng. & prsvng. of meat	Blanching		▨	▨	▨	▨	▨	▨	▨	▨	▨				45 - 90
	Cleaning					▨	▨	▨	▨	▨	▨				60 - 90
	Cooking											▨	▨		90 - 100
	Drying					▨	▨	▨	▨						60 - 80
	Smoking	▨	▨	▨	▨	▨	▨	▨	▨	▨					20 - 85
	Washing, sterilization					▨	▨	▨	▨	▨	▨				60 - 90
Prcng. & prsvng. of fruit & vegetables	Blanching						▨	▨	▨	▨	▨	▨			65 - 95
	Drying	▨	▨	▨	▨	▨	▨	▨	▨						40 - 80
	Extraction					▨									60 - 65
Mfg. of vegetable and animal oils &	Extraction				▨										55 - 60
	Animal fat -Steam injection														90 - 90
	Palm-oil -Jacket heat exchangers														75 - 75
SECTOR NAME	PROCESS	40		50		60		70		80		90		100	RANGE [°C]

Temperature [°C]

Temperature [°C]

SECTOR NAME		PROCESS	40		50		60		70		80		90		100	RANGE [°C]
Mfg. of dairy products		Boiler feed water					▨	▨	▨	▨	▨	▨				60 - 90
		Cleaning					▨	▨	▨	▨	▨	▨				60 - 90
		Concentrates					▨	▨	▨	▨						60 - 80
		Washing	▨	▨	▨	▨	▨	▨	▨	▨						35 - 80
		Cleaning in process	▨	▨	▨	▨	▨	▨	▨	▨	▨					10 - 85
		Heating	▨	▨	▨	▨	▨	▨	▨							5 - 75
		condensed milk production	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨		5 - 100
		Sour milk production	▨	▨	▨	▨	▨	▨								5 - 70
		Cream cheese production														5 - 23
		Soft cheese production														5 - 39
		Butter production														5 - 13
		Whipped cream production														5 - 40
		Yogurt production														5 - 40
		Cheese -Jacket heat exchangers (Temp > 75°C)														75 - 75
		Clotted cream production														5 - 40
		Pressurization					▨	▨	▨	▨						60 - 80
		Batch Pasteurization					▨									62 - 65
		High-temperature-short-time Pasteurization (HTST)							▨							72 - 75
		Higher-heat-shorter-time Pasteurization (HHST)										▨				85 - 90
		Boiler feedwater					▨	▨	▨	▨	▨	▨				60 - 90
	Mfg. of grain mill products etc.	Sterilization					▨	▨	▨	▨						60 - 80
	Mfg. of bakery products	Press	▨	▨	▨	▨										40 - 60
Mfg. of cocoa, chocolate and sugar confectionery		Conching					▨	▨	▨	▨						60 - 80
		Melting	▨	▨	▨	▨										40 - 60
		Temper	▨	▨	▨	▨	▨	▨	▨	▨						40 - 80
		Dark chocolate -Jacket heat exchangers		▨	▨	▨										45 - 60
		White chocolate -Jacket heat exchangers	▨	▨												40 - 50
		Pasteurization								▨	▨					75 - 85
Beverages	Beverages	Pasteurization					▨	▨								60 - 70
		Washing, sterilization					▨	▨	▨	▨						60 - 80
Mfg. of wines		Bottle washing					▨	▨	▨	▨	▨	▨				60 - 90
		Cooling (absorption)									▨	▨	▨			80 - 95
		Washing, bleaching and dying					▨	▨	▨	▨	▨	▨				60 - 90
Mfg. of malt liquors and malt		Bottle washing					▨	▨	▨	▨	▨	▨				60 - 90
		Cleaning					▨	▨	▨	▨						60 - 80
		Cooling														90 - 90
		Crate washing					▨	▨	▨	▨						60 - 80
		Drying														60 - 60
		Hot water supply	▨	▨	▨	▨	▨	▨	▨	▨						20 - 80
		Wort boiling														100 - 100
		Pasteurization					▨	▨	▨							60 - 75
Mfg. of soft drinks; mineral waters etc		Bottle washing				▨	▨	▨	▨	▨						55 - 80
		Cleaning					▨	▨	▨	▨						60 - 80
		Evaporation processes	▨	▨	▨	▨	▨	▨								40 - 70
		Extraction				▨	▨									55 - 65
		Tunnel pasteurization -Glass							▨	▨	▨	▨				70 - 90
		Tunnel pasteurization -PET														64 - 64
		Pasteurization					▨	▨								60 - 70
		Washing, sterilization					▨	▨	▨	▨						60 - 80
		High-temperature-short-time Pasteurization (HTST)							▨							72 - 75
	Textile, leather & clothing	Washing, bleaching and dying					▨	▨	▨	▨	▨	▨				60 - 90
SECTOR NAME	PROCESS		40		50		60		70		80		90		100	RANGE [°C]

Temperature [°C]

Temperature [°C]

SECTOR NAME	PROCESS	40		50		60		70		80		90		100	RANGE [°C]
Textiles	Bleaching	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨		40 - 100
	Dyeing							▨	▨	▨	▨				70 - 90
	Pressing									▨	▨	▨	▨		80 - 100
	Wool - Chromium dye	▨	▨	▨	▨	▨	▨	▨	▨						25 - 80
	Wool - Reactive dye						▨								65 - 70
	Acrylic fibre - Disperse dye	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨		25 - 100
	Plant fibre - Reactive dye	▨	▨	▨	▨	▨	▨	▨	▨						40 - 80
	Polyamide fibre - Acid dye							▨	▨						70 - 80
	Polyamide fibre - Reactive dye														95 - 95
	Cleaning the facility	▨	▨	▨	▨	▨	▨								30 - 70
	Laundering	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨		40 - 100
	Bleaching, dyeing					▨	▨	▨	▨	▨	▨				60 - 90
Wood & wood products	Cooking									▨	▨				80 - 90
	Pickling	▨	▨	▨	▨	▨	▨								40 - 70
	Steaming							▨	▨	▨	▨	▨	▨		70 - 100
	Staining			▨	▨	▨	▨	▨	▨						50 - 80
	Coking									▨	▨				80 - 90
	Pre-heating water					▨	▨	▨	▨	▨	▨				60 - 90
	Thermodifussion beams									▨	▨	▨	▨		80 - 100
Sawmilling and planing of wood	Drying					▨	▨	▨	▨	▨	▨	▨	▨		60 - 100
	Preheating water					▨	▨	▨	▨	▨	▨				60 - 90
	Thermodiffusion beams									▨	▨	▨	▨		80 - 100
Paper & paper products	Boiler feed water					▨	▨	▨	▨	▨	▨				60 - 90
	Cooking and drying					▨	▨	▨	▨						60 - 80
	De-inking			▨	▨	▨	▨								50 - 70
	Preheating of substances	▨	▨	▨	▨	▨	▨	▨	▨						40 - 80
	Cleaning the facility	▨	▨	▨	▨	▨	▨								30 - 70
	Boiler feedwater					▨	▨	▨	▨	▨	▨				60 - 90
	Cooking, drying					▨	▨	▨	▨						60 - 80
Chemical & petrochemicals	Biochemical reaction	▨	▨	▨											25 - 55
	Preheating water					▨	▨	▨	▨	▨	▨				60 - 90
	Bioreactions	▨	▨	▨	▨										20 - 60
Chemicals & chemical products	Preheating of substances														60 - 60
	Cleaning the facility	▨	▨	▨	▨	▨	▨								30 - 70
	Pre-heating water					▨	▨	▨	▨	▨	▨				60 - 90
Rubber & plastics products	Preheating			▨	▨	▨	▨								50 - 70
Machinery	Cleaning	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨				40 - 90

SECTOR NAME PROCESS **40 50 60 70 80 90 100 RANGE [°C]**

Temperature [°C]

		Temperature [°C]													
SECTOR NAME	**PROCESS**	**40**		**50**		**60**		**70**		**80**		**90**		**100**	**RANGE [°C]**
Fabricated metal products	Cleaning	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨				40 - 90
	Degreasing	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨		20 - 100
	Electroplating	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨			30 - 95
	Phosphating	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨			30 - 95
	Pickling	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨		10 - 100
	Purging	▨	▨	▨	▨	▨	▨								40 - 70
	Washing	▨	▨	▨	▨										30 - 60
	Chrome plating	▨	▨	▨	▨	▨	▨	▨							20 - 75
	Main treatment -Electrodeposition of Metal	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨				20 - 90
	Main treatment -Anodizing oxidation	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨			15 - 95
	Main treatment -Phosphatization	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨				35 - 90
	Main treatment -Chromatizing	▨	▨	▨	▨	▨	▨								20 - 70
	Post Processing -Painting	▨	▨	▨	▨	▨	▨	▨	▨						25 - 80
	Post Processing -Condense	▨	▨	▨	▨	▨	▨	▨	▨						25 - 80
	Post Processing -Rinsing	▨	▨	▨	▨	▨	▨								40 - 70
	Pre-treatment -Pickling	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨			20 - 98
	Pre-treatment -Electrolytic degreasing	▨	▨	▨	▨	▨	▨	▨	▨						25 - 80
	Pre-treatment -Hot / boil decreasing	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨		30 - 100
	Pre-treatment -Rinsing	▨	▨	▨	▨	▨	▨								40 - 70
Pre	Pre-treatment -Typical substrate surface treatment	▨	▨	▨	▨										25 - 60
	Cleaning the facility	▨	▨	▨	▨	▨	▨								30 - 70
	Galvanic	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨		20 - 100
	Chromating	▨	▨	▨	▨	▨	▨	▨	▨						20 - 80
	Chromatings	▨	▨	▨	▨	▨	▨	▨							20 - 75
Machinery & eq	Cleaning	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨				40 - 90
Motor vehicles,	Degreasing	▨	▨	▨											35 - 55
SECTOR NAME	**PROCESS**	**40**		**50**		**60**		**70**		**80**		**90**		**100**	**RANGE [°C]**
		Temperature [°C]													

Appendix B Specific water intake per bird

Table 41: Specific water intake (SWI) in litre per bird for fifteen (15) abattoirs. Source: WRC (2017)

Abattoir	Capacity [birds / year]	Actual annual consumption [kl]	Calculated SWI [l per bird]	SWI lower limit [l per bird]	SWI Upper limit [l per bird]
1	105 534 000	1 383 200	13.1	13	14
2	70 200 000	1 133 863	16.2	11	12
3	85 800 000	1 135 541	13.2	10	11
4	39 000 000	427 897	11.0	10	11
5	23 660 000	370 000	15.6	12	13
6	28 080 000	411 720	14.7	11	12
7	25 480 000	312 704	12.3	10	11
8	14 300 000	182 000	12.7	12	13
9	49 400 000	Not given		13	14
10	1 820 000	616 000	338.5	9	10
11	78 000	Not given		15	16
12	33 800 000	349 200	10.3	>16	
13	104 000	520	5.0	>16	
14	78 000	520	6.7	>16	
15	83 200 000	1 104 000	13.3	13	14
Grand Total	**560 534 000**	7 427 165			
Average	37 368 933	571 320	**13.0**		
Uncertainty			**2.4**		

Appendix C Detail EES code of the system

```
"-------------------------------------------------------------------------------------------------------------------------"
"| PROGRAM TO DETERMINE THE IMPACT OF HEAT PUMP ON THE                                                                   |"
"| CHICKEN SLAUGHTERING INDUSTRY IN SOUTH-AFRICA                                                                         |"
"|                                                                                                                       |"
"|  WRITTEN BY WH KAISER                                                                                                 |"
"-------------------------------------------------------------------------------------------------------------------------"


"-------------------INPUT VALUES AND CALCULATIONS-------------------"
"-------------------------------------------------------------------------------------------"

"---------------GENERAL LOOKUP VALUES---------------"

"----------INPUTS WHEN NOT PARAMETRIC TABLE----------"

$IFNOT PARAMETRICTABLE

   ZONE$ = 'ZONE_01'
   Pr_fr = 1
   Pr_type$ = 'Full_production'                " Production type to full production "
   Day_year# = 1
   Town$ = 'Various'
   Abattoir$ = 'Generic'
   Site# = 1
   Month# = 1
   Weekday$ = 'Mon'


{
   ZONE$ = 'ZONE_01'
   Pr_fr = 0.5
   Pr_type$ = 'Half_production'                " Production type to half production "
   Day_year# = 1
   Town$ = 'Various'
   Abattoir$ = 'Generic'
   Month# = 1
   Weekday$ = 'Sat'
   Day_month# = 1
}
{
   ZONE$ = 'ZONE_01'
   Pr_fr = 0
   Pr_type$ = 'No_production'                  " Production type to no production "
   Day_year# = 1
   Town$ = 'Various'
   Abattoir$ = 'Generic'
   Month# = 1
   Weekday$ = 'Sun'
   Day_month# = 1
}
$ENDIF
```

```
"----------INPUTS WHEN PARAMETRIC TABLE----------"
{
$IF PARAMETRICTABLE " Used in the calculatoin if the Zone 01 - 06 values "

    ZONE$ = TABLENAME$
    // ZONE$ = 'ZONE_01'
    Day_year# = TABLERUN#
    Pr_fr = LOOKUP ('Production_schedule', Day_year#, 'Production_fr')
    Pr_type$ = LOOKUP$ ('Production_schedule', Day_year#, 'Pr_type')   " Production type lookup "
    Month# = LOOKUP ('Production_schedule', Day_year#, 'Month')
   Day_month# = LOOKUP ('Production_schedule', Day_year#, 'Day_month')
    Weekday$ = LOOKUP$ ('Production_schedule', Day_year#, 'Weekday')

$ENDIF
}
"----------INPUTS WHEN PARAMETRIC TABLE----------"

$IF PARAMETRICTABLE " Used in the calculatoin for the national impact "

    // ZONE$ = Value in table
    // Day_year# = Value in table
    Pr_fr = LOOKUP ('Production_schedule', Day_year#, 'Production_fr')
    Pr_type$ = LOOKUP$ ('Production_schedule', Day_year#, 'Pr_type')   " Production type lookup "
    Month# = LOOKUP ('Production_schedule', Day_year#, 'Month')
   Day_month# = LOOKUP ('Production_schedule', Day_year#, 'Day_month')
    Weekday$ = LOOKUP$ ('Production_schedule', Day_year#, 'Weekday')

$ENDIF


"---------------PLANT INPUTS---------------"

"----------AMBIENT CONDITIONS----------"

$IFNOT PARAMETRICTABLE

    T_db = 16 [°C]
    T_wb = 12 [°C]
    P_atm = 101.325 [kPa]

$ENDIF


$IF PARAMETRICTABLE

    T_db = INTERPOLATE1 ( ZONE$, T_db, Day_year#, Day_year# = Day_year# ) " Drybulb
temperature "
    T_wb = INTERPOLATE1 ( ZONE$, T_wb, Day_year#, Day_year# = Day_year# ) " Wetbulb
temperature "
    P_atm_hPa = INTERPOLATE1 ( ZONE$, P_atm, Day_year#, Day_year# = Day_year# ) "
Atmospheric pressure "

$ENDIF


P_atm = P_atm_hPa * CONVERT ( hPa, kPa)

h_atm = ENTHALPY ( AirH2O, P = P_atm, T = T_db, B = T_wb ) " Determine the enthalpy of the
atmosphere "
```

```
"----------CONVERSION---------- "

 T_db_K = CONVERTTEMP (C, K, T_db )

 T_wb_K = CONVERTTEMP (C, K, T_wb )


 "----------WATER USED PER BIRD IN THE ABATTOIR----------"

SWI_l\bird = 13 [l/bird]                    " Water used per bird "

SWI_l\bird_UNCT = 2.4 [l/birds]             " Water used per bird uncertainty "

HW_% = 21.9 [%]                             " Percentage hot water per animal "

f_SHW = 0.5                                 " Fraction of water used of ablution for showers "

f_SHW_UNCT = 0.1                            " Fraction of water used of ablution for showers
uncertainty "

"### -FIND NUMBER OF HP CALCULATIONS "

"----------NUMBER OF BIRDS PER MINUTE----------"

$IFNOT PARAMETRICTABLE
Birds\min = 100 [birds/min]                 " Birds per minute that are processed -Comment if
number of birds need be calculated ito HP"

// Birds\min = 206 [birds/min]              " Birds per minute that are processed -Comment if
number of birds need be calculated ito HP"

$ENDIF

Birds\s = Birds\min / CONVERT ( min, s )    " Birds per second "


 "----------FEED WATER----------"

p_FW = 300 [kPa]                            " Feed water pressure "


T_FW = 10 [°C]                              " Feed water temperature "
T_FW_UNCT = 5 [°C]                          " Feed water temperature uncertainty "

"----------PROPERTIES OF WATER----------"

c_P_FW = Cp ( Water, T=T_fw , P = P_fw )

rho_fw = DENSITY ( Water, T=T_fw , P = P_fw )

rho_HP_65_HW = DENSITY ( Water, T = T_HP_65_HW , P = P_fw )

rho_HP_90_HW = DENSITY ( Water, T = T_HP_90_HW , P = P_fw )
```

```
"----------MASS FLOW FOR THE VARIOUS PROCESSES----------"

"-----MASS FLOW OF SCALDING-----"

m_dot_SC = rho_fw * Q_dot_vol_SC                " Hot water for scalding "

Q_dot_vol_SC = l\bird_SC * CONVERT ( l , m^3) * Birds\s                          "
Volume flow for scalding "
l\bird_SC = LOOKUP ('# POULTRY -SWI', 2, 'PROCESS')
l\bird_SC_UNCT = LOOKUP ('# POULTRY -SWI', 2, 'PROCESS_UNCT')


"-----MASS FLOW OF FLOOR WASHING AND EQUIPMENT-----"

m_dot_FE = rho_fw * Q_dot_vol_FE                " Mass flow for floor washing and Equipment "

Q_dot_vol_FE = l\bird_FE * CONVERT ( l , m^3) * Birds\s                          "
Volume flow for floor washing and Equipment "
l\bird_FE = LOOKUP ('# POULTRY -SWI', 7, 'PROCESS')
l\bird_FE_UNCT = LOOKUP ('# POULTRY -SWI', 7, 'PROCESS_UNCT')


"-----MASS FLOW OF SHOWERING AND HAND WASH BASINS-----"

m_dot_SH = rho_fw * Q_dot_vol_SH                " Mass flow for showering "

Q_dot_vol_SH = l\bird_SH * CONVERT ( l , m^3) * Birds\s * f_SHW " Volume flow for showering "
l\bird_SH = LOOKUP ('# POULTRY -SWI', 11, 'PROCESS')
l\bird_SH_UNCT = LOOKUP ('# POULTRY -SWI', 11, 'PROCESS_UNCT')


 "-----MASS FLOW OF STERILZATION-----"

m_dot_ST = rho_fw * Q_dot_vol_ST

Q_dot_vol_ST = l\bird_ST * CONVERT ( l , m^3) * Birds\s
l\bird_ST = LOOKUP ('# POULTRY -SWI', 8, 'PROCESS')
l\bird_ST_UNCT = LOOKUP ('# POULTRY -SWI', 8, 'PROCESS_UNCT')

"-----MASS FLOW OF CHILLED WATER-----"

m_dot_CW = rho_fw * Q_dot_vol_CW

Q_dot_vol_CW = l\bird_CW * CONVERT ( l , m^3) * Birds\s
l\bird_CW = LOOKUP ('# POULTRY -SWI', 4, 'PROCESS')
l\bird_CW_UNCT = LOOKUP ('# POULTRY -SWI', 4, 'PROCESS_UNCT')


"----------NUMBER OF HP----------"

"-----NUMBER OF HOURS CW WORKS AT TEMP-----"

HP_CW_90_SP_hrs\day = 0

// HP_CW_65_SP_hrs\day = 0
```

```
"-----COMMENT IF NUMBER OF HEAT PUMPS NEED TO BE DETERMINED-----"

$IFNOT PARAMETRICTABLE

N_HP = 20 [-]                                  " Comment if number of birds need to be determined
or number of HP "

// N_HP = 1 [-]                                " Uncomment if number of birds need to be
determined per HP "

$ENDIF

"-----UNCOMMENT IF NUMBER OF HEAT PUMPS NEED TO BE DETERMINED-----"

// HP_SP_hrs\day = HP_DM_hrs\day

"----------PROCESS TEMPERATURES IN THE POULTRY PLANT----------"

T_SC = 50 [°C]                                 " Scalding water temperature (Soft scalding) "

T_FE = 42 [°C]                                 " Floor and Equipment washing water temperature "

T_SH = 65 [°C]                                 " Shower washing water temperature "

T_ST = 82 [°C]                                 " Sterilization water temperature "

T_CW = 4 [°C]                                  " Chilled water temperature "


"----------OPERATIONAL TIMES & DATA FOR PLANT----------"


"-----TOTAL HOURS PER DAY-----"

TL_hrs\day = 24 [hr/day]                       " Total hours per day "

"-----PLANT OPERATIONAL TIMES-----"


OP_DM_hrs\day = LOOKUP ( 'Operational times', 1, Pr_type$)  " Operational time (Slaughter hours
per day)"

OP_DM_hrs\day_FR = OP_DM_hrs\day / TL_hrs\day                                          "
Operational time fraction per day "

"-----CHILLED WATER SYSTEM-----"

CW_DM_hrs\day = LOOKUP ( 'Operational times', 3, Pr_type$)

CW_DM_hrs\day_FR = CW_DM_hrs\day / TL_hrs\day                                          "
Chilled water fraction per day "
```

```
"-----STEAM BOILER SYSTEM-----"

SB_hrs\day = LOOKUP ( 'Operational times', 2, Pr_type$)

SB_hrs\day_FR = SB_hrs\day / TL_hrs\day        " Steam boiler fraction per day "


"-----ELECTRIC BOILER SYSTEM-----"

EB_hrs\day = SB_hrs\day                         " Assume electric boiler is operated the hours as
steam boiler "

EB_hrs\day_FR = SB_hrs\day_FR                   " Assume electric boiler is operated the hours as
steam boiler "



"-----AMMONIA CHILLER SYSTEM-----"

AC_hrs\day = LOOKUP ( 'Operational times', 4, Pr_type$)

AC_hrs\day_FR = AC_hrs\day / TL_hrs\day         " Ammonia fraction per day "


"-----MAXIMUM HP RUN TIME-----"

HP_DM_hrs\day = 24 [hr/day]  " Operational time (Slaughter hours per day)"

HP_DM_hrs\day_FR = HP_DM_hrs\day / TL_hrs\day                                        "
Operational time fraction per day "


{
$IFNOT PARAMETRICTABLE
   T_fw = 10 [°C]                               " Feed water temperature "
$ENDIF


$IF PARAMETRICTABLE
   T_fw = INTERPOLATE1 ( T_fw, ZONE$ , MONTH, MONTH = Month# )      " Feed water
temperature based on monthly values"
$ENDIF
 }

T_fw_K = CONVERTTEMP ( C, K ,T_fw )


"----------AMMONIA CHILLED WATER SYSTEM DATA----------"

EER_AC = EER_AC_MULT * ( 0.0004 [1/kW] * Q_dot_AC + 2.502 )   " Comment this when
Q_dot_AC is not know "

EER_AC_MULT = 1

EER_AC_MULT_UNCT = 0.04                         " Uncertainty of the EER (COP) of the chiller "


"---------------HEAT PUMP DATA----------"
```

```
"-----OPERATING TEMPERATURES FOR THE HEAT PUMP-----"

T_HP_90_HW = 90 [°C]                    " Hot water outlet temperature: From data sheet of
supplier "

T_HP_65_HW = 65 [°C]                    " Hot water outlet temperature: From data sheet of
supplier "

T_HP_CW = 15 [°C]                       " Chilled water outlet temperature: From data sheet
of supplier -Use for verificaiton purposes"

T_HP_WW_65_CW = T_FW                    " Assume the inlet water temperature for the HP is
the feed water temperature "

T_HP_WW_90_CW = T_FW                    " Assume the inlet water temperature for the HP is
the feed water temperature "


"-----INPUT PROPERTIES FOR THE CURVE FITS-----"

T_HP_CW_K = CONVERTTEMP ( C, K ,T_HP_CW )

T_HP_WW_65_CW_K = CONVERTTEMP ( C, K ,T_HP_WW_65_CW )

T_HP_WW_90_CW_K = CONVERTTEMP ( C, K ,T_HP_WW_65_CW )

DELTAT_90_HW = T_HP_90_HW - T_FW

DELTAT_65_HW = T_HP_65_HW - T_FW



"-----INPUT PROPERTIES FOR THE CHILLED WATER SIDE OF THE HP-----"

BRINE$ = 'PG'                           " Brine used in heat pump (Propylene Glycol-Water)"

CTRN = 50 [%]                           " Brine Concentration "

DELTAT_HP_CW = -5 [°C]                  " Delta T between inlet and outlet of chiller water part
-From data sheet "


"-----HEAT PUMP COP. Q_h, Q_c AND MASS FLOW COEFFICIENTS-----"

Duplicate i = 1, 6
   C_Q_c_65[i] = lookup('Q_HP', i, 1 )  " Q cooling for WW at 65°C"
   C_Q_c_90[i] = lookup('Q_HP', i, 3 )  " Q cooling for WW at 90°C"

   C_WW_65_C[i] = lookup('COP', i, 1 )  " COP cooling for WW at 65°C"
   C_WW_65_H[i] = lookup('COP', i, 2 )  " COP heating for WW at 65°C"
   C_WW_90_C[i] = lookup('COP', i, 3 )  " COP cooling for WW at 90°C"
   C_WW_90_H[i] = lookup('COP', i, 4 )  " COP heating for WW at 90°C"
   C_AW[i] = lookup('COP', i, 5 )

   C_m_65_C[i] = lookup('HP_m_dot', i, 1 )
   C_m_65_H[i] = lookup('HP_m_dot', i, 2 )   " Mass flow"
```

```
    C_m_90_C[i] = lookup('HP_m_dot', i, 3 )
    C_m_90_H[i] = lookup('HP_m_dot', i, 4 )
    C_m_hw[i] = lookup('HP_m_dot', i , 5)

End

"-----HEAT PUMP UNCERTAINTIES FOR THE CURVE FIT-----"

Q_C_MULT = 1

Q_C_MULT_UNCT = 0.033


COP_HW_MULT = 1

COP_HW_MULT_UNCT = 0.028


m_BCW_MULT = 1

m_BCW_MULT_UNCT = 0.032


m_HW_MULT = 1

m_HW_MULT_UNCT = 0.025



"-----DETERMINE Q_C OF THE HEAT PUMP-----"

Q_c_65_CW\HP = Q_C_MULT * ( C_Q_c_65[1] + C_Q_c_65[2] * T_HP_WW_65_CW_K +
C_Q_c_65[3] * DELTAT_65_HW + C_Q_c_65[4] * T_HP_WW_65_CW_K * DELTAT_65_HW +
C_Q_c_65[5] * T_HP_WW_65_CW_K^2 + C_Q_c_65[6] * DELTAT_65_HW^2 )

Q_c_90_CW\HP  = Q_C_MULT * ( C_Q_c_90[1] + C_Q_c_90[2] * T_HP_WW_90_CW_K +
C_Q_c_90[3] * DELTAT_90_HW + C_Q_c_90[4] * T_HP_WW_90_CW_K * DELTAT_90_HW +
C_Q_c_90[5] * T_HP_WW_90_CW_K^2 + C_Q_c_90[6] * DELTAT_90_HW^2 )


"-----DETERMINE COP OF THE HEAT PUMP-----"

COP_WW_65  = COP_HW_MULT * ( C_WW_65_H[1] + C_WW_65_H[2] * T_HP_WW_65_CW_K +
C_WW_65_H[3] * DELTAT_65_HW + C_WW_65_H[4] * T_HP_WW_65_CW_K * DELTAT_65_HW +
C_WW_65_H[5] * T_HP_WW_65_CW_K^2 + C_WW_65_H[6] * DELTAT_65_HW^2 )

COP_AW_65  = COP_HW_MULT * ( C_AW[1] + C_AW[2] * h_atm + C_AW[3] * DELTAT_65_HW +
C_AW[4] * h_atm * DELTAT_65_HW + C_AW[5] * h_atm^2 + C_AW[6] * DELTAT_65_HW^2 )

COP_WW_90 = COP_HW_MULT * ( C_WW_90_H[1] + C_WW_90_H[2] * T_HP_WW_90_CW_K +
C_WW_90_H[3] * DELTAT_90_HW + C_WW_90_H[4] * T_HP_WW_90_CW_K * DELTAT_90_HW +
C_WW_90_H[5] * T_HP_WW_90_CW_K^2 + C_WW_90_H[6] * DELTAT_90_HW^2 )

COP_AW_90 = COP_HW_MULT * ( C_AW[1] + C_AW[2] * h_atm + C_AW[3] * DELTAT_90_HW +
C_AW[4] * h_atm * DELTAT_90_HW + C_AW[5] * h_atm^2 + C_AW[6] * DELTAT_90_HW^2 )
```

```
"----------DETERMINE MASS FLOW OF THE HEAT PUMP----------"

"-----COMMENT IF NUMBER OF HEAT PUMPS NEED TO BE DETERMINED-----"

"### -FIND NUMBER OF HP CALCULATIONS "

m_dot_HP_CW_65_SP\HP = m_BCW_MULT * ( C_m_65_C[1] + C_m_65_C[2] *
T_HP_WW_65_CW_K + C_m_65_C[3] * DELTAT_65_HW + C_m_65_C[4] * T_HP_WW_65_CW_K *
DELTAT_65_HW + C_m_65_C[5] * T_HP_WW_65_CW_K^2 + C_m_65_C[6] * DELTAT_65_HW^2 )

m_dot_HP_CW_90_SP\HP = m_BCW_MULT * ( C_m_90_C[1] + C_m_90_C[2] *
T_HP_WW_90_CW_K + C_m_90_C[3] * DELTAT_90_HW + C_m_90_C[4] * T_HP_WW_90_CW_K *
DELTAT_90_HW + C_m_90_C[5] * T_HP_WW_90_CW_K^2 + C_m_90_C[6] * DELTAT_90_HW^2 )


m_dot_HP_WW_65_SP\HP = m_HW_MULT * ( C_m_65_H[1] + C_m_65_H[2] *
T_HP_WW_65_CW_K + C_m_65_H[3] * DELTAT_65_HW + C_m_65_H[4] * T_HP_WW_65_CW_K *
DELTAT_65_HW + C_m_65_H[5] * T_HP_WW_65_CW_K^2 + C_m_65_H[6] * DELTAT_65_HW^2 )

m_dot_HP_AW_65_SP\HP = C_m_hw[1] + C_m_hw[2] * h_atm + C_m_hw[3] * DELTAT_65_HW +
C_m_hw[4] * h_atm * DELTAT_65_HW + C_m_hw[5] * h_atm^2 + C_m_hw[6] * DELTAT_65_HW^2


m_dot_HP_WW_90_SP\HP = m_HW_MULT * (C_m_90_H[1] + C_m_90_H[2] *
T_HP_WW_90_CW_K + C_m_90_H[3] * DELTAT_90_HW + C_m_90_H[4] * T_HP_WW_90_CW_K *
DELTAT_90_HW + C_m_90_H[5] * T_HP_WW_90_CW_K^2 + C_m_90_H[6] * DELTAT_90_HW^2 )

m_dot_HP_AW_90_SP\HP = C_m_hw[1] + C_m_hw[2] * h_atm + C_m_hw[3] * DELTAT_90_HW +
C_m_hw[4] * h_atm * DELTAT_90_HW + C_m_hw[5] * h_atm^2 + C_m_hw[6] * DELTAT_90_HW^2


"-----MINIMUM MASS FLOWS FOR THE HP TO DETERMINE NUMBER OF HEAT PUMPS-----"

{
"-----UNCOMMENT IF NUMBER OF HEAT PUMPS NEED TO BE DETERMINED-----"


m_dot_HP_CW_65_SP\HP = 2.04 [kg/s]

m_dot_HP_CW_90_SP\HP = 2.00 [kg/s]

m_dot_HP_AW_90_SP\HP = 0.14 [kg/s]

m_dot_HP_WW_65_SP\HP = 0.21 [kg/s]

m_dot_HP_AW_65_SP\HP = 0.22 [kg/s]

m_dot_HP_WW_90_SP\HP = 0.13 [kg/s]
}


 "-----DETERMINE HOW MUCH THE HEAT PUMP CAN SUPPLY PER HOUR-----"

Q_c_65_CW_SP = Q_c_65_CW\HP * N_HP

Q_c_65_CW_SP\hr = Q_c_65_CW_SP * 1 [hr]
```

```
 "-----DETERMINE THE MASS FLOW PER HOUR-----"

m_dot_HP_CW_65_SP\HP_ton\hr = m_dot_HP_CW_65_SP\HP * CONVERT (kg/s, tonne/hr)

m_dot_HP_CW_90_SP\HP_ton\hr = m_dot_HP_CW_90_SP\HP * CONVERT (kg/s, tonne/hr)

m_dot_HP_WW_65_SP\HP_ton\hr = m_dot_HP_WW_65_SP\HP * CONVERT (kg/s, tonne/hr)

m_dot_HP_AW_65_SP\HP_ton\hr = m_dot_HP_AW_65_SP\HP * CONVERT (kg/s, tonne/hr)

m_dot_HP_WW_90_SP\HP_ton\hr = m_dot_HP_WW_90_SP\HP * CONVERT (kg/s, tonne/hr)

m_dot_HP_AW_90_SP\HP_ton\hr = m_dot_HP_AW_90_SP\HP * CONVERT (kg/s, tonne/hr)


"----------TANK SIZES----------"

VOL_TANK\HP_CW_DSN = 30 [tonne]

VOL_TANK\HP_65_DSN = 60 [tonne]

VOL_TANK\HP_90_DSN = 4 [tonne]

m_Tank = VOL_TANK\HP_CW_DSN * CONVERT ( tonne, kg )


 "---------------ELEMENT ASSUMPTIONS---------------"

"----------PIPE DATA----------"

alpha_pipe = 0.0 [-]                              " Percentage in pressure drop for a pipe "
Q_dot_pipe = 0 [kW]                               " Heat loss for a pipe "
DELTAT_pipe = -2 [°C]

"----------STEAM BOILER DATA----------"

Q_Loss_SB = 0 [kW]                                " Heat loss for steam boilers "
alpha_SB = 0.9 [-]                                " Percentage in pressure drop for a steam boilers "


"----------HEAT EXCHANGER DATA----------"

epsilon_HX = 0.9                                  " Effectiveness of the heat exchanger "


"----------CALORIFIER DATA----------"

Q_Loss_CAL = 0 [kW]                               " Heat loss for calorifier "

alpha_CAL = 0 [-]                                 " Percentage in pressure drop for a calorifier "

epsilon_CAL = epsilon_HX                          " Effectiveness of the calorifier "
```

```
"----------MIXING VALVE DATA----------"

alpha_MXV = 0 [-]
Q_Loss_MXV = 0 [kW]                " Heat loss for mixing valve "
Q_dot_MXV = 0 [kW]


"----------MIXING VALVE DATA----------"
alpha_tank = 0 [-]
Q_Loss_tank = 0 [kW]               " Heat loss for mixing valve "
Q_dot_tank = 0 [kW]


"---------------SAFETY MARGINS AND BOUNDARY CONDITIONS---------------"

"----------SAFETY MARGIN OF STEAM BOILER, CHILLER ELECTRIC BOILER & HP SYSTEM----------"

SM_EQP = 10 [%]                    " Safety margin of steam system "

SM_EQP_UNCT = 5 [%]


 "----------STEAM BOILER SYSTEM----------"

p_0_SB = 900 [kPa]                 " Boiler absolute pressure operating conditions "
p_0_SB_UNCT = 50 [kPa]


"----------ELECTRIC BOILER SYSTEM----------"

T_EB_HTHW = 82 [°C]                " Hot water outlet temperature: Assumption "

T_EB_STHW = 65 [°C]                " Hot water outlet temperature: Assumption "

T_EB_STHW_UNCT = 5[°C]

"----------EFFIECIENCY OF ELECTRIC AND STEAM BOILER SYSTEMS----------"

eta_CSB = 77 [%]                   " Coal steam boiler efficiency"
eta_CSB_UNCT = 13 [%]              " Coal steam boiler efficiency uncertainty"

eta_PRF = 73 [%]                   " Paraffin steam boiler efficiency"
eta_PRF_UNCT = 7 [%]               " Paraffin steam boiler efficiency uncertainty "

eta_LPG = 77 [%]                   " LPG steam boiler efficiency"
eta_LPG_UNCT = 13 [%]              " LPG steam boiler efficiency uncertainty"

eta_EB = 88 [%]                    " Electric boiler efficiency"
eta_EB_UNCT = 12 [%]               " Electric boiler efficiency uncertainty"
```

```
"---------------ECONOMIC INPUTS---------------"

"----------CARBON TAX----------"


CO2_TAX_R\ton = 120 [#R/tonne]

CO2_TAX_R\kg = CO2_TAX_R\ton * CONVERT ( kg, tonne )

"----------COST OF STEAM BOILER SYSTEM----------"

Coal_R\ton = 510.12 [#R/tonne]
Coal_R\ton_UNCT = 19.26 [#R/tonne]

LPG_R\kg = 29.00 [#R/kg]
LPG_R\kg_UNCT = 1.31 [#R/kg]

PRF_R\lit = 10.59 [#R/l]
PRF_R\lit_UNCT = 0.55 [#R/l]


"----------ELECTRIC COST----------"

ENERGY_COST_kWh_18\19 = 1.32 [#R/kWh]   " Business rate Energy charge, Ancillary service &
network demand charge for 2018-2019 "

ENERGY_COST_kWh_19\20 = 1.56 [#R/kWh]   " Business rate Energy charge, Ancillary service &
network demand charge for 2019-2020 "

ENERGY_COST_kWh = IF ( Month# , 6 , ENERGY_COST_kWh_18\19,
ENERGY_COST_kWh_19\20, ENERGY_COST_kWh_19\20 )


"---------------ENERGY INPUTS---------------"

"----------CALORIFIC VALUE OF FUELS----------"

CV_CSB_MJ = 25.42 [MJ/kg]
CV_CSB_MJ_UNCT = 2.69 [MJ/kg]

CV_LPG_MJ = 48.21 [MJ/kg]
CV_LPG_MJ_UNCT = 2.48 [MJ/kg]


CV_PRF_MJ\kg = 43.43 [MJ/kg]
CV_PRF_MJ\kg_UNCT = 5.12 [MJ/kg]

CV_PRF_MJ\l = 35.2 [MJ/l]
CV_PRF_MJ\l_UNCT = 2.0 [MJ/l]

CV_COAL_ESC_MJ = 19.78 [MJ/kg]
CV_COAL_ESC_MJ_UNCT = 0.16 [MJ/kg]


CV_ELEC_MJ = 3.6 [MJ/kWh]
```

```
"---------------ENVIRONMENTAL INPUTS---------------"

"----------DENSITY OF FUELS----------"

rho_PRF = 813 [kg/m^3]


"----------ESKOM COAL ENVIRONMENTAL IMPACT----------"

CO2_kg\TJ_ESC = 96100 [kg/TJ]
CO2_kg\TJ_ESC_UNCT = 2493 [kg/TJ]

CH4_kg\TJ_ESC = 1.00 [kg/TJ]
CH4_kg\TJ_ESC_UNCT = 0.70 [kg/TJ]

N2O_kg\TJ_ESC = 1.50 [kg/TJ]
N2O_kg\TJ_ESC_UNCT = 1.00 [kg/TJ]


"----------COAL BOILER ENVIRONMENTAL IMPACT----------"

CO2_kg\TJ_CSB = 94600 [kg/TJ]
CO2_kg\TJ_CSB_UNCT = 4164 [kg/TJ]

CH4_kg\TJ_CSB = 1.00 [kg/TJ]
CH4_kg\TJ_CSB_UNCT = 0.70 [kg/TJ]

N2O_kg\TJ_CSB = 1.50 [kg/TJ]
N2O_kg\TJ_CSB_UNCT = 1.00 [kg/TJ]


"----------LPG BOILER ENVIRONMENTAL IMPACT----------"

CO2_kg\TJ_LPG = 63100 [kg/TJ]
CO2_kg\TJ_LPG_UNCT = 1500 [kg/TJ]

CH4_kg\TJ_LPG = 1.00 [kg/TJ]
CH4_kg\TJ_LPG_UNCT = 0.70 [kg/TJ]

N2O_kg\TJ_LPG = 0.10 [kg/TJ]
N2O_kg\TJ_LPG_UNCT = 0.07 [kg/TJ]


"----------PARAFFIN BOILER ENVIRONMENTAL IMPACT----------"

CO2_kg\TJ_PRF = 71900 [kg/TJ]
CO2_kg\TJ_PRF_UNCT = 1100 [kg/TJ]

CH4_kg\TJ_PRF = 3.00 [kg/TJ]
CH4_kg\TJ_PRF_UNCT = 2.00 [kg/TJ]

N2O_kg\TJ_PRF = 0.60 [kg/TJ]
N2O_kg\TJ_PRF_UNCT = 0.40 [kg/TJ]
```

```
"----------ELECTRIC ENVIRONMENTAL IMPACT----------"

CO2_kg\kWh = 0.97 [kg/kWh]
CO2_kg\kWh_UNCT = 0.03 [kg/kWh]

NOx_g\kWh = 4.04 [g/kWh]
NOx_g\kWh_UNCT = 0.1 [g/kWh]

SOx_g\kWh = 8.10 [g/kWh]
SOx_g\kWh_UNCT = 0.26 [g/kWh]

Particle_g\kWh = 0.32 [g/kWh]
Particle_g\kWh_UNCT = 0.04 [g/kWh]

Coal_kg\kWh = 0.523 [kg/kWh]
Coal_kg\kWh_UNCT = 0.005 [kg/kWh]

Water_l\kWh = 1.38 [l/kWh]
Water_l\kWh_UNCT = 0.05 [l/kWh]

Ash_g\kWh = 148.45 [g/kWh]
Ash_g\kWh_UNCT = 3.33 [g/kWh]

N2O_g\kWh = 0.0124 [g/kWh]
N2O_g\kWh_UNCT = 0.0004 [g/kWh]


"-----ELECTRIC ENVIRONMENTAL IMPACT (USED TO VALIDATE ESKOM VALUES)-----"

CO2_CPS_kg\kWh = 1.04 [kg/kWh]

Coal_CPS_kg\kWh = 0.573 [kg/kWh]

N2O_CPS_g\kWh = 0.0124 [g/kWh]


"-----COMPARE VALUES WITH THAT OF ESKOM POWER STATION FOR COAL-----"

ELEC_CPS_Coal\kWh = 1 [kWh] * Coal_CPS_kg\kWh

ELEC_Coal\kWh = 1 [kWh] * Coal_kg\kWh


ESKOM_CO2_kg\kWh = 1 [kWh] * CO2_CPS_kg\kWh

EMM_CO2_kg\kWh = ELEC_Coal\kWh * ( CV_COAL_ESC_MJ * CONVERT ( MJ, TJ) ) *
CO2_kg\TJ_ESC

ELEC_CO2_DIFF = ESKOM_CO2_kg\kWh - EMM_CO2_kg\kWh

ELEC_CO2_DIFF% = ELEC_CO2_DIFF / ESKOM_CO2_kg\kWh * 100 [%]


ESKOM_N2O_g\kWh = 1 [kWh] * N2O_CPS_g\kWh

EMM_N2O_g\KWh = ELEC_CPS_Coal\kWh * ( CV_COAL_ESC_MJ * CONVERT ( MJ, TJ) ) *
N2O_kg\TJ_ESC * CONVERT ( kg, g )

ELEC_N2O_DIFF = ESKOM_N2O_g\kWh - EMM_N2O_g\KWh
```

```
ELEC_N2O_DIFF% = ELEC_N2O_DIFF / ESKOM_N2O_g\kWh * 100 [%]


EMM_N2O_g\KWh_CALC = ELEC_CPS_Coal\kWh * ( CV_COAL_ESC_MJ * CONVERT ( MJ, TJ) ) *
N2O_kg\TJ_ESC_CALC * CONVERT ( kg, g )

ELEC_N2O_DIFF_CALC = ESKOM_N2O_g\kWh - EMM_N2O_g\KWh_CALC

ELEC_N2O_DIFF_CALC = 0


"----------ELECTRIC ENVIRONMENTAL IMPACT (BASED ON COAL)----------"


 {
CONVERT_kWh_TJ = CONVERT ( kWh, TJ)


CH4_kg\kWh = CH4_kg\TJ_ESC * CONVERT ( kWh, TJ)

CH4_kg\kWh_UNCT = CH4_kg\TJ_ESC_UNCT * CONVERT ( kWh, TJ)


N2O_kg\kWh = N2O_kg\TJ_ESC * CONVERT ( kWh, TJ)

N2O_kg\kWh_UNCT = N2O_kg\TJ_ESC_UNCT * CONVERT ( kWh, TJ)
 }


"----------WATER USED PER BIRD----------"

SWI_m3 = SWI_l\bird * CONVERT ( l/bird , m^3/bird)                                   " Water
needed per bird "

Q_dot_vol_HW_l\bird = HW_% / 100 [%] * SWI_l\bird                                    " Hot
water volume per bird "

Q_dot_vol_HW_l\s = Q_dot_vol_HW_l\bird * birds\s                                     " Hot
water volume per second "

Q_dot_vol_HW = Q_dot_vol_HW_l\s * CONVERT ( l/s , m^3/s )  " Hot water volume "

"----------Other unit formats----------"

Q_dot_vol_HW_l\hr = Q_dot_vol_HW_l\s * CONVERT ( l/s , l/hr )

Q_dot_vol_HW_m3\hr = Q_dot_vol_HW_l\s * CONVERT ( l/s , m^3/hr )



"---------------TOTAL COST OF THE HP---------------"

COST\HP = 1495000 [#R]

TOTAL_HP_COST = N_HP * COST\HP

TOTAL_TANK_COST = 2092067 [#R]
```

```
TOTAL_EQUIPMENT_COST = 75515016 [#R]

TOTAL_INPUT_COST = ( TOTAL_EQUIPMENT_COST ) * ( 1 + 0.4 + 0.7 + 0.2 + 0.1 + 0.05)

"---------------ARAYS TABLE INPUTS -TRY FIX UNITS THAT MIX UP---------------"

"----------ARAY 1----------"
"-----Measurable values-----"
T_0[1] = 10 [°C]
h_0[1] = 10 [kJ/kg]
p_0[1] = 100 [kPa]
m_dot[1] = 10 [kg/s]

Q_dot_E[1] = 1 [kW]
Q_dot_max_E[1] = 1 [kW]

x_0[1] = 0.5 [-]

" DELTA "
DELTAT_0[1] = 10 [K]
DELTAT_E[1] = 10 [K]

DELTAp_0[1] = 10 [kPa]
DELTAp_E[1] = 10 [kPa]

"-----Component characteristics-----"
alpha_E[1] = 0.9 [-]
Epsilon[1] = 0.9 [-]
C_min_E[1] = 1 [kW/K]
C[1] = 1 [kW/K]


"----------ARAY 101----------"

"-----Measurable values-----"
T_0[101] = 10 [°C]
h_0[101] = 10 [kJ/kg]
p_0[101] = 100 [kPa]

m_dot[101] = 10 [kg/s]
Q_dot_E[101] = 1 [kW]
Q_dot_max_E[101] = 1 [kW]

x_0[101] = 0.5 [-]

"-----DELTA-----"
DELTAT_0[101] = 10 [K]
DELTAT_E[101] = 10 [K]

DELTAp_0[101] = 10 [kPa]
DELTAp_E[101] = 10 [kPa]

"-----Component characteristics-----"
alpha_E[101] = 0.9 [-]
Epsilon[101] = 0.9 [-]
C_min_E[101] = 1 [kW/K]
C[101] = 1 [kW/K]
```

```
"-------------------CALCULATIONS-------------------"
"-----------------------------------------------------------"


"--------------AMMONIA CHILLER--------------"
"-------------------------------------------------------"

"----------153 (Chilled water)----------"


"-----Boundary conditions-----"
T_0[153] = T_CW                             " Assume inlet is feedwater temp "
// p_0[153] = P_FW                          " Comment at Element 151 "
m_dot[153] = m_dot_CW
h_0[153] = Enthalpy ( Water, T = T_0[153] , p = p_0[153])


"----------E-152 (Pipe 152 from node 152-153)----------"

"-----Component characteristics-----"
alpha_E[152] = alpha_pipe
- DELTAp_E[152] = alpha_E[152] * average( p_0[153], p_0[152] )     " Pressure drop for a pipe "
// DELTAp_E[152] = 0 [kPa]
Q_dot_E[152] = Q_dot_pipe
// DELTAT_E[152] = DELTAT_pipe                " Temperature drop accros pipe "

"-----Conservation equations-----"
m_dot[152] = m_dot[153]                     " Conservation of mass "
DELTAp_E[152]= p_0[153] - p_0[152]          " Conservation of momentum "
Q_dot_E[152] = m_dot[152] * (h_0[153] - h_0[152])                              "
Conservation of energy "
DELTAT_E[152] = T_0[153] - T_0[152]

"-----Fluid properties-----"
T_0[152] = TEMPERATURE ( Water, h = h_0[152] , p = p_0[152])


"----------E-151 (Chiller @ 2°C)----------"

"-----Boundary conditions-----"
T_0[151] = T_FW                             " Assume inlet is feedwater "
p_0[151] = P_FW                             " Assume inlet is feedwater "


"-----Component characteristics-----"
DELTAp_E[151] = 0 [kPa]                     " Pressure drop for the chiller "


"-----Conservation equations-----"
m_dot[151] = m_dot[152]                     " Conservation of mass "
DELTAp_E[151] = p_0[152] - p_0[151]         " Conservation of momentum "
Q_dot_E[151] = m_dot[151] * (h_0[152] - h_0[151])                              "
Conservation of energy "

"-----Fluid properties-----"
T_0[151] = TEMPERATURE ( Water, h = h_0[151] , p = p_0[151])


"-----------------------STEAM BOILERS-----------------------"
```

```
"---------------------------------------------------------------------------"


"-------------------LOW TEMP HEAT EXCHANGER-------------------"

"---------------SCALDING--------------------"

"----------113 -SCALDING TANK----------"

"-----Boundary conditions-----"
m_dot[113] = m_dot_SC                         " Scalding mass flow "
T_0[113] = T_SC                               " Scalding temperature "
// p_0[113] = p_FW                            " Comment at Element 111 "
h_0[113] = enthalpy( Water, T = T_0[113] , p = p_0[113] )


"----------E-111 -FEEDWATER INLET-------------------"

"-----Boundary conditions-----"
// m_dot[111] = will be determined
T_0[111] = T_FW                               " Assume feed water temperature"
p_0[111] = p_FW                               " Assume feed water pressure "
h_0[111] = enthalpy( Water, T = T_0[111] , p = p_0[111] )
//x_0[111] = QUALITY( Water, T = T_0[111] , p = p_0[111] )


"----------E-112 (Pipe 112 from node 112-113)----------"

"-----Component characteristics-----"
alpha_E[112] = alpha_pipe
- DELTAp_E[112] = alpha_E[112] * average( p_0[113], p_0[112] )      " Pressure drop for a pipe "
Q_dot_E[112] = Q_dot_pipe                     " Heat transfer for a pipe "
// DELTAT_E[112] = DELTAT_pipe

"-----Conservation equations-----"
m_dot[112] = m_dot[113]                       " Conservation of mass "
DELTAp_E[112]= p_0[113] - p_0[112]            " Conservation of momentum "
Q_dot_E[112] = m_dot[112] * (h_0[113] - h_0[112])                                      "
Conservation of energy "
DELTAT_E[112] = T_0[113] - T_0[112]

"-----Fluid properties-----"
T_0[112] = TEMPERATURE ( Water, h = h_0[112] , p = p_0[112])
//x_0[112] = QUALITY( Water, T = T_0[112] , p = p_0[112] )


"----------E-111 (STEAM HX WATER(COLD) SIDE)----------"

"-----Component characteristics-----"
DELTAp_E[111] = 0 [kPa]                       " Pressure drop for the boiler "

"-----Conservation equations-----"
m_dot[111] = m_dot[112]                       " Conservation of mass "
DELTAp_E[111]= p_0[112] - p_0[111]            " Conservation of momentum "
Q_dot_E[111] = m_dot[111] * (h_0[112] - h_0[111])                                      "
Conservation of energy "

"-----Fluid properties-----"
```

```
 // T_0[111] = TEMPERATURE ( Water, h = h_0[111] , p = p_0[111])     "Already calculated "


"-----------------------------HIGH TEMP (87°C) CALORIFIER BOILER-----------------------------"


"-----------------------------STERILIZATION-----------------------------"

"----------143 (Sterilization boundary)----------"


"-----Boundary conditions-----"
m_dot[143] = m_dot_ST                               " Shower and hand wash mass flow "
T_0[143] = T_ST                                     " Shower and hand wash temperature "
// p_0[143] = P_FW                                  " Comment at E 141 "
h_0[143] = enthalpy( Water, T = T_0[143], p = p_0[143] )


"----------E-142 (Pipe 142 from node 142-143)----------"

"-----Component characteristics-----"
alpha_E[142] = alpha_pipe
- DELTAp_E[142] = alpha_E[142] * average( p_0[143], p_0[142] )     " Pressure drop for a pipe "
Q_dot_E[142] = Q_dot_pipe                           " Heat transfer for a pipe "
// DELTAT_E[142] = DELTAT_pipe

"-----Conservation equations-----"
m_dot[142] = m_dot[143]                             " Conservation of mass "
DELTAp_E[142]= p_0[143] - p_0[142]                  " Conservation of momentum "
Q_dot_E[142] = m_dot[142] * (h_0[143] - h_0[142])                                            "
Conservation of energy "
DELTAT_E[142] = T_0[143] - T_0[142]

"-----Fluid properties-----"
T_0[142] = TEMPERATURE ( Water, h = h_0[142] , p = p_0[142])
// T_0[143] = TEMPERATURE ( Water, h = h_0[143] , p = p_0[143])


"----------E-141 (Steam calorifier @ 87°C)----------"

"-----Boundary conditions-----"
T_0[141] = T_FW                                     " Assume inlet is feedwater temp "
p_0[141] = P_FW                                     " Assume inlet is feedwater pressure "

"-----Component characteristics-----"
alpha_E[141] = alpha_CAL
- DELTAp_E[141] = alpha_E[141] * average( p_0[142], p_0[141] )     " Pressure drop for a calorifier "


"-----Conservation equations-----"
m_dot[141] = m_dot[142]                             " Conservation of mass "
DELTAp_E[141]= p_0[142] - p_0[141]                  " Conservation of momentum "
Q_dot_E[141] = m_dot[141] * (h_0[142] - h_0[141]) + Q_loss_CAL      " Conservation of energy "

"-----Fluid properties-----"
T_0[141] = TEMPERATURE ( Water, h = h_0[141] , p = p_0[141])
```

```
"-----------------------------FLOOR AND EQUIPMENT WASHING------------------------------"

 "----------E-126 -FEEDWATER INLET----------"

"-----Boundary conditions-----"
T_0[126] = T_FW                                " Water temperature is feed water temperature"
// p_0[126] = P_FW                             " Comment at E-125 "
h_0[126] = enthalpy( Water, T = T_0[126], p = p_0[126] )


"----------127 -FLOOR AND EQUIPMENT WASHING----------"

"-----Boundary conditions-----"
m_dot[127] = m_dot_FE                          " Floor and EQUIPMENT washing mass flow "
T_0[127] = T_FE                                " Floor and EQUIPMENT washing temperature "
// p_0[127] = P_FW                             " Comment at E-125"
h_0[127] = enthalpy( Water, T = T_0[127] , p = p_0[127] )



"----------E-125 -MIXING VALVE----------"

"-----Component characteristics-----"
// Q_dot_E[125] = Q_dot_MXV                    " Assume no heat loss over the mixing valve "
Q_dot_E[125] = 0 [kW]                          " Assume no heat loss over the mixing valve "
alpha_E[125] = alpha_MXV
// - DELTAp_E[125] = alpha_E[125] * average( p_0[127], p_0[125] )     " Pressure drop for a pipe "
DELTAp_E[125] = 0 [kPa]                        " Assume there is no pressure drop in the mixing
valve"


"-----Conservation equations-----"
m_dot[127] = m_dot[125] + m_dot[126]           " Conservation of mass"
DELTAp_E[125] = p_0[127] - p_0[125]            " Conservation of momentum "
p_0[125] = p_0[126]                            " Inlet pressures of mixing streams need to be the
same "
// Q_dot_E[125] = m_dot[127] * h_0[127] - m_dot[126] * h_0[126] - m_dot[125] * h_0[125]      "
Conservation of energy "
m_dot[127] * h_0[127] = m_dot[126] * h_0[126] + m_dot[125] * h_0[125]       " Conservation of energy
"


 "-----Fluid properties-----"
T_0[125] = TEMPERATURE ( Water, h = h_0[125] , p = p_0[125])


"-----------------------------SHOWERING AND HAND WASH BASINS------------------------------"

"----------131 -SHOWERING----------"

"--Boundary conditions--"
m_dot[132] = m_dot_SH                          " Shower and hand wash mass flow "
// p_0[132] = p_FW
T_0[132] = T_SH                                " Shower and hand wash temperature "
h_0[132] = enthalpy( Water, T = T_0[132] , p = p_0[132] )

"----------E-131 (Pipe 231 from node 231-232)----------"

"-----Component characteristics-----"
```

```
alpha_E[131] = alpha_pipe
- DELTAp_E[131] = alpha_E[131] * average( p_0[132], p_0[131] )      " Pressure drop for a pipe "
// DELTAp_E[131] = 0 [kPa]
// Q_dot_E[131] = Q_dot_pipe                          " Heat transfer for a pipe "
DELTAT_E[131] = 0 [K]

"-----Component characteristics-----"
m_dot[131] = m_dot[132]                               " Conservation of mass "
DELTAp_E[131]= p_0[132] - p_0[131]                    " Conservation of momentum "
Q_dot_E[131] = m_dot[131] * (h_0[132] - h_0[131])                                           "
Conservation of energy "
DELTAT_E[131] = T_0[132] - T_0[131]

"-----Fluid properties-----"
T_0[131] = TEMPERATURE ( Water, h = h_0[131] , p = p_0[131])


"-------------------Linking nodes 124 with 131----------"
T_0[124] = T_0[131]
p_0[124] = p_0[131]
h_0[124] = h_0[131]
m_dot[124] = m_dot[131]


"----------E-123 -T PIECE------------------"

"--Boundary conditions--"
T_0[123] = T_0[124]
T_0[123] = T_0[125]

"-----Component characteristics-----"
Q_dot_E[123] = 0 [kW]                                 " Assume no heat loss over the mixing valve "
DELTAp_E[123] = 0 [kPa]                               " Assume there is no pressure drop in the mixing
valve"


"-----Component characteristics-----"
m_dot[123] = m_dot[124] + m_dot[125]                  " Conservation of mass"
DELTAp_E[123] = p_0[123] - p_0[125]                   " Conservation of momentum "
p_0[126] = p_0[124]                                   " Conservation of momentum "
Q_dot_E[124] = m_dot[124] * h_0[124] + m_dot[123] * h_0[123] - m_dot[125] * h_0[125]      "
Conservation of energy "

 "-----Fluid properties-----"
T_0[123] = TEMPERATURE ( Water, h = h_0[123] , p = p_0[123])
// T_0[124] = TEMPERATURE ( Water, h = h_0[124] , p = p_0[124])

"----------E-122 (Pipe 122 from node 122-123)----------"

"-----Component characteristics-----"
alpha_E[122] = alpha_pipe
- DELTAp_E[122] = alpha_E[122] * average( p_0[123], p_0[122] )" Pressure drop for a pipe "
// DELTAp_E[122] = 0 [kPa]
Q_dot_E[122] = Q_dot_pipe                             " Heat transfer for a pipe "
// DELTAT_E[122] = DELTAT_pipe

"-----Component characteristics-----"
m_dot[122] = m_dot[123]                               " Conservation of mass "
DELTAp_E[122]= p_0[123] - p_0[122]                    " Conservation of momentum "
```

```
Q_dot_E[122] = m_dot[122] * (h_0[123] - h_0[122])                                    "
Conservation of energy "
DELTAT_E[122] = T_0[123] - T_0[122]

"-----Fluid properties-----"
T_0[122] = TEMPERATURE ( Water, h = h_0[122] , p = p_0[122])


"----------E-121 (Steam Calorifier @ 65°C -Water side)----------"

"----------- Boundary conditions -----------"
T_0[121] = T_FW                        " Assume inlet is feedwater temp "
p_0[121] = p_FW                        " Assume inelet is feedwater pressure "


"----------- Component characteristics -----------"
DELTAp_E[121] = 0 [kPa]                " Pressure drop for the boiler "

"-----Conservation equations-----"
m_dot[121] = m_dot[122]                " Conservation of mass "
DELTAp_E[121]= p_0[122] - p_0[121]     " Conservation of momentum "
Q_dot_E[121] = m_dot[121] * (h_0[122] - h_0[121])                                    "
Conservation of energy "

"-----Fluid properties-----"
T_0[121] = TEMPERATURE ( Water, h = h_0[121] , p = p_0[121])


"------------------- E-172 (HX171 from node 172-173) ----------"

"----------- Component characteristics -----------"
alpha_E[172] = 0 [-]
DELTAp_E[172] = 0 [kPa]
epsilon_E[172] = epsilon_HX
DELTAp_E[172] = p_0[173] - p_0[172]
p_0[172] = p_0_SB
Q_dot_E[172] = - Q_dot_E[111]


"-----Component characteristics-----"
x_0[172] = 1 [-]
h_0[172] = ENTHALPY ( Steam_IAPWS, x = x_0[172] ,p = p_0[172] )
T_0[172] = TEMPERATURE ( Steam_IAPWS, x = x_0[172] ,p = p_0[172] )


x_0[173] = 0 [-]
h_0[173] = ENTHALPY ( Steam_IAPWS, x = x_0[173] ,p = p_0[173] )
T_0[173] = TEMPERATURE ( Steam_IAPWS, x = x_0[173] ,p = p_0[173] )


 "-----Conservation equations-----"
{
C[111] = m_dot[111] * cp(Water, T = T_0[111], p = p_0[111])
C[172] = m_dot[172] * cp(Steam, T = T_0[172], p = p_0[172])

C_MIN_E[172] = min( C[111], C[172] )
Q_dot_max_E[172] = C_MIN_E[172] * ( T_0[172] - T_0[111] )
Q_dot_E[172] = epsilon_E[172] * Q_dot_max_E[272]                                      " Heat
transfer for a HX "
```

```
Q_dot_E[172] = m_dot[172] * ( h_0[173] - h_0[172] )

m_dot[172] = m_dot[173]

}

// Q_dot_E[172] = epsilon_E[172] * m_dot[172] * ( h_0[173] - h_0[172] )

Q_dot_E[172] = m_dot[172] * ( h_0[173] - h_0[172] )

DELTAh[172] = ( h_0[173] - h_0[172] )

DELTAh[111] = ( h_0[112] - h_0[111] )

m_dot[172] = m_dot[173]

"-----Fluid properties-----"


"----------E-171 (PIPE172 from node 171-172)----------"

"-----Component characteristics-----"
alpha_E[171] = alpha_pipe
- DELTAp_E[171] = alpha_E[171] * average( p_0[171], p_0[172] )      " Pressure drop for a pipe "
// DELTAp_E[171] = 0 [kPa]
Q_dot_E[171] = Q_dot_pipe                        " Heat transfer for a pipe "
// DELTAT_E[171] = DELTAT_pipe

"-----Conservation equations-----"
m_dot[171] = m_dot[172]                          " Conservation of mass "
DELTAp_E[171]= p_0[172] - p_0[171]               " Conservation of momentum "
Q_dot_E[171] = m_dot[202] * (h_0[172] - h_0[171])                                   "
Conservation of energy "
DELTAT_E[171] = T_0[203] - T_0[171]

"-----Fluid properties-----"
T_0[171] = TEMPERATURE ( Water, h = h_0[171] , p = p_0[171])


"----------E-192 (CALORIFIER192 from node 192-193)----------"

"-----Component characteristics-----"
alpha_E[192] = 0 [-]
DELTAp_E[192] = 0 [kPa]
epsilon_E[192] = epsilon_CAL
// - DELTAp_E[192] = alpha_E[192] * average( p_0[193], p_0[192] )      " Pressure drop for a pipe "
DELTAp_E[192] = p_0[193] - p_0[192]
p_0[192] = p_0_SB
Q_dot_E[192] = - Q_dot_E[121]

x_0[192] = 1 [-]
h_0[192] = ENTHALPY ( Steam_IAPWS, x = x_0[192] ,p = p_0[192] )

x_0[193] = 0 [-]
h_0[193] = ENTHALPY ( Steam_IAPWS, x = x_0[193] ,p = p_0[193] )

Q_dot_E[192] = m_dot[192] * ( h_0[193] - h_0[192] )
```

```
DELTAh_0[192] = ( h_0[193] - h_0[192] )

"-----Conservation equations-----"
m_dot[192] = m_dot[193]

"-----Fluid properties-----"
T_0[192] = TEMPERATURE ( Water, h = h_0[192] , p = p_0[192])
T_0[193] = TEMPERATURE ( Water, h = h_0[193] , p = p_0[193])


"----------E-191 (PIPE192 from node 191-192)----------"

"-----Component characteristics-----"
alpha_E[191] = alpha_pipe
- DELTAp_E[191] = alpha_E[191] * average( p_0[191], p_0[192] )      " Pressure drop for a pipe "
// DELTAp_E[191] = 0 [kPa]
Q_dot_E[191] = Q_dot_pipe                        " Heat transfer for a pipe "
// DELTAT_E[191] = DELTAT_pipe

"-----Conservation equations-----"
m_dot[191] = m_dot[192]                          " Conservation of mass "
DELTAp_E[191]= p_0[192] - p_0[191]               " Conservation of momentum "
Q_dot_E[191] = m_dot[202] * (h_0[192] - h_0[191])                                          "
Conservation of energy "
DELTAT_E[191] = T_0[203] - T_0[191]

"-----Fluid properties-----"
T_0[191] = TEMPERATURE ( Water, h = h_0[191] , p = p_0[191])


"----------E-196 (CAL196 from node 196-197)----------"

"-----Component characteristics-----"
alpha_E[196] = 0 [-]
DELTAp_E[196] = 0 [kPa]
epsilon_E[196] = epsilon_CAL
// - DELTAp_E[196] = alpha_E[196] * average( p_0[197], p_0[196] )     " Pressure drop for a calorifier "
DELTAp_E[196] = p_0[197] - p_0[196]
p_0[196] = p_0_SB
Q_dot_E[196] = - Q_dot_E[141]


x_0[196] = 1 [-]
h_0[196] = ENTHALPY ( Steam_IAPWS, x = x_0[196] ,p = p_0[196] )


x_0[197] = 0 [-]
h_0[197] = ENTHALPY ( Steam_IAPWS, x = x_0[197] ,p = p_0[197] )


Q_dot_E[196] = m_dot[196] * ( h_0[197] - h_0[196] )

"-----Component characteristics-----"
m_dot[196] = m_dot[197]                          " Conservation of mass "

"-----Fluid properties-----"
T_0[196] = TEMPERATURE ( Water, h = h_0[196] , p = p_0[196])
T_0[197] = TEMPERATURE ( Water, h = h_0[197] , p = p_0[197])
```

```
"----------E-195 (Pipe 195 from node 195-196)----------"

"-----Component characteristics-----"
alpha_E[195] = alpha_pipe
DELTAp_E[195] = alpha_E[195] * average( p_0[196], p_0[195] )" Pressure drop for a pipe "

Q_dot_E[195] = Q_dot_pipe                   " Heat transfer for a pipe "


"-----Component characteristics-----"
m_dot[195] = m_dot[196]                     " Conservation of mass "
DELTAp_E[195]= p_0[196] - p_0[195]          " Conservation of momentum "
Q_dot_E[195] = m_dot[195] * (h_0[196] - h_0[195])                             "
Conservation of energy "
DELTAT_E[195] = T_0[196] - T_0[195]

"-----Fluid properties-----"
T_0[195] = TEMPERATURE ( Water, h = h_0[195] , p = p_0[195])

"----------E-166 -T PIECE------------------"

"-----Component characteristics-----"
Q_dot_E[166] = 0 [kW]                       " Assume no heat loss over the mixing valve "
DELTAp_E[166] = 0 [kPa]                     " Assume there is no pressure drop in the mixing
valve"


"-----Component characteristics-----"
m_dot[166] = m_dot[191] + m_dot[195]        " Conservation of mass"
DELTAp_E[166] = p_0[166] - p_0[195]         " Conservation of momentum "
//p_0[166] = p_0[191]                       " Conservation of momentum "
Q_dot_E[166] = m_dot[166] * h_0[166] - m_dot[195] * h_0[195] - m_dot[191] * h_0[191]    "
Conservation of energy "

 "-----Fluid properties-----"
T_0[166] = TEMPERATURE ( Water, h = h_0[166] , p = p_0[166])


"----------E-165 (Pipe 165 from node 165-166)----------"

"-----Component characteristics-----"
alpha_E[165] = alpha_pipe
DELTAp_E[165] = alpha_E[165] * average( p_0[166], p_0[165] )" Pressure drop for a pipe "

Q_dot_E[165] = Q_dot_pipe                   " Heat transfer for a pipe "


"-----Component characteristics-----"
m_dot[165] = m_dot[166]                     " Conservation of mass "
DELTAp_E[165]= p_0[166] - p_0[165]          " Conservation of momentum "
Q_dot_E[165] = m_dot[165] * (h_0[166] - h_0[165])                             "
Conservation of energy "
DELTAT_E[165] = T_0[166] - T_0[165]

"-----Fluid properties-----"
T_0[165] = TEMPERATURE ( Water, h = h_0[165] , p = p_0[165])
```

```
"-------------------STEAM DISTRIBTUTION -------------------"


"----------E-161 (PUMP 161 from node 161-162)----------"

"-----Fluid properties-----"
rho_0[161] =DENSITY ( Water, h = h_0[161] , p = p_0[161] )

"-----Component characteristics-----"
eta_E[161] = 0.9

"-----Conservation equations-----"
//m_dot[161] = m_dot[172] + m_dot[192] + m_dot[196]                                 "
Conservation of mass (comment if loop is clossed)"

P_E[161] = m_dot[161] / ( rho_0[161] * eta_E[161] ) * (p_0[162] -p_0[161] )

"-----Fluid properties-----"
T_0[161] = TEMPERATURE ( Water, h = h_0[161] , p = p_0[161])


"----------E-162 (SB162 from node 162-163)----------"

"-----Component characteristics-----"
p_0[163] = p_0_SB
// alpha_E[162] = alpha_SB
DELTAp_E[162] = - 200 [kPa]                   " Pressure drop for the boiler "
- DELTAp_E[162] = alpha_E[162] * average( p_0[163], p_0[162] )" Pressure drop for a boiler "

"-----Conservation equations-----"
m_dot[162] = m_dot[161]                       " Conservation of mass "
DELTAp_E[162]= p_0[163] - p_0[162]            " Conservation of momentum "
Q_dot_E[162] = m_dot[162] * (h_0[163] - h_0[162])                                   "
Conservation of energy "
Q_dot_ID_162 = m_dot[162] * ( h_0[163] - h_0_ID_162 )

"-----Fluid properties-----"
x_0[163] = 1 [-]
h_0[163] = ENTHALPY ( Steam_IAPWS, x = x_0[163] ,p = p_0[163] )
T_0[163] = TEMPERATURE ( Steam_IAPWS, h = h_0[163] ,p = p_0[163] )

x_0[162] = 0 [-]
h_0[162] = ENTHALPY ( Steam_IAPWS, x = x_0[162] ,p = p_0[162] )
h_0_ID_162 = ENTHALPY ( Steam_IAPWS, x = x_0[162] ,p = p_0[163] )

T_0[162] = TEMPERATURE ( Steam_IAPWS, h = h_0[162] ,p = p_0[162] )


"----------E-163 (Pipe 163 from node 163-164)----------"

"-----Component characteristics-----"
alpha_E[163] = alpha_pipe
DELTAp_E[163] = alpha_E[163] * average( p_0[164], p_0[163] )" Pressure drop for a pipe "

Q_dot_E[163] = Q_dot_pipe                     " Heat transfer for a pipe "

"-----Component characteristics-----"
m_dot[163] = m_dot[162]                       " Conservation of mass "
DELTAp_E[163]= p_0[164] - p_0[163]            " Conservation of momentum "
```

```
Q_dot_E[163] = m_dot[163] * (h_0[164] - h_0[163])                                     "
Conservation of energy "
DELTAT_E[163] = T_0[164] - T_0[163]

"-----Fluid properties-----"
T_0[164] = TEMPERATURE ( Water, h = h_0[164] , p = p_0[164])


"----------E-164 -T PIECE-------------------"

"-----Component characteristics-----"
Q_dot_E[164] = 0 [kW]                         " Assume no heat loss over the mixing valve "
DELTAp_E[164] = 0 [kPa]                       " Assume there is no pressure drop in the mixing
valve"

"-----Component characteristics-----"
m_dot[164] = m_dot[165] + m_dot[171]          " Conservation of mass"
//DELTAp_E[164] = p_0[164] - p_0[171]         " Conservation of momentum "
//p_0[165] = p_0[171]                         " Conservation of momentum "
// Q_dot_E[164] = m_dot[164] * h_0[164] - m_dot[165] * h_0[165] - m_dot[171] * h_0[171]      "
Conservation of energy "

 "-----Fluid properties-----"
// T_0[165] = TEMPERATURE ( Water, h = h_0[165] , p = p_0[165])



"----------------------Condesate feed into boiler-------------------------------------"

"----------E-173 (Pipe 173 from node 173-174)----------"

"-----Component characteristics-----"
alpha_E[173] = alpha_pipe
- DELTAp_E[173] = alpha_E[173] * average( p_0[174], p_0[173] )" Pressure drop for a pipe "
// DELTAp_E[173] = 0 [kPa]
Q_dot_E[173] = Q_dot_pipe                     " Heat transfer for a pipe "
// DELTAT_E[173] = DELTAT_pipe

"-----Component characteristics-----"
m_dot[173] = m_dot[174]                       " Conservation of mass "
DELTAp_E[173]= p_0[174] - p_0[173]            " Conservation of momentum "
Q_dot_E[173] = m_dot[173] * (h_0[174] - h_0[173])                                     "
Conservation of energy "
DELTAT_E[173] = T_0[174] - T_0[173]

"-----Fluid properties-----"
T_0[174] = TEMPERATURE ( Water, h = h_0[174] , p = p_0[174])


"----------E-174 -T-JUNCTION------------------"

"--Boundary conditions--"

"-----Component characteristics-----"
Q_dot_E[174] = 0 [kW]                         " Assume no heat loss over the mixing valve "
DELTAp_E[174] = 0 [kPa]                       " Assume there is no pressure drop in the mixing
valve"

"-----Component characteristics-----"
```

```
m_dot[175] = m_dot[174] + m_dot[193]            " Conservation of mass"
// DELTAp_E[174] = p_0[175] - p_0[174]          " Conservation of momentum "
// DELTAp_E[174] = p_0[175] - p_0[193]          " Conservation of momentum "
p_0[193] = p_0[175]                             " Conservation of momentum "
//p_0[193] = p_0[174]                           " Conservation of momentum "


// Q_dot_E[174] = m_dot[174] * h_0[174] + m_dot[193] * h_0[193] - m_dot[175] * h_0[175]      "
Conservation of energy "
m_dot[175] * h_0[175] = m_dot[174] * h_0[174] + m_dot[193] * h_0[193]     " Conservation of energy "

"-----Fluid properties-----"
T_0[175] = TEMPERATURE ( Water, h = h_0[175] , p = p_0[175])


"----------E-175 (Pipe 175 from node 175-176)----------"

"-----Component characteristics-----"
alpha_E[175] = alpha_pipe
- DELTAp_E[175] = alpha_E[175] * average( p_0[176], p_0[175] )" Pressure drop for a pipe "
Q_dot_E[175] = Q_dot_pipe                       " Heat transfer for a pipe "

"-----Component characteristics-----"
m_dot[175] = m_dot[176]                         " Conservation of mass "
DELTAp_E[175]= p_0[176] - p_0[175]              " Conservation of momentum "
Q_dot_E[175] = m_dot[175] * (h_0[176] - h_0[175])                                      "
Conservation of energy "
DELTAT_E[175] = T_0[176] - T_0[175]

"-----Fluid properties-----"
T_0[176] = TEMPERATURE ( Water, h = h_0[176] , p = p_0[176])


 "----------E-176 -T-JUNCTION-------------------"

"--Boundary conditions--"


"-----Component characteristics-----"
Q_dot_E[176] = 0 [kW]                           " Assume no heat loss over the mixing valve "
DELTAp_E[176] = 0 [kPa]                         " Assume there is no pressure drop in the mixing
valve"

"-----Component characteristics-----"
m_dot[177] = m_dot[176] + m_dot[197]            " Conservation of mass"
DELTAp_E[176] = p_0[177] - p_0[176]             " Conservation of momentum "

// Q_dot_E[174] = m_dot[174] * h_0[174] + m_dot[197] * h_0[197] - m_dot[176] * h_0[176]      "
Conservation of energy "
m_dot[177] * h_0[177] = m_dot[176] * h_0[176] + m_dot[197] * h_0[197]     " Conservation of energy "

"-----Fluid properties-----"
T_0[177] = TEMPERATURE ( Water, h = h_0[177] , p = p_0[177])


"----------E-177 (Pipe 177 from node 177-178)----------"

"-----Component characteristics-----"
alpha_E[177] = alpha_pipe
```

```
- DELTAp_E[177] = alpha_E[177] * average( p_0[178], p_0[177] )" Pressure drop for a pipe "
Q_dot_E[177] = Q_dot_pipe                          " Heat transfer for a pipe "


"-----Component characteristics-----"
m_dot[177] = m_dot[178]                            " Conservation of mass "
DELTAp_E[177]= p_0[178] - p_0[177]                 " Conservation of momentum "
Q_dot_E[177] = m_dot[177] * (h_0[178] - h_0[177])                                                "
Conservation of energy "
DELTAT_E[177] = T_0[178] - T_0[177]

"-----Fluid properties-----"
T_0[178] = TEMPERATURE ( Water, h = h_0[178] , p = p_0[178])


"----------E-178 (Feedtank 177 from node 178-179)----------"
"Assume no make up water -Feedtank then a pipe"


"-----Component characteristics-----"
alpha_E[178] = alpha_pipe
- DELTAp_E[178] = alpha_E[178] * average( p_0[179], p_0[178] )" Pressure drop for a pipe "
Q_dot_E[178] = Q_dot_pipe                          " Heat transfer for a pipe "


"-----Component characteristics-----"
m_dot[178] = m_dot[179]                            " Conservation of mass "
DELTAp_E[178]= p_0[179] - p_0[178]                 " Conservation of momentum "
Q_dot_E[178] = m_dot[178] * (h_0[179] - h_0[178])                                                "
Conservation of energy "
DELTAT_E[178] = T_0[179] - T_0[178]

"-----Fluid properties-----"
T_0[179] = TEMPERATURE ( Water, h = h_0[179] , p = p_0[179])


"----------E-179 (Pipe 180 from node 179-180)----------"

"-----Component characteristics-----"
alpha_E[179] = alpha_pipe
- DELTAp_E[179] = alpha_E[179] * average( p_0[180], p_0[179] )" Pressure drop for a pipe "
Q_dot_E[179] = Q_dot_pipe                          " Heat transfer for a pipe "

"-----Component characteristics-----"
m_dot[179] = m_dot[180]                            " Conservation of mass "
DELTAp_E[179]= p_0[180] - p_0[179]                 " Conservation of momentum "
Q_dot_E[179] = m_dot[179] * (h_0[180] - h_0[179])                                                "
Conservation of energy "
DELTAT_E[179] = T_0[180] - T_0[179]

"-----Fluid properties-----"
T_0[180] = TEMPERATURE ( Water, h = h_0[180] , p = p_0[180])


"--------------------Clossing the loop----------"

m_dot[161] = m_dot[180]
h_0[161] = h_0[180]
P_0[161] = P_0[180]
```

```
"---------------------------------------------ELECTRIC BOILERS ---------------------------------------------------"
"-------------------------------------------------------------------------------------------------------------------------"

"----------------------------LOW TEMP (65°C) BOILER----------------------------"

"-------------------SCALDING--------------------"

"----------213 -SCALDING TANK----------"

"-----Boundary conditions-----"
m_dot[213] = m_dot_SC                        " Scalding mass flow "
T_0[213] = T_SC                              " Scalding temperature "
// p_0[213] = p_FW                           " Comment at E-203 "
h_0[213] = enthalpy( Water, T = T_0[213] , p = p_0[213] )


"----------E-212 -FEEDWATER INLET----------"

"-----Boundary conditions-----"// m_dot[212] = will be determined
T_0[212] = T_FW                              " Assume T_0[212] = Feed water temperature"
// p_0[212] = p_FW                           " Comment at E-211 "
h_0[212] = enthalpy( Water, T = T_0[212] , p = p_0[212] )


"----------E-211 -MIXING VALVE----------"

"-----Component characteristics-----"
Q_dot_E[211] = 0 [kW]                        " Assume no heat loss over the mixing valve "
alpha_E[211] = alpha_MXV
// DELTAp_E[211] = 0 [kPa]                   " Assume there is no pressure drop in the mixing
valve"
- DELTAp_E[211] = alpha_E[211] * average( p_0[213], p_0[211] )    " Pressure drop for a mixing
valve "

"-----Conservation equations-----"
m_dot[213] = m_dot[211] + m_dot[212]         " Conservation of energy"
DELTAp_E[211] = p_0[213] - p_0[211]          " Conservation of momentum "
p_0[211] = p_0[212]                          " Inlet pressures for a mixing valve need to be the
same "
Q_dot_E[211] = m_dot[213] * h_0[213] - m_dot[211] * h_0[211] - m_dot[212] * h_0[212]"
Conservation of energy "

 "-----Fluid properties-----"
T_0[211] = TEMPERATURE ( Water, h = h_0[211] , p = p_0[211])


"-------------------Linking nodes 211 with 204----------"
T_0[211] = T_0[204]
p_0[211] = p_0[204]
h_0[211] = h_0[204]
m_dot[211] = m_dot[204]


"----------------------------FLOOR AND EQUIPMENT WASHING----------------------------"

  "----------E-212 -FEEDWATER INLET----------"
```

```
"-----Boundary conditions-----"
T_0[222] = T_FW                              " Water temperature is feed water temperature"
// p_0[222] = P_FW                           " Comment at E-221 "
h_0[222] = enthalpy( Water, T = T_0[222], p = p_0[222] )


"----------E223 -FLOOR AND EQUIPMENT WASHING----------"

"-----Boundary conditions-----"
m_dot[223] = m_dot_FE                        " Floor and equipment washing mass flow "
T_0[223] = T_FE                              " Floor and equipment washing temperature "
// p_0[223] = P_FW                           " Comment at E-203 "
h_0[223] = enthalpy( Water, T = T_0[223] , p = p_0[223] )


"----------E-221 -MIXING VALVE----------"

"-----Component characteristics-----"
Q_dot_E[223] = 0 [kW]                        " Assume no heat loss over the mixing valve "
alpha_E[223] = alpha_MXV
// DELTAp_E[223] = 0 [kPa]                   " Assume there is no pressure drop in the mixing
valve"
- DELTAp_E[223] = alpha_E[223] * average( p_0[223], p_0[221] )     " Pressure drop for a mixing
valve "

"-----Conservation equations-----"
m_dot[223] = m_dot[221] + m_dot[222]         " Conservation of mass"
DELTAp_E[223] = p_0[223] - p_0[221]          " Conservation of momentum "
p_0[221] = p_0[222]                          " Inlet pressures for a mixing valve need to be the
same "
Q_dot_E[223] = m_dot[223] * h_0[223] - m_dot[221] * h_0[221] - m_dot[222] * h_0[222]     "
Conservation of energy "

 "-----Fluid properties-----"
T_0[221] = TEMPERATURE ( Water, h = h_0[221] , p = p_0[221])


"--------------------Linking nodes 221 with 205----------"
T_0[221] = T_0[205]
p_0[221] = p_0[205]
h_0[221] = h_0[205]
m_dot[221] = m_dot[205]


"----------------------------SHOWERING AND HAND WASH BASINS-------------------"

"----------E-231 -SHOWERING----------"

"-----Boundary conditions-----"
m_dot[231] = m_dot_SH                        " Shower and hand wash mass flow "
// p_0[231] = p_FW                           " Comment at E-201 "
T_0[231] = T_SH                              " Shower and hand wash temperature "
h_0[231] = enthalpy( Water, T = T_0[231] , p = p_0[231] )


"--------------------Linking nodes 231 with 206----------"
T_0[231] = T_0[206]
p_0[231] = p_0[206]
```

```
h_0[231] = h_0[206]
m_dot[231] = m_dot[206]



"----------E-203 -T PIECE-------------------"

"--------------------Boundary conditions ----------"
T_0[211] = T_0[203]
T_0[221] = T_0[203]

"-----Component characteristics-----"
Q_dot_E[203] = 0 [kW]                        " Assume no heat loss over the mixing valve "
DELTAp_E[203] = 0 [kPa]                      " Assume there is no pressure drop in the mixing
valve"


"-----Conservation equations-----"
m_dot[203] = m_dot[204] + m_dot[205] + m_dot[206]                                        "
Conservation of energy"
DELTAp_E[203] = p_0[203] - p_0[204]          " Conservation of momentum "
p_0[204] = p_0[205]                          " Assume exit pressures are all the same "
p_0[204] = p_0[206]                          " Assume exit pressures are all the same "
Q_dot_E[203] = m_dot[203] * h_0[203] - m_dot[204] * h_0[204] - m_dot[205] * h_0[205] - m_dot[206]
* h_0[206]     " Conservation of energy "

 "-----Fluid properties-----"
T_0[203] = TEMPERATURE ( Water, h = h_0[203] , p = p_0[203])
// T_0[206] = TEMPERATURE ( Water, h = h_0[206] , p = p_0[206])


"----------E-202 (Pipe 202 from node 202-203)----------"

"-----Component characteristics-----"
alpha_E[202] = alpha_pipe
- DELTAp_E[202] = alpha_E[202] * average( p_0[203], p_0[202] )     " Pressure drop for a pipe "
// DELTAp_E[202] = 0 [kPa]
Q_dot_E[202] = Q_dot_pipe                    " Heat transfer for a pipe "
// DELTAT_E[202] = DELTAT_pipe

"-----Conservation equations-----"
m_dot[202] = m_dot[203]                      " Conservation of mass "
DELTAp_E[202]= p_0[203] - p_0[202]           " Conservation of momentum "
Q_dot_E[202] = m_dot[202] * (h_0[203] - h_0[202])                                        "
Conservation of energy "
DELTAT_E[202] = T_0[203] - T_0[202]

"-----Fluid properties-----"
T_0[202] = TEMPERATURE ( Water, h = h_0[202] , p = p_0[202])


"----------E-201 (Electric boiler @ 65°C)----------"

"-----Boundary conditions-----"
T_0[201] = T_FW                              " Assume inlet is feedwater temp "
p_0[201] = P_FW                              " Assume inlet is feedwater pressure "


"-----Component characteristics-----"
```

```
DELTAp_E[201] = 0 [kPa]                        " Pressure drop for the boiler "

"-----Conservation equations-----"
m_dot[201] = m_dot[202]                        " Conservation of mass "
DELTAp_E[201]= p_0[202] - p_0[201]             " Conservation of momentum "
Q_dot_E[201] = m_dot[201] * (h_0[202] - h_0[201])                                   "
Conservation of energy "

"-----Fluid properties-----"
T_0[201] = TEMPERATURE ( Water, h = h_0[201] , p = p_0[201])


"----------------------------HIGH TEMP (87°C) ELECTRIC BOILER----------------------------"

 "----------------------------STERILIZATION-----------------"

"----------231 -STERILIZATION-------"

"-----Boundary conditions-----"
m_dot[243] = m_dot_ST                          " Shower and hand wash mass flow "
T_0[243] = T_ST                                " Comment at E-241"
// p_0[243] = P_FW                             " Assume water pressure just before the floor and
equipment washing taps is feed water pressure "
h_0[243] = enthalpy( Water, T = T_0[243], p = p_0[243] )


"----------E-242 (Pipe 242 from node 242-243)----------"

"-----Component characteristics-----"
alpha_E[242] = alpha_pipe
- DELTAp_E[242] = alpha_E[242] * average( p_0[243], p_0[242] )      " Pressure drop for a pipe "
// DELTAp_E[242] = 0 [kPa]
Q_dot_E[242] = Q_dot_pipe                      " Heat transfer for a pipe "
// DELTAT_E[242] = DELTAT_pipe

"-----Conservation equations-----"
m_dot[242] = m_dot[243]                        " Conservation of mass "
DELTAp_E[242]= p_0[243] - p_0[242]             " Conservation of momentum "
Q_dot_E[242] = m_dot[242] * (h_0[243] - h_0[242])                                   "
Conservation of energy "
DELTAT_E[242] = T_0[243] - T_0[242]

"-----Fluid properties-----"
T_0[242] = TEMPERATURE ( Water, h = h_0[242] , p = p_0[242])
// T_0[243] = TEMPERATURE ( Water, h = h_0[243] , p = p_0[243])

"----------E-241 (Electric boiler @ 87°C)----------"

"-----Boundary conditions-----"
T_0[241] = T_FW                                " Assume inlet is feedwater temp "
p_0[241] = p_FW                                " Assume inlet is feedwater pressure "


"-----Component characteristics-----"
DELTAp_E[241] = 0 [kPa]                        " Pressure drop for the boiler "

"-----Conservation equations-----"
m_dot[241] = m_dot[242]                        " Conservation of mass "
DELTAp_E[241]= p_0[242] - p_0[241]             " Conservation of momentum "
```

```
Q_dot_E[241] = m_dot[241] * (h_0[242] - h_0[241])                                    "
Conservation of energy "

"-----Fluid properties-----"
T_0[241] = TEMPERATURE ( Water, h = h_0[241] , p = p_0[241])



"----------------------------HEAT PUMP WATER WATER (65°C, 90°C, 2°C) ---------------------------------"
"-----------------------------------------------------------------------------------------------------------------------"

"--------------------BOUNDARY CONDITIONS--------------------"

// T_0[306] = 65 [C]                              " COMMENT WHEN AT ELEMENT 305 T PIECE"
// T_0[307] = 65 [C]                              " COMMENT WHEN AT ELEMENT 305 T PIECE"

"-----------------------------LOW TEMP (65°C) HEAT PUMP-----------------------------"

"--------------------SCALDING--------------------"

"----------313 -( Scalding tank boundary)----------"

"-----Boundary conditions-----"
m_dot[313] = m_dot_SC                             " Scalding mass flow "
T_0[313] = T_SC                                   " Scalding temperature "
// p_0[313] = p_FW                                " Comment at E-305 "
h_0[313] = enthalpy( Water, T = T_0[313] , p = p_0[313] )


 "----------E-312 -FEEDWATER INLET----------"

"-----Boundary conditions-----"// m_dot[312] = will be determined
T_0[312] = T_FW                                   " Assume T_0[312] = Feed water temperature"
// p_0[312] = p_FW                                " Comment at E-311 "
h_0[312] = enthalpy( Water, T = T_0[312] , p = p_0[312] )


"----------E-311 -MIXING VALVE----------"

"-----Component characteristics-----"
Q_dot_E[311] = Q_dot_MXV                          " Assume no heat loss over the mixing valve "
// Q_dot_E[311] = 0 [kW]                          " Assume no heat loss over the mixing valve "
alpha_E[311] = alpha_MXV
// DELTAp_E[313] = 0 [kPa]                        " Assume there is no pressure drop in the mixing
valve"
- DELTAp_E[311] = alpha_E[311] * average( p_0[313], p_0[311] )      " Pressure drop for a mixing
valve "


"-----Conservation equations-----"
m_dot[313] = m_dot[311] + m_dot[312]              " Conservation of energy"
DELTAp_E[311] = p_0[313] - p_0[311]               " Conservation of momentum "
p_0[311] = p_0[312]                               " Inlet pressures for a mixing valve need to be the
same "
Q_dot_E[311] = m_dot[313] * h_0[313] - m_dot[311] * h_0[311] - m_dot[312] * h_0[312]      "
Conservation of energy "

 "-----Fluid properties-----"
T_0[311] = TEMPERATURE ( Water, h = h_0[311] , p = p_0[311])
```

```
"--------------------Linking nodes 211 with 204----------"
T_0[311] = T_0[306]
p_0[311] = p_0[306]
h_0[311] = h_0[306]
m_dot[311] = m_dot[306]


"------------------------------FLOOR AND EQUIPMENT WASHING------------------------------"

"----------E-323 -FLOOR AND EQUIPMENT WASHING----------"

"-----Boundary conditions-----"
m_dot[323] = m_dot_FE                           " Floor and equipment washing mass flow "
T_0[323] = T_FE                                 " Floor and equipment washing temperature "
// p_0[323] = P_FW                              " Comment at E-321 "
h_0[323] = enthalpy( Water, T = T_0[323] , p = p_0[323] )


 "----------E-312 -FEEDWATER INLET----------"

"-----Boundary conditions-----"
T_0[322] = T_FW                                 " Water temperature is feed water temperature"
// p_0[322] = P_FW                              " Comment at E-301 "
h_0[322] = enthalpy( Water, T = T_0[322], p = p_0[322] )


"----------E-321 -MIXING VALVE----------"

"-----Component characteristics-----"
Q_dot_E[321] = Q_dot_MXV                        " Assume no heat loss over the mixing valve "
// DELTAp_E[321] = 0 [kPa]                      " Assume there is no pressure drop in the mixing
valve"
alpha_E[321] = alpha_MXV
- DELTAp_E[321] = alpha_E[321] * average( p_0[323], p_0[321] )     " Pressure drop for a mixing
valve "

"-----Conservation equations-----"
m_dot[323] = m_dot[321] + m_dot[322]            " Conservation of mass"
DELTAp_E[321] = p_0[323] - p_0[321]             " Conservation of momentum "
p_0[321] = p_0[322]                             " Inlet pressures for a mixing valve need to be the
same "
Q_dot_E[321] = m_dot[323] * h_0[323] - m_dot[321] * h_0[321] - m_dot[322] * h_0[322]      "
Conservation of energy "

 "-----Fluid properties-----"
T_0[321] = TEMPERATURE ( Water, h = h_0[321] , p = p_0[321])


"--------------------Linking nodes 221 with 205----------"
T_0[321] = T_0[307]
p_0[321] = p_0[307]
h_0[321] = h_0[307]
m_dot[321] = m_dot[307]


"-----------------------------SHOWERING AND HAND WASH BASINS-----------------------------"
```

```
"----------E-331 -SHOWERING----------"

"-----Boundary conditions-----"
m_dot[331] = m_dot_SH                       " Shower and hand wash mass flow "
// p_0[331] = p_FW                          " Comment at E-305 "
T_0[331] = T_SH                             " Shower and hand wash temperature "
h_0[331] = enthalpy( Water, T = T_0[331] , p = p_0[331] )


"--------------------Linking nodes 231 with 206----------"
T_0[331] = T_0[308]
p_0[331] = p_0[308]
h_0[331] = h_0[308]
m_dot[331] = m_dot[308]



"------------------------------LOW TEMPERATURE CIRCUIT------------------------------"

"----------E-305 -T PIECE-------------------"

"-----Component characteristics-----"
Q_dot_E[305] = 0 [kW]                       " Assume no heat loss over the mixing valve "
DELTAp_E[305] = 0 [kPa]                     " Assume there is no pressure drop in the mixing
valve"

"-----Conservation equations-----"
m_dot[305] = m_dot[306] + m_dot[307] + m_dot[308]                                  "
Conservation of energy"
DELTAp_E[305] = p_0[305] - p_0[306]         " Conservation of momentum "
p_0[306] = p_0[307]                         " Assume exit pressures are all the same "
p_0[306] = p_0[308]                         " Assume exit pressures are all the same "
Q_dot_E[305] = m_dot[305] * h_0[305] - m_dot[306] * h_0[306] - m_dot[307] * h_0[307] - m_dot[308]
* h_0[308]      " Conservation of energy "
T_0[307] = T_0[305]                         " Assume exit temperatures are all the same "

T_0[308] = T_0[305]                         " Assume exit temperatures are all the same "

 "-----Fluid properties-----"
T_0[305] = TEMPERATURE ( Water, h = h_0[305] , p = p_0[305])
// T_0[308] = TEMPERATURE ( Water, h = h_0[308] , p = p_0[308])


"----------E-304 (Pipe 304 from node 304-305)----------"

"-----Component characteristics-----"
alpha_E[304] = alpha_pipe
- DELTAp_E[304] = alpha_E[304] * average( p_0[305], p_0[304] )     " Pressure drop for a pipe "
// DELTAp_E[304] = 0 [kPa]
Q_dot_E[304] = Q_dot_pipe                   " Heat transfer for a pipe "
// DELTAT_E[304] = DELTAT_pipe

"-----Conservation equations-----"
m_dot[304] = m_dot[305]                     " Conservation of mass "
DELTAp_E[304]= p_0[305] - p_0[304]          " Conservation of momentum "
Q_dot_E[304] = m_dot[304] * (h_0[305] - h_0[304])                                  "
Conservation of energy "
DELTAT_E[304] = T_0[305] - T_0[304]
```

```
"-----Fluid properties-----"
T_0[304] = TEMPERATURE ( Water, h = h_0[304] , p = p_0[304])


"----------E-303 (Tank 303 from node 303-304)----------"

"-----Component characteristics-----"
alpha_E[303] = alpha_tank
- DELTAp_E[303] = alpha_E[303] * average( p_0[304], p_0[303] )    " Pressure drop for a pipe "
// DELTAp_E[303] = 0 [kPa]
Q_dot_E[303] = Q_dot_tank                        " Heat transfer for a pipe "
// DELTAT_E[303] = 0 [K]

"-----Conservation equations-----"
m_dot[303] = m_dot[304]                          " Conservation of mass "
DELTAp_E[303]= p_0[304] - p_0[303]               " Conservation of momentum "
Q_dot_E[303] = m_dot[303] * (h_0[304] - h_0[303])                                       "
Conservation of energy "
DELTAT_E[303] = T_0[304] - T_0[303]

"-----Fluid properties-----"
T_0[303] = TEMPERATURE ( Water, h = h_0[303] , p = p_0[303])


"----------E-302 (Pipe 302 from node 302-303)----------"

"-----Component characteristics-----"
alpha_E[302] = alpha_pipe
- DELTAp_E[302] = alpha_E[302] * average( p_0[303], p_0[302] )    " Pressure drop for a pipe "
// DELTAp_E[302] = 0 [kPa]
Q_dot_E[302] = Q_dot_pipe                        " Heat transfer for a pipe "
// DELTAT_E[302] = DELTAT_pipe

"-----Conservation equations-----"
m_dot[302] = m_dot[303]                          " Conservation of mass "
DELTAp_E[302]= p_0[303] - p_0[302]               " Conservation of momentum "
Q_dot_E[302] = m_dot[302] * (h_0[303] - h_0[302])                                       "
Conservation of energy "
DELTAT_E[302] = T_0[305] - T_0[302]

"-----Fluid properties-----"
T_0[302] = TEMPERATURE ( Water, h = h_0[302] , p = p_0[302])


"----------E-301 (Electric Heat pump)----------"

"-----Boundary conditions-----"
T_0[301] = T_FW                                  " Assume inlet is feedwater temp "
p_0[301] = p_FW                                  " Assume inlet is feedwater pressure "


"-----Component characteristics-----"
DELTAp_E[301] = 0 [kPa]                          " Pressure drop for the boiler "

"-----Conservation equations-----"
m_dot[301] = m_dot[302]                          " Conservation of mass "
DELTAp_E[301]= p_0[302] - p_0[301]               " Conservation of momentum "
Q_dot_E[301] = m_dot[301] * (h_0[302] - h_0[301])                                       "
Conservation of energy "
```

```
"-----Fluid properties-----"
T_0[301] = TEMPERATURE ( Water, h = h_0[301] , p = p_0[301])



"----------------------------HIGH TEMP (90°C) ELECTRIC HEAT PUMP-----------------------------"

"--------------------BOUNDARY CONDITIONS--------------------"

// T_0[344] = 90 [°C]                        " Comment at E-341 "

"----------------------------STERILIZATION------------------"

"----------347 -STERILIZATION-------"

"-----Boundary conditions-----"
m_dot[347] = m_dot_ST                        " Shower and hand wash mass flow "
T_0[347] = T_ST                              " Comment at E-341 "
// p_0[347] = P_FW                           " Assume water pressure just before the floor and
equipment washing taps is feed water pressure "
h_0[347] = enthalpy( Water, T = T_0[347], p = p_0[347] )

 "----------346 -FEEDWATER INLET----------"

"-----Boundary conditions-----"
T_0[346] = T_FW                              " Water temperature is feed water temperature"
//p_0[346] = P_FW                            " Comment at E-346"
h_0[346] = enthalpy( Water, T = T_0[346], p = p_0[346] )


"----------E346 -MIXING VALVE----------"

"-----Component characteristics-----"
Q_dot_E[345] = 0 [kW]                        " Assume no heat loss over the mixing valve "
alpha_E[345] = alpha_MXV
- DELTAp_E[345] = alpha_E[345] * average( p_0[347], p_0[345] )    " Pressure drop for a mixing
valve "
// DELTAp_E[345] = 0 [kPa]                   " Assume there is no pressure drop in the mixing
valve"

"-----Conservation equations-----"
m_dot[347] = m_dot[345] + m_dot[346]         " Conservation of mass"
DELTAp_E[345] = p_0[347] - p_0[345]          " Conservation of momentum "
p_0[346] = p_0[345]                          " For mixing valve the inlet pressure need to be the
same "
Q_dot_E[345] = m_dot[347] * h_0[347] - m_dot[345] * h_0[345] - m_dot[346] * h_0[346]     "
Conservation of energy "

 "-----Fluid properties-----"
T_0[345] = TEMPERATURE ( Water, h = h_0[345] , p = p_0[345])


"----------E-344 (Pipe 344 from node 344-345)----------"

"-----Component characteristics-----"
alpha_E[344] = alpha_pipe
- DELTAp_E[344] = alpha_E[344] * average( p_0[345], p_0[344] )    " Pressure drop for a pipe "
// DELTAp_E[344] = 0 [kPa]
```

```
Q_dot_E[344] = Q_dot_pipe                              " Heat transfer for a pipe "
// DELTAT_E[344] = DELTAT_pipe

"-----Conservation equations-----"
m_dot[344] = m_dot[345]                                " Conservation of mass "
DELTAp_E[344]= p_0[345] - p_0[344]                     " Conservation of momentum "
Q_dot_E[344] = m_dot[344] * (h_0[345] - h_0[344])                                         "
Conservation of energy "
DELTAT_E[344] = T_0[345] - T_0[344]

"-----Fluid properties-----"
T_0[344] = TEMPERATURE ( Water, h = h_0[344] , p = p_0[344])
// T_0[345] = TEMPERATURE ( Water, h = h_0[345] , p = p_0[345])


"----------E-343 (Tank 343 from node 343-342)----------"

"-----Component characteristics-----"
alpha_E[343] = alpha_Tank
- DELTAp_E[343] = alpha_E[343] * average( p_0[344], p_0[343] )     " Pressure drop for a tank "
// DELTAp_E[343] = 0 [kPa]
// Q_dot_E[343] = Q_dot_pipe                           " Heat transfer for a pipe "
DELTAT_E[343] = 0 [K]

"-----Conservation equations-----"
m_dot[343] = m_dot[344]                                " Conservation of mass "
DELTAp_E[343]= p_0[344] - p_0[343]                     " Conservation of momentum "
Q_dot_E[343] = m_dot[343] * (h_0[344] - h_0[343])                                         "
Conservation of energy "
DELTAT_E[343] = T_0[344] - T_0[343]

"-----Fluid properties-----"
T_0[343] = TEMPERATURE ( Water, h = h_0[343] , p = p_0[343])


"----------E-342 (Pipe 342 from node 342-343)----------"

"-----Component characteristics-----"
alpha_E[342] = alpha_pipe
- DELTAp_E[342] = alpha_E[342] * average( p_0[343], p_0[342] )     " Pressure drop for a pipe "
// DELTAp_E[342] = 0 [kPa]
// Q_dot_E[342] = Q_dot_pipe                           " Heat transfer for a pipe "
DELTAT_E[342] = 0 [K]

"-----Conservation equations-----"
m_dot[342] = m_dot[343]                                " Conservation of mass "
DELTAp_E[342]= p_0[343] - p_0[342]                     " Conservation of momentum "
Q_dot_E[342] = m_dot[342] * (h_0[343] - h_0[342])                                         "
Conservation of energy "
DELTAT_E[342] = T_0[343] - T_0[342]

"-----Fluid properties-----"
T_0[342] = TEMPERATURE ( Water, h = h_0[342] , p = p_0[342])
// T_0[343] = TEMPERATURE ( Water, h = h_0[343] , p = p_0[343])


"----------E-341 (Electric heat pump at 90°C)----------"

"-----Boundary conditions-----"
```

```
T_0[341] = T_FW                              " Assume inlet is feedwater temp "
p_0[341] = P_FW                              " Assume inlet is feedwater pressure "

T_0[342] = T_HP_90_HW                        " Assume HP is 90°C "


"-----Component characteristics-----"
DELTAp_E[341] = 0 [kPa]                      " Pressure drop for the boiler "

"-----Conservation equations-----"
m_dot[341] = m_dot[342]                      " Conservation of mass "
DELTAp_E[341]= p_0[342] - p_0[341]           " Conservation of momentum "
Q_dot_E[341] = m_dot[341] * (h_0[342] - h_0[341])                                    "
Conservation of energy "

"-----Fluid properties-----"
T_0[341] = TEMPERATURE ( Water, h = h_0[341] , p = p_0[341])



"----------------------------CHILLER COUPLED TO THE HEAT PUMP -----------------------------"


"----------E-353 (Chilled water)----------"

"-----Boundary conditions-----"
T_0[353] = T_CW                              " Chilled water inlet temperature "
// p_0[353] = P_FW                           " Comment at element E 351 "
m_dot[353] = m_dot_CW

"--Boundary fluid properties ----------"
h_0[353] = Enthalpy ( Water, T = T_0[353] , p = p_0[353])


"----------E-352 (Pipe 352 from node 352-353)----------"

"-----Component characteristics-----"
alpha_E[352] = alpha_pipe
- DELTAp_E[352] = alpha_E[352] * average( p_0[353], p_0[352] )     " Pressure drop for a pipe "
DELTAT_E[352] = 0 [K]                        " Temperature drop acros pipe "

"-----Conservation equations-----"
m_dot[352] = m_dot[353]                      " Conservation of mass "
DELTAp_E[352]= p_0[353] - p_0[352]           " Conservation of momentum "
Q_dot_E[352] = m_dot[352] * (h_0[353] - h_0[352])                                    "
Conservation of energy "
DELTAT_E[352] = T_0[353] - T_0[352]

"-----Fluid properties-----"
T_0[352] = TEMPERATURE ( Water, h = h_0[352] , p = p_0[352])


"----------E-351 (Thermal storage tank 351 from node 351-352)----------"

"-----Boundary conditions-----"
T_0[351] = T_FW                              " Assume inlet is feedwater temperature "
p_0[351] = P_FW                              " Assume inlet to chiller is feedwater pressure "
```

```
"-----Component characteristics-----"
DELTAp_E[351] = 0 [kPa]                          " Pressure drop for the chiller "

"-----Conservation equations-----"
m_dot[351] = m_dot[352]                          " Conservation of mass "
DELTAp_E[351] = p_0[352] - p_0[351]              " Conservation of momentum "
Q_dot_E[351] = m_dot[351] * (h_0[352] - h_0[351])                                    "
Conservation of energy "

"-----Fluid properties-----"
T_0[351] = TEMPERATURE ( Water, h = h_0[351] , p = p_0[351])


"------------------Circuit 371 -Chilled water side of heat pump (m_dot for ideal case)------------------"

"-----Boundary conditions-----"
// T_0[371] = 0 [°C]                             " Comment at E-372 "
p_0[371] = P_FW
// m_dot[372] = 5 [kg/s]                         " Initial guess value "
// m_dot[372] = m_dot_HP_WW_65_CW_SUP

"--Boundary fluid properties ----------"
h_0[371] = ENTHALPY ( BRINE$, T = T_0[371] , C = CTRN, p = p_0[371] )


 "----------E-371 (Pipe 371 from node 371-372)----------"

"-----Component characteristics-----"
alpha_E[371] = alpha_pipe
- DELTAp_E[371] = alpha_E[371] * average( p_0[372], p_0[371] )      " Pressure drop for a pipe "
// DELTAT_E[371] = 0 [K]                         " Temperature drop accros pipe "
Q_dot_E[371] = Q_dot_pipe

"-----Conservation equations-----"
m_dot[371] = m_dot[372]                          " Conservation of mass "
DELTAp_E[371]= p_0[372] - p_0[371]               " Conservation of momentum "
Q_dot_E[371] = m_dot[371] * (h_0[372] - h_0[371])                                    "
Conservation of energy "

"-----Fluid properties-----"
 h_0[372] = ENTHALPY ( BRINE$, T = T_0[372] , C = CTRN, p = p_0[372] )



"----------E-372 (HX372 from node 372-373)----------"

"-----Component characteristics-----"
alpha_E[372] = 0 [-]
// DELTAp_E[372] = 0 [kPa]
epsilon_E[372] = epsilon_HX
- DELTAp_E[372] = alpha_E[372] * average( p_0[373], p_0[372] )      " Pressure drop for a pipe "


 "-----Conservation equations-----"
DELTAp_E[372] = p_0[373] - p_0[372]
Q_dot_E[372] = - Q_dot_E[351]

m_dot[372] = m_dot[373]
```

```
C[372] = m_dot[372] * cp( BRINE$, T = T_0[372] , C = CTRN, p = p_0[372] )
C[351] = m_dot[351] * cp(Water, T = T_0[351], p = p_0[351])

C_MIN_E[372] = min( C[372], C[351] )
Q_dot_max_E[372] = C_MIN_E[372] * ( T_0[351] - T_0[372] )
Q_dot_E[372] = epsilon_E[372] * Q_dot_max_E[372]                                    " Heat
transfer for a HX "

Q_dot_E[372] = m_dot[372] * (h_0[373] - h_0[372])

"-----Fluid properties-----"
h_0[373] = ENTHALPY ( BRINE$, T = T_0[373] , C = CTRN, p = p_0[373] )


 "----------E-373 (Pipe 373 from node 373-374)----------"

"-----Component characteristics-----"
alpha_E[373] = alpha_pipe
- DELTAp_E[373] = alpha_E[373] * average( p_0[374], p_0[373] )     " Pressure drop for a pipe "
// DELTAp_E[373] = 0 [kPa]
// DELTAT_E[373] = 0 [K]                          " Temperature drop accros pipe "
Q_dot_E[373] = 0 [kW]

"-----Conservation equations-----"
m_dot[373] = m_dot[374]                           " Conservation of mass "
DELTAp_E[373]= p_0[374] - p_0[373]                " Conservation of momentum "
Q_dot_E[373] = m_dot[373] * (h_0[374] - h_0[373])                                  "
Conservation of energy "

"-----Fluid properties-----"

h_0[374] = ENTHALPY ( BRINE$, T = T_0[374] , C = CTRN, p = p_0[374] )



 "-------------------CHILLER PART OF HEAT PUMP-------------------"

"-----Component characteristics-----"
DELTAT_E[374] = DELTAT_HP_CW
DELTAT_E[374] = T_0[375] - T_0[374]
DELTAp_E[374] = 0 [kPa]

"-----Conservation equations-----"
m_dot[374] = m_dot[375]                           " Conservation of mass "
DELTAp_E[374]= p_0[375] - p_0[374]                " Conservation of momentum "
Q_dot_E[374] = m_dot[375] * (h_0[375] - h_0[374])                                  "
Conservation of energy "

"-----Fluid properties-----"
h_0[375] = ENTHALPY ( BRINE$, T = T_0[375] , C = CTRN, p = p_0[375] )

 "-------------------CLOSING THE LOOP-------------------"

// p_0[371] = p_0[375]
// m_dot[372] = m_dot[375]
 T_0[371] = T_0[375]
```

```
"------------------- RUNNING FRACTION FOR HEAT PUMP BASED ON DEMAND---------------------"
"--------------------------------------------------------------------------------------------------------------------------"


"-------------------- ENERGY USED TO HEAT THE WATER WITH INLINE HEATER ------------"

Q_dot_HP_65 = Q_dot_E[301] * ( 1 + SM_EQP / 100 [%] )  " Low water temp Inline heater "

Q_dot_HP_90 = Q_dot_E[341] * ( 1 + SM_EQP / 100 [%] )  " High water temp Inline heater "

{
Q_dot_HP_65 = Q_dot_E[301]    " Low water temp Inline heater "

Q_dot_HP_90 = Q_dot_E[341]    " High water temp Inline heater "
}

Q_dot_HP = Q_dot_HP_65 + Q_dot_HP_90


"-------------------- MASS FLOW OF THE WATER WITH HP --------------------"

m_dot_CW_DM = m_dot[351]

m_dot_HP_CW_HX = m_dot[371]


m_dot_HP_65_DM = m_dot[301]

m_dot_HP_90_DM = m_dot[341]



"-------------------- MASS FLOW OF THE WATER WITH HP --------------------"

N_HP_CW = CEIL (m_dot_CW_DM/m_dot_HP_CW_65_SP\HP)     " Assume that HP @ 65°C
supplies CW "

N_HP_90°C = CEIL (m_dot_HP_90_DM/m_dot_HP_AW_90_SP\HP)     " Assume that HP @ 90°C is
only supplied by AW mass flow "


N_HP_65°C = N_HP_65°C_AW + N_HP_65°C_WW

N_HP_65°C_WW = N_HP_CW                         " Assume the WW HP at 65°C works with CW "

// N_HP_65°C_AW = CEIL ( ( m_dot_HP_65_DM - m_dot_HP_65_AW_DM ) /
m_dot_HP_WW_65_SP\HP )

m_dot_HP_65_AW_CALC = N_HP_65°C_AW * m_dot_HP_AW_65_SP\HP

m_dot_HP_65_WW_CALC = N_HP_65°C_WW * m_dot_HP_WW_65_SP\HP

m_dot_HP_65_WW_SP = m_dot_HP_65_DM - m_dot_HP_65_AW_CALC

N_HP_65°C_AW = 15


"-------------------- CHECK MASS FLOW OF THE WATER WITH HP --------------------"
```

```
m_dot_HP_65_CALC = m_dot_HP_65_AW_CALC + m_dot_HP_65_WW_CALC

 m_dot_HP_65_DIFF =  m_dot_HP_65_CALC - m_dot_HP_65_DM

"-------------------- ABATTOIR WATER DEMAND FOR FULL PRODUCTION [kg/hr]--------------------"
"-----------------------------------------------------------------------------------------------------------------------"

m_dot_HP_CW_DM_ton\hr = m_dot_HP_CW_HX / CONVERT ( s, hr ) * CONVERT (kg, tonne)

m_dot_HP_65_DM_ton\hr = m_dot_HP_65_DM / CONVERT ( s, hr ) * CONVERT (kg, tonne)

m_dot_HP_90_DM_ton\hr = m_dot_HP_90_DM / CONVERT ( s, hr ) * CONVERT (kg, tonne)

m_dot_HP_HW_DM_ton\hr = m_dot_HP_65_DM_ton\hr + m_dot_HP_90_DM_ton\hr

"-------------------- ABATTOIR WATER DEMAND FOR FULL PRODUCTION [kg/day]--------------------"
"-----------------------------------------------------------------------------------------------------------------------"

m_dot_HP_CW_DM_ton\day =m_dot_HP_CW_DM_ton\hr * OP_DM_hrs\day

m_dot_HP_65_DM_ton\day = m_dot_HP_65_DM_ton\hr * OP_DM_hrs\day

m_dot_HP_90_DM_ton\day = m_dot_HP_90_DM_ton\hr * OP_DM_hrs\day

m_dot_HP_HW_DM_ton\day = m_dot_HP_65_DM_ton\day + m_dot_HP_90_DM_ton\day

"------------ ABATTOIR HOT WATER DEMAND FRACTION FOR FULL PRODUCTION ------------"
"-----------------------------------------------------------------------------------------------------------------------"

FR_m_65_DMD = m_dot_HP_65_DM_ton\hr / m_dot_HP_HW_DM_ton\hr

FR_m_90_DMD = m_dot_HP_90_DM_ton\hr / m_dot_HP_HW_DM_ton\hr

FR_m_TOT_DMD = FR_m_65_DMD + FR_m_90_DMD

"------------------- DETERMINE THE TIME THE HP RUNS AT TO PRODUCE CW ---------------------"
"-----------------------------------------------------------------------------------------------------------------------"
"------------ HOURS HP FOR CHILLED WATER ------------"

m_dot_HP_CW_DM_ton\day = m_dot_HP_CW_65_SP_ton\hr * HP_CW_65_SP_hrs\day +
m_dot_HP_CW_90_SP_ton\hr * HP_CW_90_SP_hrs\day

HP_CW_SP_hrs\day = HP_CW_65_SP_hrs\day + HP_CW_90_SP_hrs\day

m_dot_HP_CW_65_SP_ton\hr = m_dot_HP_CW_65_SP\HP_ton\hr * N_HP

m_dot_HP_CW_90_SP_ton\hr = m_dot_HP_CW_90_SP\HP_ton\hr * N_HP


HP_WW_65_SP_hrs\day = HP_CW_65_SP_hrs\day

HP_WW_90_SP_hrs\day = HP_CW_90_SP_hrs\day
```

```
"------------ HOURS HP FOR HW AT 65°C ------------"

m_dot_HP_65_DM_ton\day = m_dot_HP_WW_65_SP_ton\hr * HP_WW_65_SP_hrs\day +
m_dot_HP_AW_65_SP_ton\hr * HP_AW_65_SP_hrs\day

HP_65_SP_hrs\day = HP_WW_65_SP_hrs\day + HP_AW_65_SP_hrs\day

m_dot_HP_WW_65_SP_ton\hr = m_dot_HP_WW_65_SP\HP_ton\hr * N_HP

m_dot_HP_AW_65_SP_ton\hr = m_dot_HP_AW_65_SP\HP_ton\hr * N_HP


"------------ HOURS HP FOR HW AT 90°C ------------"

m_dot_HP_90_DM_ton\day = m_dot_HP_WW_90_SP_ton\hr * HP_WW_90_SP_hrs\day +
m_dot_HP_AW_90_SP_ton\hr * HP_AW_90_SP_hrs\day

HP_90_SP_hrs\day = HP_WW_90_SP_hrs\day + HP_AW_90_SP_hrs\day

m_dot_HP_WW_90_SP_ton\hr = m_dot_HP_WW_90_SP\HP_ton\hr * N_HP

m_dot_HP_AW_90_SP_ton\hr = m_dot_HP_AW_90_SP\HP_ton\hr * N_HP


"------------ TOTAL HOURS HP RUNS ------------"

HP_SP_hrs\day = HP_WW_65_SP_hrs\day + HP_AW_65_SP_hrs\day + HP_WW_90_SP_hrs\day +
HP_AW_90_SP_hrs\day


"------------ DETERMINE THE SUPPLY MASS FLOW PER HEAT PUMP [kg/s]------------"


m_dot_HP_CW_65_SP = m_dot_HP_CW_65_SP_ton\hr * convert ( tonne/hr, kg/s )

m_dot_HP_CW_90_SP = m_dot_HP_CW_90_SP_ton\hr * convert ( tonne/hr, kg/s )


m_dot_HP_WW_65_SP = m_dot_HP_WW_65_SP_ton\hr * convert ( tonne/hr, kg/s )

m_dot_HP_AW_65_SP = m_dot_HP_AW_65_SP_ton\hr * convert ( tonne/hr, kg/s )


m_dot_HP_WW_90_SP = m_dot_HP_WW_90_SP_ton\hr * convert ( tonne/hr, kg/s )

m_dot_HP_AW_90_SP = m_dot_HP_AW_90_SP_ton\hr * convert ( tonne/hr, kg/s )



"------------ DETERMINE THE SUPPLY MASS FLOW PER HEAT PUMP [tonne/day]------------"


m_dot_HP_CW_65_SP_ton\day = m_dot_HP_CW_65_SP_ton\hr * HP_CW_65_SP_hrs\day

m_dot_HP_CW_90_SP_ton\day = m_dot_HP_CW_90_SP_ton\hr * HP_CW_90_SP_hrs\day

m_dot_HP_CW_SP_ton\day = m_dot_HP_CW_65_SP_ton\day + m_dot_HP_CW_90_SP_ton\day
```

```
m_dot_HP_WW_65_SP_ton\day = m_dot_HP_WW_65_SP_ton\hr * HP_WW_65_SP_hrs\day

m_dot_HP_AW_65_SP_ton\day = m_dot_HP_AW_65_SP_ton\hr * HP_AW_65_SP_hrs\day

m_dot_HP_65_SP_ton\day = m_dot_HP_WW_65_SP_ton\day + m_dot_HP_AW_65_SP_ton\day


m_dot_HP_WW_90_SP_ton\day = m_dot_HP_WW_90_SP_ton\hr * HP_WW_90_SP_hrs\day

m_dot_HP_AW_90_SP_ton\day = m_dot_HP_AW_90_SP_ton\hr * HP_AW_90_SP_hrs\day

m_dot_HP_90_SP_ton\day = m_dot_HP_WW_90_SP_ton\day + m_dot_HP_AW_90_SP_ton\day


"--------------- ENERGY USED TO HEAT AND CHILL THE WATER WITH HEAT PUMP ----------"
"------------------------------------------------------------------------------------------------------------------------"


"------------- ENERGY USED TO HEAT AND CHILL THE WATER WITH HEAT PUMP ------------"

Q_dot_CW = Q_dot_E[372] * ( 1 + SM_EQP / 100 [%] )   " Chilled water HP "

Q_dot_HP_WW_65 = m_dot_HP_WW_65_SP * c_P_FW * DELTAT_65_HW * ( 1 + SM_EQP / 100
[%] )   " Low water temp HP "

Q_dot_HP_AW_65 = m_dot_HP_AW_65_SP * c_P_FW * DELTAT_65_HW * ( 1 + SM_EQP / 100
[%] )   " Low water temp HP "

Q_dot_HP_WW_90 = m_dot_HP_WW_90_SP * c_P_FW * DELTAT_90_HW * ( 1 + SM_EQP / 100
[%] )   " Low water temp HP "

Q_dot_HP_AW_90 = m_dot_HP_AW_90_SP * c_P_FW * DELTAT_90_HW * ( 1 + SM_EQP / 100
[%] )   " Low water temp HP "


"-------------------- POWER USED TO HEAT AND CHILL THE WATER WITH WATER WATER HP ------
------"

P_HP_WW_65 = Q_dot_HP_WW_65 / COP_WW_65

P_HP_AW_65 = Q_dot_HP_AW_65 / COP_AW_65


P_HP_WW_90 = Q_dot_HP_WW_90 / COP_WW_90

P_HP_AW_90 = Q_dot_HP_AW_90 / COP_AW_90

 "------------------ ENERGY USE OF HEAT PUMP DURING NORMAL OPERATION --------------- "

P_HP_65\day = ( HP_WW_65_SP_hrs\day * P_HP_WW_65 + HP_AW_65_SP_hrs\day *
P_HP_AW_65 )

P_HP_90\day = ( HP_WW_90_SP_hrs\day * P_HP_WW_90 + HP_AW_90_SP_hrs\day *
P_HP_AW_90 )

P_HP\day = P_HP_65\day + P_HP_90\day
```

```
 "----------------- ENERGY USE ITO AW & WW PART OF THE HP -------------- "

P_HP_WW\day = ( HP_WW_65_SP_hrs\day * P_HP_WW_65 + HP_WW_90_SP_hrs\day *
P_HP_WW_90 )

P_HP_WW_65\day = HP_WW_65_SP_hrs\day * P_HP_WW_65

P_HP_AW_65\day = HP_AW_65_SP_hrs\day * P_HP_AW_65

P_HP_AW\day = ( HP_AW_65_SP_hrs\day * P_HP_AW_65 + HP_AW_90_SP_hrs\day *
P_HP_AW_90 )

P_HP_WW_90\day = HP_WW_90_SP_hrs\day * P_HP_WW_90

P_HP_AW_90\day = HP_AW_90_SP_hrs\day * P_HP_AW_90

P_HP_AWW\day = P_HP_WW\day + P_HP_AW\day


"----------------- COST OF OPERATION FOR HP-----------------"

COST_HP\day = P_HP\day * ENERGY_COST_kWh



"------------------------------ COST OF RUNNING A COAL STEAM BOILER------------------------------"
"---------------------------------------------------------------------------------------------------------------"


"---------------- ELECTRICTY USED BY STEAM BOIER (Chiller, pump etc)-----------------"

P_SB = P_AC + P_CP

P_SB\day = P_AC\day + P_CP\day

"----- ELECTRICTY USED BY CONDENDATE PUMP -----"

P_CP = P_E[161] * ( 1 + SM_EQP / 100 [%] )       " Include safety margin in calculations "

P_CP\day = P_CP * SB_hrs\day                     " Energy used per day "


 "------------------- AMMONIA CHILLED ENERGY DEMAND PER DAY-------------------"

Q_dot_AC_DM\day = Q_dot_AC * AC_hrs\day

Q_dot_AC = Q_dot_E[151] * ( 1 + SM_EQP / 100 [%] )                               "
Include safety margin in calculations "

"------------------ ELECTRIC POWER USED TO COOL THE WATER WITH AMMONIA CHILLER ------
"

P_AC = - Q_dot_AC / ( EER_AC )                   " Electric Energy used by Ammonia chiller"

// P_AC\day = P_AC * TL_hrs\day                  " Electricty used by Ammonia chiller - Assume chiller
is used 24 hours "
```

```
P_AC\day = P_AC * AC_hrs\day                    " Electricty used by Ammonia chiller"

COST_AC\day = P_AC\day * ENERGY_COST_kWh

"------THERMAL DEMAND STEAM BOILER (INCLUDING OVERSIZING)------------"

Q_dot_SB = Q_dot_E[162] * ( 1 + SM_EQP / 100 [%] )                                  "
Include safety margin in calculations "
Q_dot_SB_ID = Q_dot_ID_162 * ( 1 + SM_EQP / 100 [%] )    " Include safety margin in calculations "

//Q_dot_SB\day = Q_dot_SB * SB_hrs\day * CONVERT (hr, s)    " Energy used per day "
Q_dot_SB\day = Q_dot_SB * SB_hrs\day    " Energy used per day "


"------COAL USED TO HEAT THE WATER IN SYSTEM FOR COAL STEAM BOILER------------"

m_dot_CSB = Q_dot_SB / ( eta_CSB / 100 [%] ) / ( CV_CSB_MJ * CONVERT ( MJ, kJ) )

SB_CSB\day = m_dot_CSB / CONVERT ( s , hr) * SB_hrs\day

SB_CSB_ton\day = SB_CSB\day * CONVERT (kg, tonne)

COST_CSB\day = SB_CSB_ton\day * Coal_R\ton

"---------- LPG USED TO HEAT THE WATER IN SYSTEM FOR COAL STEAM BOILER----------"

m_dot_LPG = Q_dot_SB / ( eta_LPG / 100 [%] ) / ( CV_LPG_MJ * CONVERT ( MJ, kJ) )

SB_LPG\day = m_dot_LPG / CONVERT ( s , hr) * SB_hrs\day

COST_LPG\day = SB_LPG\day * LPG_R\kg


"--- PARAFFIN USED TO HEAT THE WATER IN SYSTEM FOR COAL STEAM BOILER ------"


SB_PRF_kg\s = Q_dot_SB / ( eta_PRF / 100 [%] ) / ( CV_PRF_MJ\kg * CONVERT ( MJ, kJ) )

SB_PRF_l\s = SB_PRF_kg\s / ( rho_PRF * CONVERT ( l , m^3) )


SB_PRF_l\day = SB_PRF_l\s / CONVERT ( s , hr) * SB_hrs\day

COST_PRF\day = SB_PRF_l\day * PRF_R\lit

"--------- ELECTRIC POWER USED TO HEAT THE WATER WITH ELECTRIC BOILERS -------"

Q_dot_EB_65 = Q_dot_E[201] * ( 1 + SM_EQP / 100 [%] )  "Low temp electric boiler "

Q_dot_EB_90 = Q_dot_E[241] * ( 1 + SM_EQP / 100 [%] )  " High temp electric boiler "

Q_dot_EB = Q_dot_EB_65 + Q_dot_EB_90          " Total energy use "

P_EB = Q_dot_EB / ( eta_EB / 100[%] )              " Electric Energy used "
```

```
P_EB\day = P_EB * EB_hrs\day

COST_EB\day = P_EB\day * ENERGY_COST_kWh

P_EB_TOT\day = P_EB\day + P_AC\day


P_HP_AWW\day# = if ( Pr_fr, 0 , 0, 1000 [kWh/day], P_HP_AWW\day)

COP_HP_EB = if ( Pr_fr, 0, 0, 0, P_EB\day / P_HP_AWW\day# )


 "------------ COMPARE ENERGY VALUES (WITHOUT OVERSIZING)------------"

Q_dot_EB_ORG = Q_dot_E[201] + Q_dot_E[241]

Q_dot_SB_ORG = Q_dot_E[162]

Q_dot_HP_ORG = Q_dot_E[301] + Q_dot_E[341]

Q_dot_SB_HX_ORG = Q_dot_E[111] + Q_dot_E[121] + Q_dot_E[141]


 "------------ ENERGY KPI ------------"

ELEC_R\MJ = ENERGY_COST_kWh / CV_ELEC_MJ

ELEC_c\MJ = ELEC_R\MJ * 100

// PRF_R\MJ = PRF_R\lit / CV_PRF_MJ\l / ( rho_PRF * CONVERT ( l , m^3) )

PRF_R\MJ = PRF_R\lit / CV_PRF_MJ\l

LPG_R\MJ = LPG_R\kg / CV_LPG_MJ

CSB_R\MJ = Coal_R\ton / CV_CSB_MJ * CONVERT ( kg , tonne )

CSB_c\MJ = CSB_R\MJ * 100

ELEC_CSB_c\MJ = ELEC_c\MJ / CSB_c\MJ

CSB_ELEC_c\MJ = CSB_c\MJ / ELEC_c\MJ


"------------------ COST OF ENERGY ------------------"

COST_EN_EB\day = P_EB\day * ENERGY_COST_kWh

COST_EN_HP\day = P_HP\day * ENERGY_COST_kWh

COST_EN_AC\day = P_AC\day * ENERGY_COST_kWh

COST_EN_PRF\day = SB_PRF_l\day * PRF_R\lit

COST_EN_LPG\day = SB_LPG\day * LPG_R\kg
```

```
COST_EN_CSB\day = SB_CSB_ton\day * Coal_R\ton

"----------------- TOTAL COST OF ENERGY -----------------"
TOTAL_EN_COST_CSB\day = COST_EN_CSB\day + COST_EN_AC\day
TOTAL_EN_COST_PRF\day = COST_EN_PRF\day + COST_EN_AC\day
TOTAL_EN_COST_LPG\day = COST_EN_LPG\day + COST_EN_AC\day
TOTAL_EN_COST_HP\day = COST_EN_HP\day
TOTAL_EN_COST_EB\day = COST_EN_EB\day + COST_EN_AC\day
TOTAL_EN_COST_AC\day = COST_EN_AC\day

"----SAVINGS OF HEAT PUMP (ONLY ENERGY COST) -----"
SAVINGS_EN_HP_VS_ELEC\day = TOTAL_EN_COST_EB\day - TOTAL_EN_COST_HP\day
SAVINGS_EN_HP_VS_CSB\day = TOTAL_EN_COST_CSB\day - TOTAL_EN_COST_HP\day
SAVINGS_EN_HP_VS_LPG\day = TOTAL_EN_COST_LPG\day - TOTAL_EN_COST_HP\day
SAVINGS_EN_HP_VS_PRF\day = TOTAL_EN_COST_PRF\day - TOTAL_EN_COST_HP\day

"----------------------ENVIRONMENTAL IMPACT OF THE VARIOUS OPTIONS-----------------------"

"------DETERMINE ENVIRONMENT IMPACT OF THE AMMONIA CHILLER------"
AC_COAL\day = P_AC\day * Coal_kg\kWh
AC_WATER\day = P_AC\day * Water_l\kWh
AC_ASH\day = P_AC\day * Ash_g\kWh * CONVERT ( g, kg )
AC_Particle\day = P_AC\day * Particle_g\kWh * CONVERT ( g, kg )
AC_CO2_ton\day = P_AC\day * CO2_kg\kWh * CONVERT ( kg, tonne )
AC_NOx\day = P_AC\day * NOx_g\kWh * CONVERT ( g, kg )
AC_SOx\day = P_AC\day* SOx_g\kWh * CONVERT ( g, kg )
AC_CH4\day = AC_COAL\day * CV_COAL_ESC_MJ * CONVERT ( MJ, TJ ) * CH4_kg\TJ_ESC
AC_N2O\day = P_AC\day * N2O_g\kWh * CONVERT ( g, kg )

"------DETERMINE ENVIRONMENT OF THE HEAT PUMP (AWW)------"
HP_COAL\day = P_HP\day * Coal_kg\kWh
HP_WATER\day = P_HP\day * Water_l\kWh
```

HP_ASH\day = P_HP\day * Ash_g\kWh * CONVERT (g, kg)

HP_Particle\day = P_HP\day * Particle_g\kWh * CONVERT (g, kg)

HP_CO2_ton\day = P_HP\day * CO2_kg\kWh * CONVERT (kg, tonne)

HP_NOx\day = P_HP\day * NOx_g\kWh * CONVERT (g, kg)

HP_SOx\day = P_HP\day * SOx_g\kWh * CONVERT (g, kg)

HP_CH4\day = HP_COAL\day * CV_COAL_ESC_MJ * CONVERT (MJ, TJ) * CH4_kg\TJ_ESC

HP_N2O\day = P_HP\day * N2O_g\kWh * CONVERT (g, kg)

"------DETERMINE ENVIRONMENT OF THE ELECTRIC BOILER------"

EB_COAL\day = P_EB_TOT\day * Coal_kg\kWh

EB_WATER\day = P_EB_TOT\day * Water_l\kWh

EB_ASH\day = P_EB_TOT\day * Ash_g\kWh * CONVERT (g, kg)

EB_Particle\day = P_EB_TOT\day * Particle_g\kWh * CONVERT (g, kg)

EB_CO2_ton\day = P_EB_TOT\day * CO2_kg\kWh * CONVERT (kg, tonne)

EB_NOx\day = P_EB_TOT\day * NOx_g\kWh * CONVERT (g, kg)

EB_SOx\day = P_EB_TOT\day * SOx_g\kWh * CONVERT (g, kg)

EB_CH4\day = EB_COAL\day * CV_COAL_ESC_MJ * CONVERT (MJ, TJ) * CH4_kg\TJ_ESC

EB_N2O\day = P_EB_TOT\day * N2O_g\kWh * CONVERT (g, kg)

"-----ENVIRONMENTAL IMPACT OF COAL STEAM BOILER-----"

CSB_CO2_ton\day = Q_dot_SB\day * CONVERT (kWh , TJ) * CO2_kg\TJ_CSB * CONVERT (kg, tonne)

CSB_CH4\day = Q_dot_SB\day * CONVERT (kWh , TJ) * CH4_kg\TJ_CSB

CSB_N2O\day = Q_dot_SB\day * CONVERT (kWh , TJ) * N2O_kg\TJ_CSB

"-----ENVIRONMENTAL IMPACT OF PARAFFIN STEAM BOILER-----"

PRF_CO2_ton\day = Q_dot_SB\day * CONVERT (kWh , TJ) * CO2_kg\TJ_PRF * CONVERT (kg, tonne)

PRF_CH4\day = Q_dot_SB\day * CONVERT (kWh , TJ) * CH4_kg\TJ_PRF

PRF_N2O\day = Q_dot_SB\day * CONVERT (kWh, TJ) * N2O_kg\TJ_PRF

"-----ENVIRONMENTAL IMPACT OF LPG STEAM BOILER-----"

LPG_CO2_ton\day = Q_dot_SB\day * CONVERT (kWh , TJ) * CO2_kg\TJ_LPG * CONVERT (kg, tonne)

LPG_CH4\day = Q_dot_SB\day * CONVERT (kWh , TJ) * CH4_kg\TJ_LPG

LPG_N2O\day = Q_dot_SB\day * CONVERT (kWh , TJ) * N2O_kg\TJ_LPG

"------DETERMINE TOTAL IMPACT ON CO2------"

TOTAL_CSB_CO2_ton\day = CSB_CO2_ton\day + AC_CO2_ton\day

TOTAL_PRF_CO2_ton\day = PRF_CO2_ton\day + AC_CO2_ton\day

TOTAL_LPG_CO2_ton\day = LPG_CO2_ton\day + AC_CO2_ton\day

TOTAL_HP_CO2_ton\day = HP_CO2_ton\day

TOTAL_EB_CO2_ton\day = EB_CO2_ton\day + AC_CO2_ton\day

"------DETERMINE TOTAL IMPACT ON CH4------"

TOTAL_CSB_CH4\day = CSB_CH4\day + AC_CH4\day

TOTAL_PRF_CH4\day = PRF_CH4\day + AC_CH4\day

TOTAL_LPG_CH4\day = LPG_CH4\day + AC_CH4\day

TOTAL_HP_CH4\day = HP_CH4\day

TOTAL_EB_CH4\day = EB_CH4\day + AC_CH4\day

"------DETERMINE TOTAL IMPACT ON N2O------"

TOTAL_CSB_N2O\day = CSB_N2O\day + AC_N2O\day

TOTAL_PRF_N2O\day = PRF_N2O\day + AC_N2O\day

TOTAL_LPG_N2O\day = LPG_N2O\day + AC_N2O\day

TOTAL_HP_N2O\day = HP_N2O\day

TOTAL_EB_N2O\day = EB_N2O\day + AC_N2O\day

"------DETERMINE TOTAL IMPACT ON COAL------"

TOTAL_CSB_COAL_ton\day = SB_CSB_ton\day + AC_COAL\day * CONVERT (kg, tonne)

TOTAL_HP_COAL_ton\day = HP_COAL\day * CONVERT (kg, tonne)

"------COMPARE ENVIRONMENT OF THE ELECTRIC BOILER VS HP------"

DELTACOAL_HP_VS_EB\day = EB_COAL\day - HP_COAL\day

```
DELTAWATER_HP_VS_EB\day = EB_WATER\day - HP_WATER\day

DELTAASH_HP_VS_EB\day = EB_ASH\day - HP_ASH\day

DELTAParticle_HP_VS_EB\day = EB_Particle\day - HP_Particle\day

DELTANOx_HP_VS_EB\day = EB_NOx\day - HP_NOx\day

DELTASOx_HP_VS_EB\day = EB_SOx\day - HP_SOx\day

{
DELTA_CO2_HP_VS_EB\day = EB_CO2_ton\day - HP_CO2_ton\day

DELTA_CH4_HP_VS_EB\day = ( EB_CH4\day - HP_CH4\day )

DELTA_N2O_HP_VS_EB\day = ( EB_N2O\day - HP_N2O\day )
}

"------COMPARE COAL HP VS------"

DELTACOAL_HP_VS_CSB\day = TOTAL_CSB_COAL_ton\day - TOTAL_HP_COAL_ton\day

"------COMPARE CO2 HP VS------"

DELTACO2_HP_VS_CSB\day = TOTAL_CSB_CO2_ton\day - TOTAL_HP_CO2_ton\day

DELTACO2_HP_VS_PRF\day = TOTAL_PRF_CO2_ton\day - TOTAL_HP_CO2_ton\day

DELTACO2_HP_VS_LPG\day = TOTAL_LPG_CO2_ton\day - TOTAL_HP_CO2_ton\day

DELTACO2_HP_VS_EB\day = TOTAL_EB_CO2_ton\day - TOTAL_HP_CO2_ton\day

"------COMPARE CH4 HP VS------"

DELTACH4_HP_VS_CSB\day = TOTAL_CSB_CH4\day - TOTAL_HP_CH4\day

DELTACH4_HP_VS_PRF\day = TOTAL_PRF_CH4\day - TOTAL_HP_CH4\day

DELTACH4_HP_VS_LPG\day = TOTAL_LPG_CH4\day - TOTAL_HP_CH4\day

DELTACH4_HP_VS_EB\day = TOTAL_EB_CH4\day - TOTAL_HP_CH4\day

"------COMPARE N2O HP VS------"

DELTAN2O_HP_VS_CSB\day = TOTAL_CSB_N2O\day - TOTAL_HP_N2O\day

DELTAN2O_HP_VS_PRF\day = TOTAL_PRF_N2O\day - TOTAL_HP_N2O\day

DELTAN2O_HP_VS_LPG\day = TOTAL_LPG_N2O\day - TOTAL_HP_N2O\day

DELTAN2O_HP_VS_EB\day = TOTAL_EB_N2O\day - TOTAL_HP_N2O\day

"------------------ TOTAL COST CARBON TAX ------------------"
```

```
"------------------ USE VALUES IF ALL ARE AVAILABLE------------------"

CO2_TAX_CSB\day = CO2_TAX_R\kg * ( CSB_CO2_ton\day * convert( tonne, kg ) + CSB_CH4\day
* 23 + CSB_N2O\day * 296 )

CO2_TAX_PRF\day = CO2_TAX_R\kg * ( PRF_CO2_ton\day * convert( tonne, kg ) + PRF_CH4\day
* 23 + PRF_N2O\day * 296 )

CO2_TAX_LPG\day = CO2_TAX_R\kg * ( LPG_CO2_ton\day * convert( tonne, kg ) + LPG_CH4\day
* 23 + LPG_N2O\day * 296 )

CO2_TAX_HP\day = CO2_TAX_R\kg * ( HP_CO2_ton\day * convert( tonne, kg ) + HP_CH4\day * 23
+ HP_N2O\day * 296 )

CO2_TAX_EB\day = CO2_TAX_R\kg * ( EB_CO2_ton\day * convert( tonne, kg ) + LPG_CH4\day *
23 + LPG_N2O\day * 296 )

CO2_TAX_AC\day = CO2_TAX_R\kg * ( AC_CO2_ton\day * convert( tonne, kg ) + AC_CH4\day * 23
+ AC_N2O\day * 296 )


"------------------ TOTAL COST INCLUDING ( ENERGY & CO2 TAX ) ------------------"

TOTALCOST_CSB\day = TOTAL_EN_COST_CSB\day + CO2_TAX_CSB\day + CO2_TAX_AC\day

TOTALCOST_PRF\day = TOTAL_EN_COST_PRF\day + CO2_TAX_PRF\day + CO2_TAX_AC\day

TOTALCOST_LPG\day = TOTAL_EN_COST_LPG\day + CO2_TAX_LPG\day + CO2_TAX_AC\day

TOTALCOST_HP\day = TOTAL_EN_COST_HP\day + CO2_TAX_HP\day

TOTALCOST_EB\day = TOTAL_EN_COST_EB\day + CO2_TAX_EB\day + CO2_TAX_AC\day

TOTALCOST_AC\day = TOTAL_EN_COST_AC\day + CO2_TAX_AC\day


"----SAVINGS OF HEAT PUMP ( ENERGY & CO2 TAX ) -----"

SAVINGS_HP_VS_ELEC\day = TOTALCOST_EB\day - TOTALCOST_HP\day

SAVINGS_HP_VS_CSB\day = TOTALCOST_CSB\day - TOTALCOST_HP\day

SAVINGS_HP_VS_LPG\day = TOTALCOST_LPG\day - TOTALCOST_HP\day

SAVINGS_HP_VS_PRF\day = TOTALCOST_PRF\day - TOTALCOST_HP\day


"------------------ PARAMETRIC TABLE CALCULATIONS ------------------"

$IF PARAMETRICTABLE


// HP_AWW_AW_hrs\day_MAX = maxparametric( ZONE$, 'HP_AWW_AW_hrs\day')


"------------------ SUM PARAMETRIC VALUES ------------------"

P_HP\yr = sumparametric( ZONE$, 'P_HP\day')
```

```
P_EB\yr = sumparametric( ZONE$, 'P_EB\day')
P_AC\yr = sumparametric( ZONE$, 'P_AC\day')
Q_dot_SB\yr = sumparametric( ZONE$, 'Q_dot_SB\day')
SB_PRF_l\yr = sumparametric( ZONE$, 'SB_PRF_l\day')
SB_LPG\yr = sumparametric( ZONE$, 'SB_LPG\day')
SB_CSB_ton\yr = sumparametric( ZONE$, 'SB_CSB_ton\day')
P_EB_TOT\yr = P_EB\yr + P_AC\yr
E_dot_SB\yr = Q_dot_SB\yr + P_AC\yr

"------------------ COST OF ENERGY ------------------"
COST_EN_EB\yr = P_EB\yr * ENERGY_COST_kWh
COST_EN_HP\yr = P_HP\yr * ENERGY_COST_kWh
COST_EN_AC\yr = P_AC\yr * ENERGY_COST_kWh
COST_EN_PRF\yr = SB_PRF_l\yr * PRF_R\lit
COST_EN_LPG\yr = SB_LPG\yr * LPG_R\kg
COST_EN_CSB\yr = SB_CSB_ton\yr * Coal_R\ton

"------------------ TOTAL COST OF ENERGY ------------------"
TOTAL_EN_COST_CSB = COST_EN_CSB\yr + COST_EN_AC\yr
TOTAL_EN_COST_PRF = COST_EN_PRF\yr + COST_EN_AC\yr
TOTAL_EN_COST_LPG = COST_EN_LPG\yr + COST_EN_AC\yr
TOTAL_EN_COST_HP = COST_EN_HP\yr
TOTAL_EN_COST_EB = COST_EN_EB\yr + COST_EN_AC\yr
TOTAL_EN_COST_AC = COST_EN_AC\yr

"----SAVINGS OF HEAT PUMP (ONLY ENERGY COST) -----"
SAVINGS_EN_HP_VS_ELEC = TOTAL_EN_COST_EB - TOTAL_EN_COST_HP
SAVINGS_EN_HP_VS_CSB = TOTAL_EN_COST_CSB - TOTAL_EN_COST_HP
SAVINGS_EN_HP_VS_LPG = TOTAL_EN_COST_LPG - TOTAL_EN_COST_HP
SAVINGS_EN_HP_VS_PRF = TOTAL_EN_COST_PRF - TOTAL_EN_COST_HP
```

```
"------DETERMINE STRAIGHT PAYBACK (ONLY ENERGY COST) ------"

SPB_EN_HP_VS_ELEC = TOTAL_INPUT_COST / SAVINGS_EN_HP_VS_ELEC

SPB_EN_HP_VS_CSB = TOTAL_INPUT_COST / SAVINGS_EN_HP_VS_CSB

SPB_EN_HP_VS_LPG = TOTAL_INPUT_COST / SAVINGS_EN_HP_VS_LPG

SPB_EN_HP_VS_PRF = TOTAL_INPUT_COST / SAVINGS_EN_HP_VS_PRF


"----------------------------------ENVIRONMENTAL IMPACT OF THE VARIOUS OPTIONS-----------------
----------------"

"-----ENVIRONMENTAL IMPACT OF COAL STEAM BOILER [tonne\yr]-----"

CSB_CO2_ton\yr = Q_dot_SB\yr * CONVERT ( kWh , TJ ) * CO2_kg\TJ_CSB * CONVERT ( kg,
tonne )

CSB_CH4\yr = Q_dot_SB\yr * CONVERT ( kWh , TJ ) * CH4_kg\TJ_CSB

CSB_N2O\yr = Q_dot_SB\yr * CONVERT ( kWh , TJ ) * N2O_kg\TJ_CSB

"-----ENVIRONMENTAL IMPACT OF PARAFFIN STEAM BOILER-----"

PRF_CO2_ton\yr = Q_dot_SB\yr * CONVERT ( kWh , TJ ) * CO2_kg\TJ_PRF * CONVERT ( kg,
tonne )

PRF_CH4\yr = Q_dot_SB\yr * CONVERT ( kWh , TJ ) * CH4_kg\TJ_PRF

PRF_N2O\yr = Q_dot_SB\yr * CONVERT ( kWh, TJ ) * N2O_kg\TJ_PRF

"-----ENVIRONMENTAL IMPACT OF LPG STEAM BOILER-----"

LPG_CO2_ton\yr = Q_dot_SB\yr * CONVERT ( kWh , TJ ) * CO2_kg\TJ_LPG * CONVERT ( kg,
tonne )

LPG_CH4\yr = Q_dot_SB\yr * CONVERT ( kWh , TJ ) * CH4_kg\TJ_LPG

LPG_N2O\yr = Q_dot_SB\yr * CONVERT ( kWh , TJ ) * N2O_kg\TJ_LPG

"------DETERMINE ENVIRONMENT IMPACT OF THE AMMONIA CHILLER------"

AC_COAL\yr = P_AC\yr * Coal_kg\kWh

AC_WATER\yr = P_AC\yr * Water_l\kWh

AC_ASH\yr = P_AC\yr * Ash_g\kWh * CONVERT ( g, kg )

AC_Particle\yr = P_AC\yr * Particle_g\kWh * CONVERT ( g, kg )

AC_CO2_ton\yr = P_AC\yr * CO2_kg\kWh * CONVERT ( kg, tonne )

AC_NOx\yr = P_AC\yr * NOx_g\kWh * CONVERT ( g, kg )
```

```
AC_SOx\yr = P_AC\yr* SOx_g\kWh * CONVERT ( g, kg )
AC_CH4\yr = AC_COAL\yr * CV_COAL_ESC_MJ * CONVERT ( MJ, TJ ) * CH4_kg\TJ_ESC
AC_N2O\yr = P_AC\yr * N2O_g\kWh * CONVERT ( g, kg )

"------DETERMINE ENVIRONMENT OF THE HEAT PUMP (AWW)------"
HP_COAL\yr = P_HP\yr * Coal_kg\kWh
HP_WATER\yr = P_HP\yr * Water_l\kWh
HP_ASH\yr = P_HP\yr * Ash_g\kWh * CONVERT ( g, kg )
HP_Particle\yr = P_HP\yr * Particle_g\kWh * CONVERT ( g, kg )
HP_CO2_ton\yr = P_HP\yr * CO2_kg\kWh * CONVERT ( kg, tonne )
HP_NOx\yr = P_HP\yr * NOx_g\kWh * CONVERT ( g, kg )
HP_SOx\yr = P_HP\yr * SOx_g\kWh * CONVERT ( g, kg )
HP_CH4\yr = HP_COAL\yr * CV_COAL_ESC_MJ * CONVERT ( MJ, TJ ) * CH4_kg\TJ_ESC
HP_N2O\yr = P_HP\yr * N2O_g\kWh * CONVERT ( g, kg )

"------DETERMINE ENVIRONMENT OF THE ELECTRIC BOILER------"
EB_COAL\yr = P_EB_TOT\yr * Coal_kg\kWh
EB_WATER\yr = P_EB_TOT\yr * Water_l\kWh
EB_ASH\yr = P_EB_TOT\yr * Ash_g\kWh * CONVERT ( g, kg )
EB_Particle\yr = P_EB_TOT\yr * Particle_g\kWh * CONVERT ( g, kg )
EB_CO2_ton\yr = P_EB_TOT\yr * CO2_kg\kWh * CONVERT ( kg, tonne )
EB_NOx\yr = P_EB_TOT\yr * NOx_g\kWh * CONVERT ( g, kg )
EB_SOx\yr =P_EB_TOT\yr * SOx_g\kWh * CONVERT ( g, kg )
EB_CH4\yr = EB_COAL\yr * CV_COAL_ESC_MJ * CONVERT ( MJ, TJ ) * CH4_kg\TJ_ESC
EB_N2O\yr = P_EB_TOT\yr * N2O_g\kWh * CONVERT ( g, kg )

"------DETERMINE TOTAL IMPACT ON CO2------"
TOTAL_CO2_CSB = CSB_CO2_ton\yr + AC_CO2_ton\yr
TOTAL_CO2_PRF = PRF_CO2_ton\yr + AC_CO2_ton\yr
TOTAL_CO2_LPG = LPG_CO2_ton\yr + AC_CO2_ton\yr
TOTAL_CO2_HP = HP_CO2_ton\yr
```

```
TOTAL_CO2_EB = EB_CO2_ton\yr + AC_CO2_ton\yr

"------DETERMINE TOTAL IMPACT ON CH4------"
TOTAL_CH4_CSB = CSB_CH4\yr + AC_CH4\yr
TOTAL_CH4_PRF = PRF_CH4\yr + AC_CH4\yr
TOTAL_CH4_LPG = LPG_CH4\yr + AC_CH4\yr
TOTAL_CH4_HP = HP_CH4\yr
TOTAL_CH4_EB = EB_CH4\yr + AC_CH4\yr

"------DETERMINE TOTAL IMPACT ON N2O------"
TOTAL_N2O_CSB = CSB_N2O\yr + AC_N2O\yr
TOTAL_N2O_PRF = PRF_N2O\yr + AC_N2O\yr
TOTAL_N2O_LPG = LPG_N2O\yr + AC_N2O\yr
TOTAL_N2O_HP = HP_N2O\yr
TOTAL_N2O_EB = EB_N2O\yr + AC_N2O\yr

"------COMPARE ENVIRONMENT OF THE ELECTRIC BOILER VS HP------"
DELTA_COAL_HP_VS_EB = EB_COAL\yr - HP_COAL\yr
DELTA_WATER_HP_VS_EB = EB_WATER\yr - HP_WATER\yr
DELTA_ASH_HP_VS_EB = EB_ASH\yr - HP_ASH\yr
DELTA_Particle_HP_VS_EB = EB_Particle\yr - HP_Particle\yr
DELTA_CO2_HP_VS_EB = EB_CO2_ton\yr - HP_CO2_ton\yr
DELTA_NOx_HP_VS_EB =EB_NOx\yr - HP_NOx\yr
DELTA_SOx_HP_VS_EB = EB_SOx\yr - HP_SOx\yr
DELTA_CH4_HP_VS_EB = ( EB_CH4\yr - HP_CH4\yr )
DELTA_N2O_HP_VS_EB = ( EB_N2O\yr - HP_N2O\yr )

"------COMPARE CO2 HP VS------"
DELTA_CO2_HP_VS_CSB = CSB_CO2_ton\yr - HP_CO2_ton\yr
DELTA_CO2_HP_VS_PRF = PRF_CO2_ton\yr - HP_CO2_ton\yr
DELTA_CO2_HP_VS_LPG = LPG_CO2_ton\yr - HP_CO2_ton\yr
```

```
// DELTA_CO2_HP_VS_EB = EB_CO2_ton\yr - HP_CO2_ton\yr

"------------------ TOTAL COST CARBON TAX ------------------"

"------------------ USE VALUES IF ALL ARE AVAILABLE------------------"

CO2_TAX_CSB = CO2_TAX_R\kg * ( CSB_CO2_ton\yr * convert( tonne, kg ) + CSB_CH4\yr * 23 +
CSB_N2O\yr * 296 )

CO2_TAX_PRF = CO2_TAX_R\kg * ( PRF_CO2_ton\yr * convert( tonne, kg ) + PRF_CH4\yr * 23 +
PRF_N2O\yr * 296 )

CO2_TAX_LPG = CO2_TAX_R\kg * ( LPG_CO2_ton\yr * convert( tonne, kg ) + LPG_CH4\yr * 23 +
LPG_N2O\yr * 296 )

CO2_TAX_HP = CO2_TAX_R\kg * ( HP_CO2_ton\yr * convert( tonne, kg ) + HP_CH4\yr * 23 +
HP_N2O\yr * 296 )

CO2_TAX_EB = CO2_TAX_R\kg * ( EB_CO2_ton\yr * convert( tonne, kg ) + LPG_CH4\yr * 23 +
LPG_N2O\yr * 296 )

CO2_TAX_AC = CO2_TAX_R\kg * ( AC_CO2_ton\yr * convert( tonne, kg ) + AC_CH4\yr * 23 +
AC_N2O\yr * 296 )

 {
"------------------USE VALUES IF ONLY CO2 VALUES ARE AVAILABLE ------------------"

CO2_TAX_CSB =CO2_TAX_R\ton * ( CSB_CO2_ton\yr )

CO2_TAX_PRF = CO2_TAX_R\ton * ( PRF_CO2_ton\yr )

CO2_TAX_LPG = CO2_TAX_R\ton * ( LPG_CO2_ton\yr )

CO2_TAX_HP = CO2_TAX_R\ton * ( HP_CO2_ton\yr )

CO2_TAX_EB = CO2_TAX_R\ton * ( EB_CO2_ton\yr )

CO2_TAX_AC = CO2_TAX_R\ton * ( AC_CO2_ton\yr )
 }

"------------------ TOTAL COST INCLUDING ( ENERGY & CO2 TAX ) ------------------"

TOTALCOST_CSB = TOTAL_EN_COST_CSB + CO2_TAX_CSB + CO2_TAX_AC

TOTALCOST_PRF = TOTAL_EN_COST_PRF + CO2_TAX_PRF + CO2_TAX_AC

TOTALCOST_LPG = TOTAL_EN_COST_LPG + CO2_TAX_LPG + CO2_TAX_AC

TOTALCOST_HP = TOTAL_EN_COST_HP + CO2_TAX_HP

TOTALCOST_EB = TOTAL_EN_COST_EB + CO2_TAX_EB + CO2_TAX_AC

TOTALCOST_AC = TOTAL_EN_COST_AC + CO2_TAX_AC
```

```
"----SAVINGS OF HEAT PUMP ( ENERGY & CO2 TAX ) -----"
SAVINGS_HP_VS_ELEC = TOTALCOST_EB - TOTALCOST_HP
SAVINGS_HP_VS_CSB = TOTALCOST_CSB - TOTALCOST_HP
SAVINGS_HP_VS_LPG = TOTALCOST_LPG - TOTALCOST_HP
SAVINGS_HP_VS_PRF = TOTALCOST_PRF - TOTALCOST_HP

"------DETERMINE STRAIGHT PAYBACK (ENERGY & CO2 TAX) ------"
SPB_HP_VS_ELEC =TOTAL_INPUT_COST / SAVINGS_HP_VS_ELEC
SPB_HP_VS_CSB = TOTAL_INPUT_COST / SAVINGS_HP_VS_CSB
SPB_HP_VS_LPG = TOTAL_INPUT_COST / SAVINGS_HP_VS_LPG
SPB_HP_VS_PRF = TOTAL_INPUT_COST / SAVINGS_HP_VS_PRF

$ENDIF
```

Appendix D Detail EES results of the CO_2 HP cycle, steam- and electric boiler

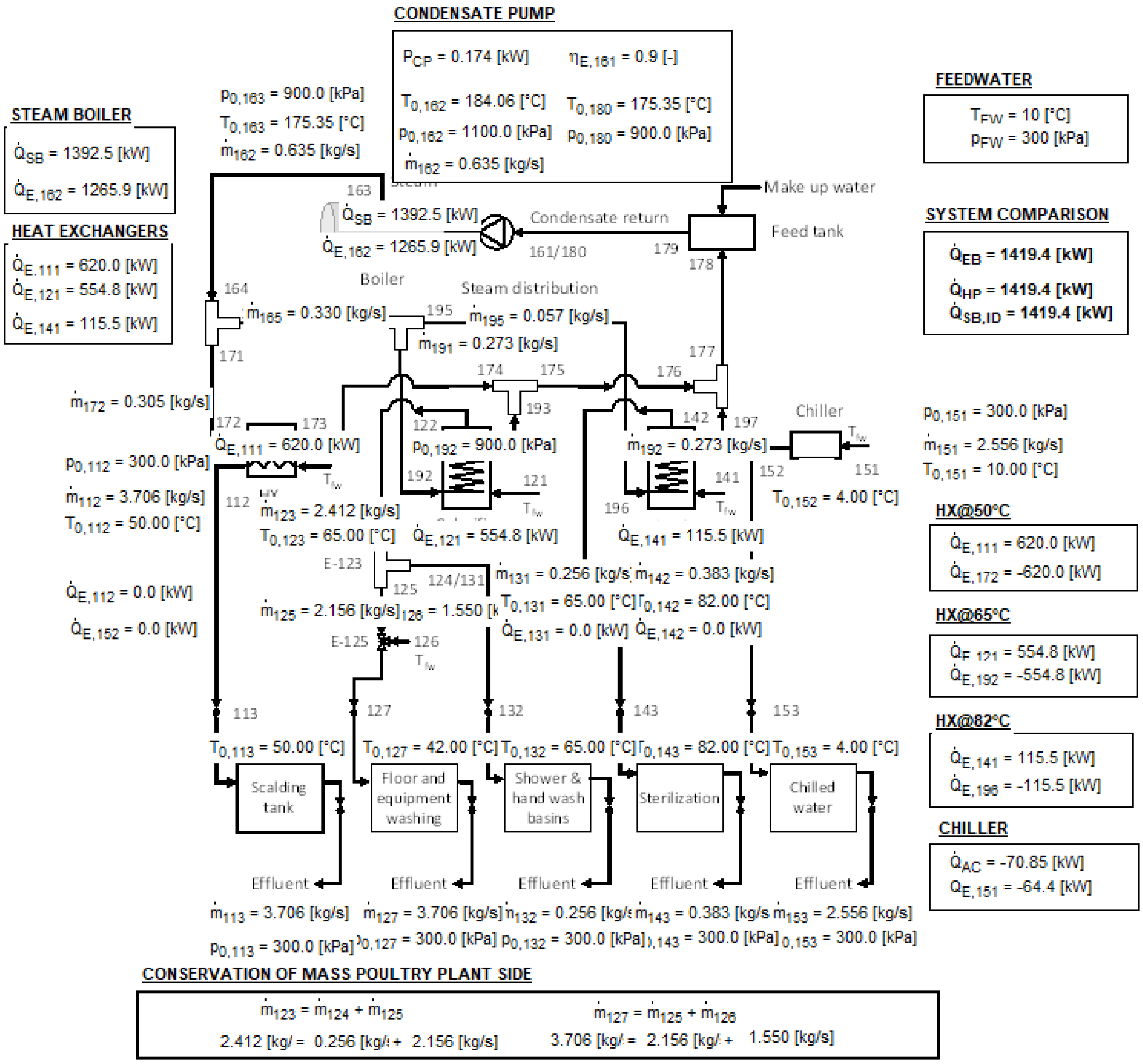


Figure 79: Detail EES results of the steam boiler

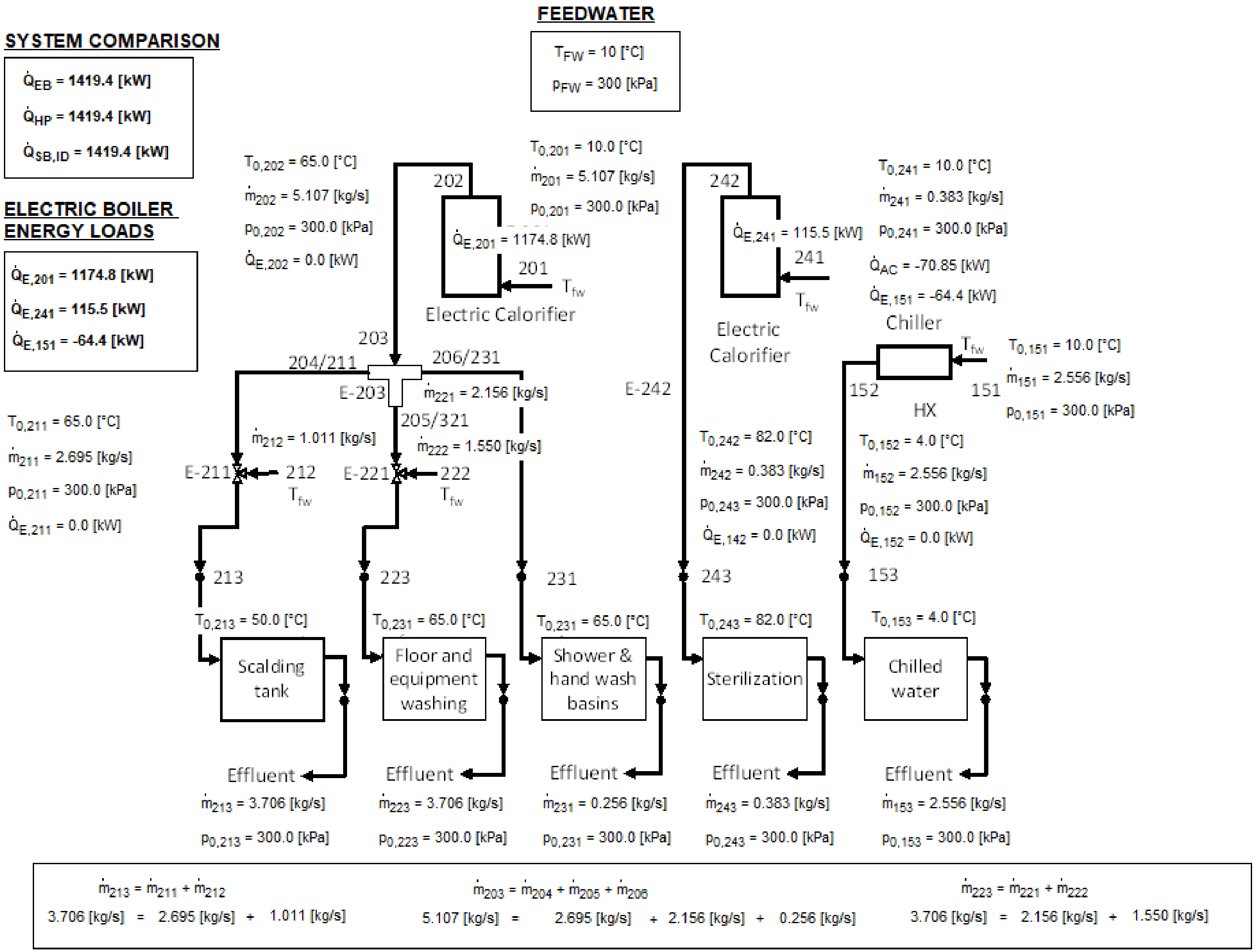


Figure 80: Detail EES results of the electric boiler.

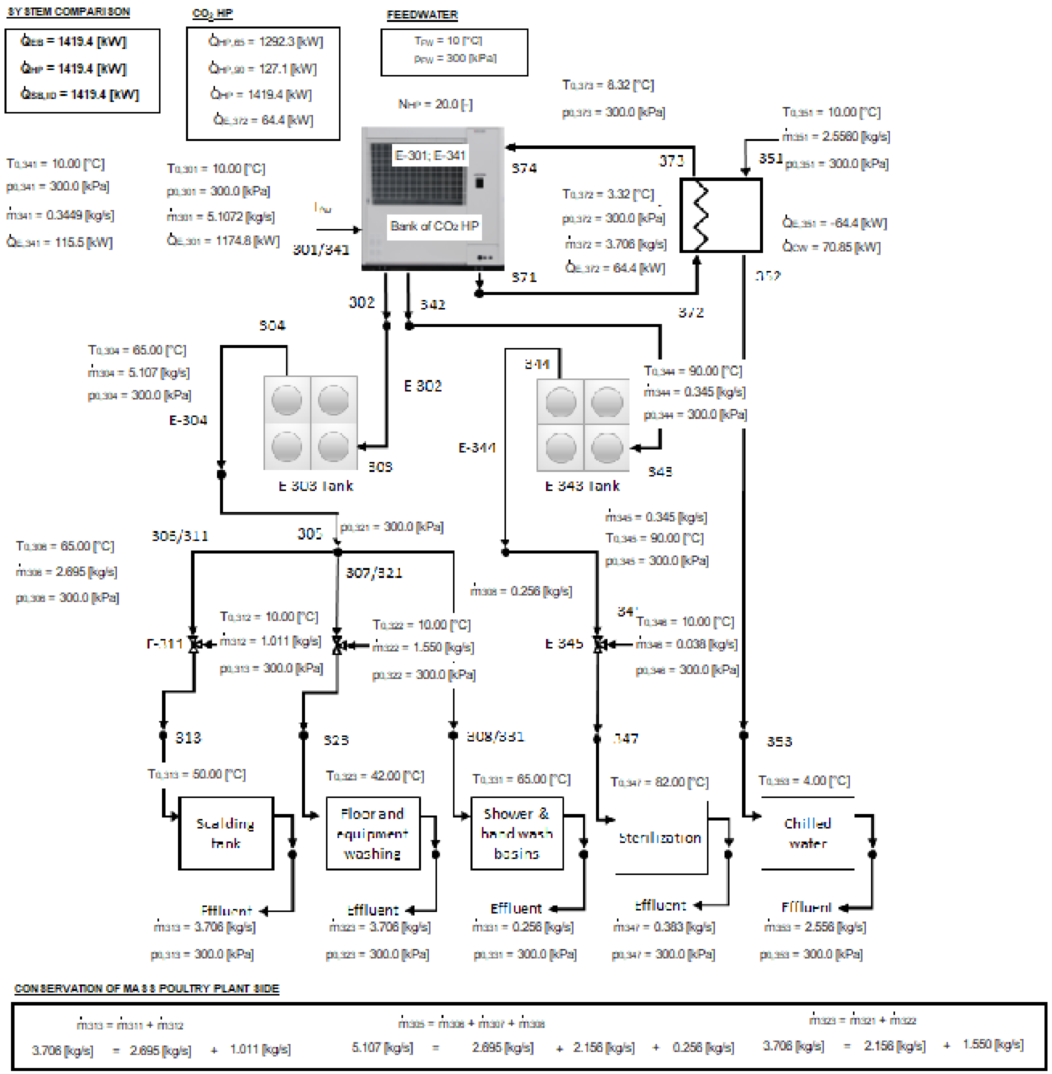
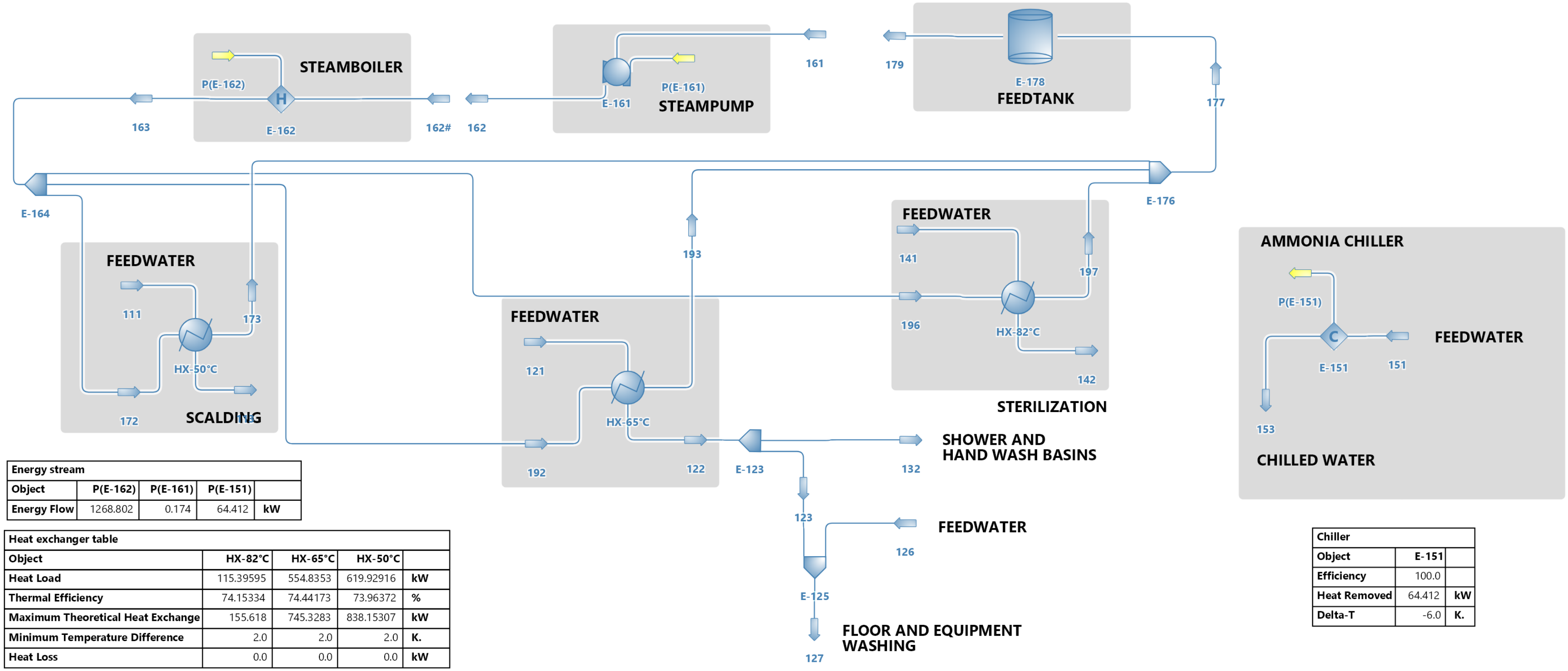


Figure 81: Detail EES results of the CO₂ HP.DHSIM results of the CO₂ HP cycle, steam- and electric boiler

Appendix E Detail DWSIM results of the CO_2 HP cycle, steam- and electric boiler



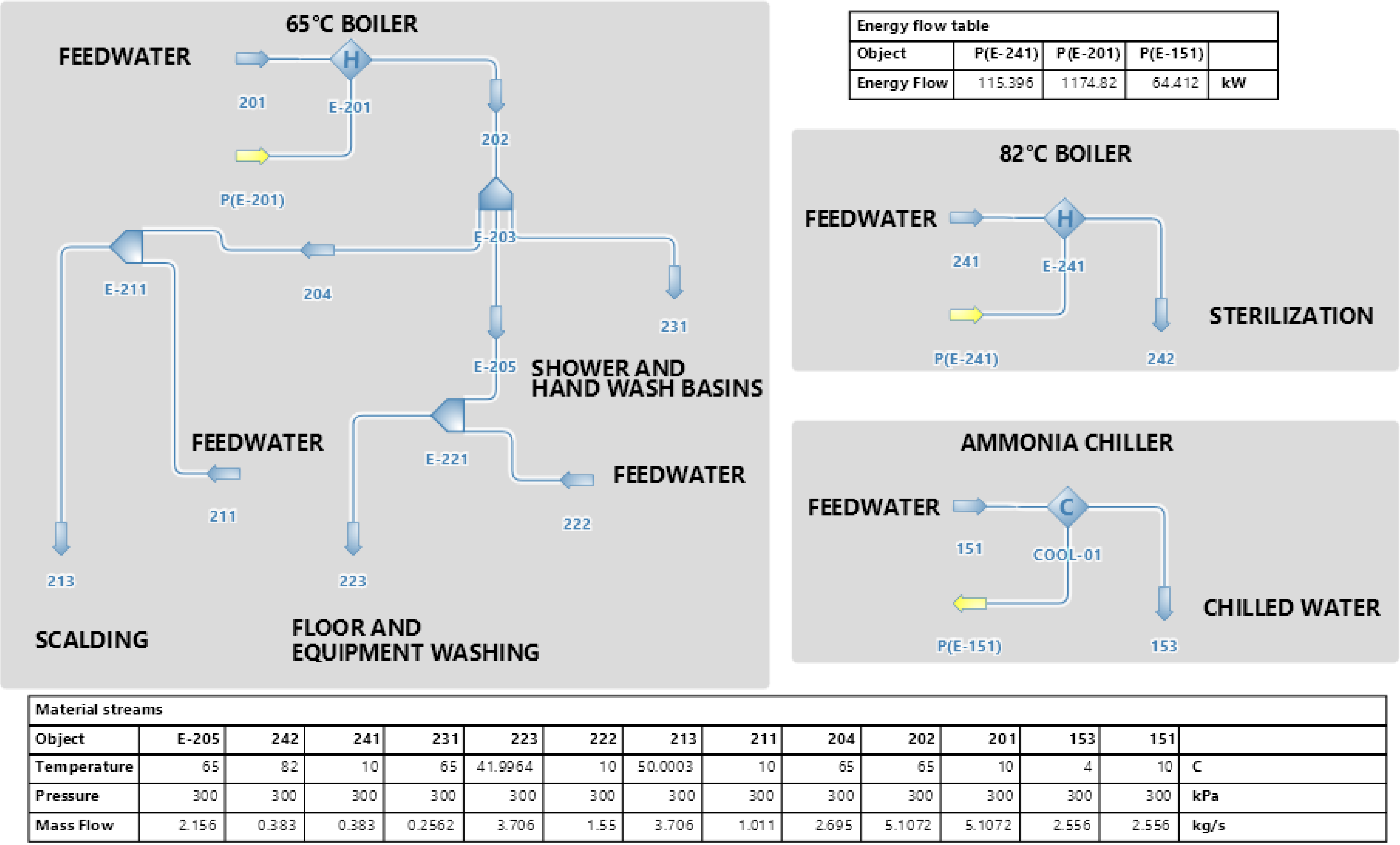
Energy stream				
Object	**P(E-162)**	**P(E-161)**	**P(E-151)**	
Energy Flow	1268.802	0.174	64.412	**kW**

Heat exchanger table				
Object	**HX-82°C**	**HX-65°C**	**HX-50°C**	
Heat Load	115.39595	554.8353	619.92916	**kW**
Thermal Efficiency	74.15334	74.44173	73.96372	**%**
Maximum Theoretical Heat Exchange	155.618	745.3283	838.15307	**kW**
Minimum Temperature Difference	2.0	2.0	2.0	**K.**
Heat Loss	0.0	0.0	0.0	**kW**

Chiller		
Object	**E-151**	
Efficiency	100.0	
Heat Removed	64.412	**kW**
Delta-T	-6.0	**K.**

Material stream																									
Object	**127**	**113**	**111**	**153**	**151**	**121**	**122**	**123**	**126**	**177**	**163**	**161**	**162#**	**179**	**162**	**141**	**142**	**173**	**172**	**192**	**193**	**132**	**196**	**197**	
Temperature	41.99642	50.0	10.0	4.0	10.0	10.0	65.0	65.0	10.0	175.35782	175.35782	175.35782	184.06968	175.35782	174.79808	10.0	82.0	175.35782	175.35782	175.35782	174.89041	65.0	175.35782	175.35782	**C**
Pressure	300.0	300.0	300.0	300.0	300.0	300.0	300.0	300.0	300.0	900.0	900.0	900.0	1100.0	900.0	1100.0	300.0	300.0	900.0	900.0	900.0	900.0	300.0	900.0	900.0	**kPa**
Mass Flow	3.706	3.706	3.706	2.556	2.556	2.412	2.412	2.156	1.55	0.637	0.637	0.637	0.637	0.637	0.635	0.383	0.383	0.307	0.307	0.273	0.273	0.256	0.057	0.057	**kg/s**

Figure 82: Detail DWSIM results of the steam boiler



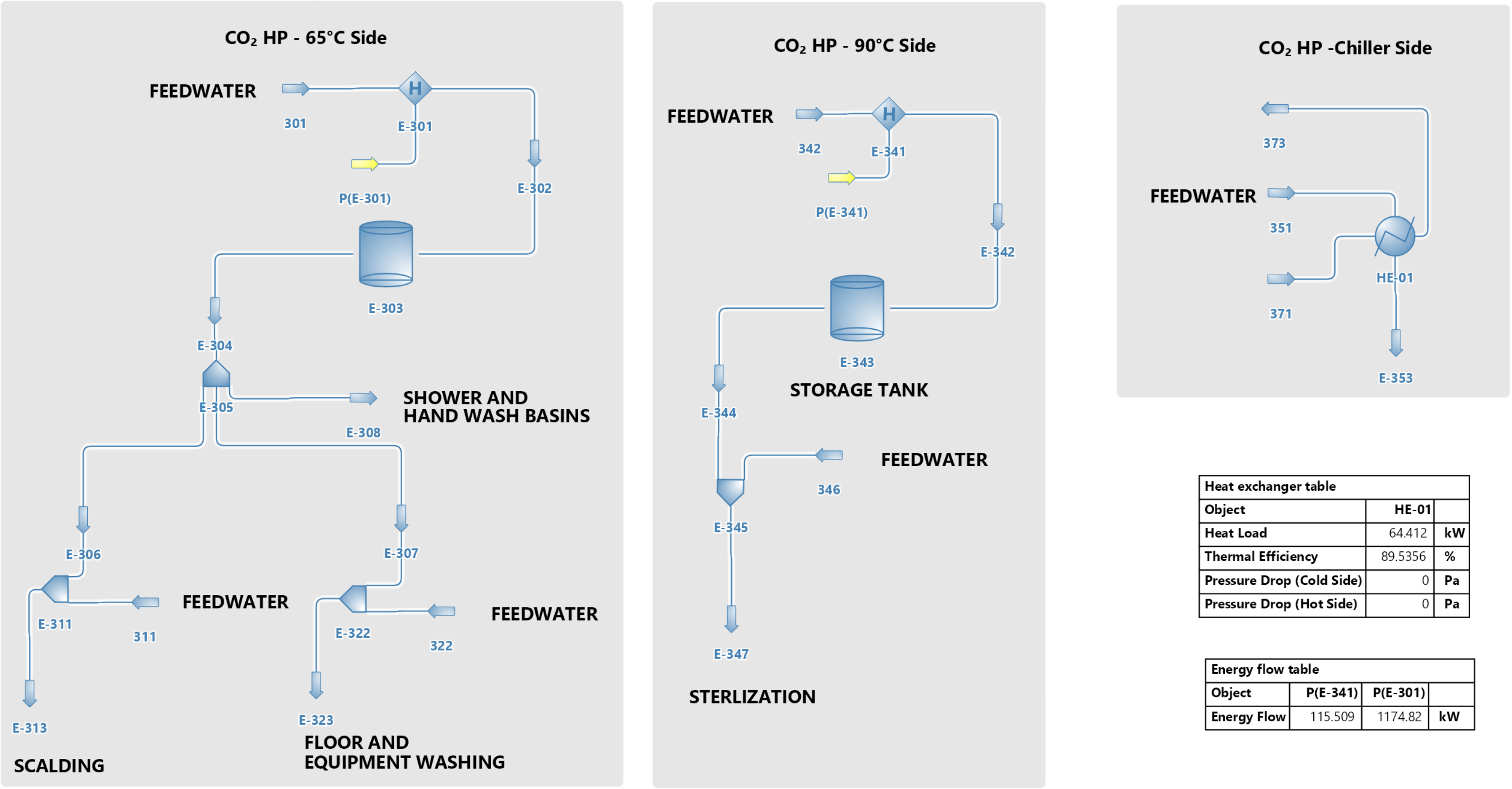
Energy flow table

Object	P(E-241)	P(E-201)	P(E-151)	
Energy Flow	115.396	1174.82	64.412	kW

Material streams

Object	E-205	242	241	231	223	222	213	211	204	202	201	153	151	
Temperature	65	82	10	65	41.9964	10	50.0003	10	65	65	10	4	10	C
Pressure	300	300	300	300	300	300	300	300	300	300	300	300	300	kPa
Mass Flow	2.156	0.383	0.383	0.2562	3.706	1.55	3.706	1.011	2.695	5.1072	5.1072	2.556	2.556	kg/s

Figure 83: Detail DWSIM results of the electric boiler



Heat exchanger table		
Object	**HE-01**	
Heat Load	64.412	**kW**
Thermal Efficiency	89.5356	**%**
Pressure Drop (Cold Side)	0	**Pa**
Pressure Drop (Hot Side)	0	**Pa**

Energy flow table			
Object	**P(E-341)**	**P(E-301)**	
Energy Flow	115.509	1174.82	**kW**

Material streams																				
Object	**E-353**	**E-347**	**E-344**	**E-342**	**E-323**	**E-313**	**E-308**	**E-307**	**E-306**	**E-304**	**E-302**	**373**	**371**	**351**	**346**	**342**	**322**	**311**	**301**	
Temperature	4	82.0888	90	90	41.9964	50.0003	65	65	65	65	65	7.4348	3.3	10	10	10	10	10	10	**C**
Pressure	300	300	300	300	300	300	300	300	300	300	300	300	300	300	300	300	300	300	300	**kPa**
Mass Flow	2.556	0.3829	0.3449	0.3449	3.706	3.706	0.2562	2.156	2.695	5.1072	5.1072	3.706	3.706	2.556	0.038	0.3449	1.55	1.011	5.1072	**kg/s**

Figure 84: Detail DWSIM results of the CO_2 HP

Appendix F Locations of cities and towns according to their climatic zone

Table 42: Locations of cities and towns according to their climatic zone. Source: (SABS, 2011a); (SABS, 2011b), Own research

Location	**Zone**	**Defined by author**	**Location**	**Zone**	**Defined by author**
Alexander	4		Colesberg	1	
Aliwal North	1		Cornelia	1	YES
Amsterdam	2		Cradock	2	
Augrabies falls	6	YES	Cramond	5	YES
Baberton	2		Cullinan	2	YES
Badplaas	2		Danielskuil	2	YES
Barrydale	4		Dealsville	1	
Beaufort West	2		Delmas	1	
Bela-Bela	2	YES	Dendron	2	
Bloemfontein	1		Derdepoort	2	
Boshoff	2		Dordrecht	1	
Bothaville	1	YES	Drakensberg	1	
Brakpan	1		Dullstroom	1	
Brandfort	2		Dundee	2	
Brits	2	YES	Durban	5	
Broederstroom	2	YES	Durbanville	4	YES
Butterworth	5		East London	5	
Calvinia	2		Elgin	4	YES
Camperdown	5	YES	Elliot	1	
Cape Agulhas	4		Ermelo		
Cape of Good Hope	4		Estcourt		
Cape Town	4		Frankfort		
Carletonville	1	YES	George		
Carolina	1	YES	Giyani		
Cato Ridge	5	YES	Gordons baai		
Cederberg	4		Gouda		
Centurion	2		Graaff-Reinet		
Ceres	2		Grabouw		

Location	Zone	Defined by author	Location	Zone	Defined by author
Grahamstown	4		Kirkwood	4	
Graskop	3		Klerksdorp	1	
Gravelot	2		Kokstad	2	
Greytown	2	YES	Komatipoort	3	
Groot Brakrivier	4	YES	Koppies	1	YES
Harding	2	YES	Kraaifontein	4	YES
Harrismith	1		Kroondal	2	YES
Hartbeesfontein	1		Kroonstad	1	
Hartebeespoort	2	YES	Kruger National Park	3	
Hartswater	2	YES	Krugersdorp	1	
Hattingspruit	2	YES	Kubus	4	
Heidelberg	4		Kuruman	2	
Hendrina	1	YES	Ladysmith	2	
Hennenman	1	YES	Laingsburg	1	
Hillcrest	5	YES	Leeudoringstad	1	YES
Hopefield	4	YES	Ellisras	3	YES
Hopetown	1		Lichtenburg	2	YES
Hotazel	2		Lydenburg	2	YES
Humansdorp	4	YES	Magaliesburg	2	YES
Hutchinson	1		Mafikeng	2	YES
Jacobsdal	6		Makhado	3	
Jagersfontein	1	YES	Malmesbury	4	YES
Jan Kempdorp	1		Margate	5	YES
Jansenville	2	YES	Marken	3	
Johannesburg	1		Nelspruit	3	YES
Joubertina	4	YES	Melmoth	5	
Kaapsehoof	2	YES	Meyerton	1	YES
Kabokweni	3	YES	Mica	3	
Kainoplaagte	6		Middelburg	1	
Kammieskroon	4		Midrand	1	
Kathu	6	YES	Mkuze	5	
Kimberley	6		Mmabatho	2	
King William's town	5	YES	Montagu	2	YES
Kirkwood	4		Mossel	4	
Klerksdorp	1		Mpumalanga	5	YES

Location	Zone	Defined by author	Location	Zone	Defined by author
Mossel Bay	4	YES	Port St Johns	5	
Mpumalanga	5	YES	Potchefstroom	1	YES
Mt. Edgecombe	5	YES	Potgietersrus	2	YES
Umtata	5	YES	Pretoria	2	YES
Musina	3		Prieska	6	
Naboomspruit	2	YES	Pudimoe	1	
Newcastle	1		Queenstown	2	
Niewoudt	4		Randfontein	1	YES
Nigel	1	YES	Randvaal	1	YES
Northam	2		Reddersburg	1	YES
Nylstroom	2	YES	Reitz	1	YES
Odendaalsrus	1	YES	Reivilo	2	
Olifantsfontein	1	YES	Richards Bay	5	
Olifantshoek	6		Richmond	2	
Ottosdal	2		Rietfontein	2	YES
Oudshoorn	2		Riversdale	4	
Paarl	4	YES	Rooibokkraal	3	
Paulpietersburg	2	YES	Rouxville	1	YES
Pearston	2	YES	Rustenburg	2	YES
Petrusburg	1		Sabie	3	
Phalaborwa	3		Sakrivier	6	
Piet Plessis	2		Saldanha	4	
Piet Retief	2		Sannieshof	1	YES
Pietermaritzburg	5		Sibasa	3	
Pilgrims Rest	2		Skeerpoort	2	YES
Plettenberg Bay	4	YES	Soweto	1	
Pofadder	6		Springs	1	
Pietersburg	2		St Lucia	5	
Pongola	2		St. Michaels On Sea	5	YES
Port Alfred	4	YES	Standerton	1	
Port Elizabeth	4		Steelpoort	2	YES
Port Nolloth	4		Stella	1	YES
Port Shepstone	5	YES	Stellenbosch	4	
Port St Johns	5		Steytlerville	2	
Potchefstroom	1	YES	Stoffberg	2	

Location	Zone	Defined by author	Location	Zone	Defined by author
Steytlerville	2		Victoria West	1	
Stoffberg	2		Viljoenskroon	1	YES
Stutterheim	2		Vioolsdrif	2	
Sundra	1	YES	Virginia	1	
Swartberg	1		Volksrust	1	
Swellendam	4		Vredefort	1	YES
Thabazimbi	3		Vryburg	2	
Theunissen	1	YES	Vryheid	2	YES
Tigane	1	YES	Warrenton	2	YES
Toska	6		Warrinton	2	
Touwsrivier	2		Watervalboven	1	
Tzaneen	2	YES	Welkom	1	
Uitenhage	4		Wellington	4	
Ulundi	5		Wesselsbron	1	YES
Umhlali	5	YES	White River	3	YES
Upington	6		Williston	1	
Utrecht	2		Windsorton	2	YES
Vanderbijlpark	1	YES	Winterveld	2	YES

Appendix G CO$_2$ HP data tables and curve fits

G.1 Original CO$_2$ HP data tables

Table 43: Original performance data of the WW CO$_2$ HP at a hot water supply temperature of 65°C. Source:Mayekawa (2013b).

Heat source [°C]			Inlet water temperature				
Inlet	Outlet	Capacity (kw)	10 °C	15 °C	20 °C	25 °C	30 °C
37	32	Heating	119.7	115.8	-	-	-
		Cooling	103.5	94.5	-	-	-
		Power	22.6	23.2	-	-	-
22	17	Heating	104.4	101.2	98.0	94.0	-
		Cooling	82.5	78.5	74.8	69.8	-
		Power	24.0	24.8	25.6	26.4	-
12	7	Heating	87.5	84.8	81.9	78.7	75.5
		Cooling	66.5	63.2	59.7	56.1	52.4
		Power	22.9	23.5	24.1	24.7	25.2
-5	-9	Heating	51.4	49.9	48.0	46.3	-
		Cooling	35.0	33.4	31.6	29.7	-
		Power	17.8	17.9	18.0	18.1	-

Table 44: Original performance data of the WW CO$_2$ HP at a hot water supply temperature of 90°C. Source: Mayekawa (2013b)

Heat source [°C]			Inlet water temperature				
Inlet	outlet	Capacity (kw)	10 °C	20 °C	30 °C	40 °C	50 °C
37	32	Heating	110.0	103.0	95.0	82.7	60.6
		Cooling	86.2	79.5	71.0	58.8	36.6
		Power	25.7	25.8	25.9	26.0	26.1
22	17	Heating	97.7	92.3	85.8	77.1	65.9
		Cooling	72.6	67.0	60.2	51.7	40.1
		Power	27.5	27.6	27.7	27.8	27.9
12	7	Heating	83.2	78.6	72.8	65.9	-
		Cooling	59.9	55.1	49.3	42.1	-
		Power	25.4	25.5	25.6	25.7	-
-5	-9	Heating	52.2	48.8	44.8	-	-
		Cooling	35.6	28.2	28.2	-	-
		Power	18.0	18.3	18.3	-	-

Table 45: Original performance data of the AW CO_2 HP. Source: Mayekawa (2011)

Ambient dry bulb temperature [°C]	**Ambient wet-bulb temperature [°C]**	**Hot water inlet temperature [°C]**	**Hot water outlet temperature [°C]**	**Heating capacity [kW]**	**Power [kW]**	**COP [-]**
25	21	24	65	92.3	21.6	4.3
16	12	17	65	81.4	20.0	4.1
7	6	9	65	77.4	25.1	3.1
25	21	24	90	90.2	25.7	3.5
16	12	17	90	78.5	23.5	3.3
7	6	9	90	73.9	27.5	2.7

G.2 Calibrated CO_2 HP data tables

Table 46: Calibrated performance data of the WW CO_2 HP at a hot water supply temperature of 65°C.

Heat source [°C]			**Inlet water temperature**				
Inlet	**Outlet**	**Capacity (kw)**	**10 °C**	**15 °C**	**20 °C**	**25 °C**	**30 °C**
22	**17**	**Heating**	105.6	102.3	99.1	95.1	-
		Cooling	88.7	84.4	80.4	75.0	-
		Power	21.2	21.9	22.6	23.3	-
12	**7**	**Heating**	81.1	78.6	75.9	72.9	69.9
		Cooling	60.1	57.2	54.0	50.7	47.4
		Power	22.5	23.1	23.7	24.3	24.8
-5	**-9**	**Heating**	51.4	49.9	48.0	46.3	-
		Cooling	35.0	33.4	31.6	29.7	-
		Power	17.8	17.9	18.0	18.1	-

Table 47: Calibrated performance data of the WW CO_2 HP at a hot water supply temperature of 90°C.

Heat source [°C]			**Inlet water temperature**				
Inlet	**outlet**	**Capacity (kw)**	**10 °C**	**20 °C**	**30 °C**	**40 °C**	**50 °C**
22	**17**	**Heating**	97.7	92.3	85.8	77.1	65.9
		Cooling	72.6	67.0	60.2	51.7	40.1
		Power	27.5	27.6	27.7	27.8	27.9
12	**7**	**Heating**	83.2	78.6	72.8	65.9	-
		Cooling	59.9	55.1	49.3	42.1	-
		Power	25.4	25.5	25.6	25.7	-
-5	**-9**	**Heating**	52.2	48.8	44.8	-	-
		Cooling	35.6	28.2	28.2	-	-
		Power	18.0	18.3	18.3	-	-

Table 48: Original performance data of the AW CO_2 HP.

Ambient dry bulb temperature [°C]	Ambient wet-bulb temperature [°C]	Hot water inlet temperature [°C]	Hot water outlet temperature [°C]	Heating capacity [kW]	Power [kW]	COP [-]
25	21	24	65	84.6	21.9	3.9
16	12	17	65	79.2	19.7	4.0
7	6	9	65	73.5	25.1	2.9
25	21	24	90	82.7	26.1	3.2
16	12	17	90	76.4	23.1	3.3
7	6	9	90	70.2	27.5	2.6

G.3 EES program to determine the coefficients of the CO_2 HP curve fit

```
"------------------------------------------------------------------------------------------------------------------------"
"|  PROGRAM TO DETERMINE THE COEFFICIENTS OF THE COP, m_dot etc                                                          |"
"|   OF THE MAYEKAWA CO2 HP                                                                                              |"
"|   WRITTEN BY WH KAISER                                                                                                |"
"------------------------------------------------------------------------------------------------------------------------"

"----- INPUTS ----- "

"-- Data table used --"
// TABLE$ = 'Unimo -WW -65°C'
TABLE$ = 'Unimo -WW -90°C'
// TABLE$ = 'Unimo -AW'

"-- Coefficient table used --"

// COEFF$ = 'COEFF -WW 65°C'
COEFF$ = 'COEFF -WW 90°C'
// COEFF$ = 'COEFF -AW'

"-- Lookup table for coefficients --"

Duplicate i = 1, 6
    c_COP_c[i] = lookup(COEFF$, i ,1)
    c_COP_h[i] = lookup(COEFF$, i ,2)
    c_m_cw[i] = lookup(COEFF$, i , 3)
    c_m_bcw[i] = lookup(COEFF$, i , 4)
    c_m_hw[i] = lookup(COEFF$, i , 5)
    c_Q_c[i] = lookup(COEFF$, i , 6)
    c_Q_h[i] = lookup(COEFF$, i , 7)
End


"-- Atmospheric conditions --"

P_atm = 101.325 [kPa]
P_w_MPa = 15 [MPa]
P_w = P_w_MPa * CONVERT ( MPa, KPa )


"-- Brine properites --"
BRINE$ =  'PG'                                          " Propylene Glycol-Water brine solution "
CTRN = 50 [%]                                           " Brine Concentration "


"----- CALCULATIONS ------"
"-----------------------------------"

"-- Number of rows --"

n = nlookuprows(TABLE$)
// n = 1                                                " Use n = 1 during debugging "

"-- Solving the coefficients --"
```

```
Duplicate i = 1, n

    HP$[i] = TABLE$

    No[i] = lookup(TABLE$, i ,1)
    T_db_in_C[i] = lookup(TABLE$, i ,2)
    T_db_out_C[i] = lookup(TABLE$, i ,3)
    T_wb_in_C[i] = lookup(TABLE$, i ,4)
    T_wb_out_C[i] = lookup(TABLE$, i ,5)
    T_cw_in_C[i] = lookup(TABLE$, i ,6)
    T_cw_out_C[i] = lookup(TABLE$, i ,7)
    T_hw_in_C[i] = lookup(TABLE$, i ,8)
    T_hw_out_C[i] = lookup(TABLE$, i ,9)
    Q_h[i] = lookup(TABLE$, i , 10)
    Q_c[i] = lookup(TABLE$, i , 11)
    P[i] = lookup(TABLE$, i , 12)

    "---DETERMINE COP--"
    COP_h[i] = Q_h[i] / P[i]
    COP_c[i] = Q_c[i] / P[i]

    "-- Detemine air inlet conditions--"
    "--------------------------------------------------"

    h_air_in[i] = enthalpy( AIRH2O , P = P_atm, T = T_db_in_C[i], B = T_wb_in_C[i] )

    "-- Detemine temperatures in Kelvin--"
    "---------------------------------------------------------"

    T_db_in[i] = converttemp('C', 'K', T_db_in_C[i])
    T_db_out[i] = converttemp('C', 'K', T_db_in_C[i])
    T_wb_in[i] = converttemp('C', 'K', T_wb_in_C[i])
    T_wb_out[i] = converttemp('C', 'K', T_wb_out_C[i])
    T_hw_in[i] = converttemp('C', 'K', T_hw_in_C[i])
    T_hw_out[i] = converttemp('C', 'K', T_hw_out_C[i])
    T_cw_in[i] = converttemp('C', 'K', T_cw_in_C[i])
    T_cw_out[i] = converttemp('C', 'K', T_cw_out_C[i])

    "--Determine the cold water mass flow--"
    "-----------------------------------------------------------"

    Q_c[i] = m_dot_cw[i] * c_p_CW[i] * DELTAT_cw[i]
    c_p_CW[i] = CP ( Water, T = T_cw_in_C[i], P = P_w )
    DELTAT_cw[i] =  - ( T_cw_out[i] - T_cw_in[i] )

    m_dot_cw_kg\min[i] = m_dot_cw[i] * CONVERT ( kg/s, kg/min )
    VOL_cw\day[i] = m_dot_cw[i] * CONVERT ( kg/s, kg/hr ) * 24 [hr/day] / rho_cw[i]
    rho_cw[i] = DENSITY ( Water, T = T_cw_in_C[i] , p = P_w )

    "--Determine the brine-chilled mass flow--"
    "--------------------------------------------------------------"

    Q_c[i] = m_dot_bcw[i] * c_p_bcw[i] * DELTAT_bcw[i]
    c_p_bcw[i] = CP ( BRINE$, T = T_cw_in_C[i] , C = CTRN, p = P_w )
    DELTAT_bcw[i] =  - ( T_cw_out[i] - T_cw_in[i] )

    m_dot_bcw_kg\min[i] = m_dot_bcw[i] * CONVERT ( kg/s, kg/min )
    VOL_bcw\day[i] = m_dot_bcw[i] * CONVERT ( kg/s, kg/hr ) * 24 [hr/day] / rho_bcw[i]
    rho_bcw[i] = DENSITY ( BRINE$, T = T_cw_in_C[i] , C = CTRN, p = P_w )
```

```
    "--Determine the hot water mass flow--"
    "-----------------------------------------------------"

    Q_h[i] = m_dot_hw[i] * ( h_hw_out[i] - h_hw_in[i] )
    h_hw_in[i] = ENTHALPY ( Water, T = T_hw_in_C[i], P = P_w )
    h_hw_out[i] = ENTHALPY ( Water, T = T_hw_out_C[i], P = P_w )
    c_p_HW[i] = CP ( Water, T = T_hw_in_C[i], P = P_w )
    DELTAT_hw[i] = T_hw_out[i] - T_hw_in[i]

    m_dot_hw_kg\min[i] = m_dot_hw[i] * CONVERT ( kg/s, kg/min )
    VOL_HW\day[i] = m_dot_hw[i] * CONVERT ( kg/s, kg/hr ) * 24 [hr/day] / rho_hw[i]
    rho_hw[i] = DENSITY ( Water, T = T_hw_in_C[i] , p = P_w )


    "  Determine the curve fit for Q cooling"
    "-----------------------------------------------------"
    Q_c_CV_WW[i] = c_Q_c[1] + c_Q_c[2] * T_cw_in[i] + c_Q_c[3] * DELTAT_hw[i] + c_Q_c[4] *
T_cw_in[i] * DELTAT_hw[i] + c_Q_c[5] * T_cw_in[i]^2 + c_Q_c[6] * DELTAT_hw[i]^2"For water-water
CO2 HP "

    Q_c_CV[i] = Q_c_CV_WW[i]

   " Determine the various errors "
    ERR_Q_c[i] = ( Q_c[i] - Q_c_CV[i] )^2                    " Determine square of the error "

    ERR_Q_c%[i] = ( Q_c[i] - Q_c_CV[i] ) / Q_c[i] * 100[%]      " Determine the error percentage "
    ABSERR_Q_c[i] = ABS ( Q_c[i] - Q_c_CV[i] )               " Determine absolute error "



    "  Determine the curve fit for Q heating"
    "-----------------------------------------------------"

    Q_h_CV_WW[i] = c_Q_h[1] + c_Q_h[2] * T_cw_in[i] + c_Q_h[3] * DELTAT_hw[i] + c_Q_h[4] *
T_cw_in[i] * DELTAT_hw[i] + c_Q_h[5] * T_cw_in[i]^2 + c_Q_h[6] * DELTAT_hw[i]^2
    "For water-water CO2 HP "
    Q_h_CV_AW[i] = c_Q_h[1] + c_Q_h[2] *h_air_in[i] + c_Q_h[3] * DELTAT_hw[i] + c_Q_h[4] *
h_air_in[i] * DELTAT_hw[i] + c_Q_h[5] * h_air_in[i]^2 + c_Q_h[6] * DELTAT_hw[i]^2
    "For air-water CO2 HP "

//  Q_h_CV[i] = Q_h_CV_AW[i]                             " Comment when WW mode is solved "
    Q_h_CV[i] = Q_h_CV_WW[i]                             " Comment when AW mode is solved "

   " Determine the various errors "
    ERR_Q_h[i] = ( Q_h[i] -Q_h_CV[i] )^2                    " Determine square of the error "
    ERR_Q_h%[i] = ( Q_h[i] -Q_h_CV[i] ) / Q_h[i] * 100[%]      " Determine the error percentage "
    ABS_ERR_Q_h[i] = ABS ( Q_h[i] -Q_h_CV[i] )              " Determine absolute error "



    "  Determine the curve fit for COP heating"
    "--------------------------------------------------------"

    COP_h_CV_WW[i] = c_COP_h[1] + c_COP_h[2] * T_cw_in[i] + c_COP_h[3] * DELTAT_hw[i] +
c_COP_h[4] * T_cw_in[i] * DELTAT_hw[i] + c_COP_h[5] * T_cw_in[i]^2 + c_COP_h[6] *
DELTAT_hw[i]^2                                           "For water-water CO2 HP "
```

```
    COP_h_CV_AW[i] = c_COP_h[1] + c_COP_h[2] * h_air_in[i] + c_COP_h[3] * DELTAT_hw[i]  +
c_COP_h[4] * h_air_in[i] * DELTAT_hw[i] + c_COP_h[5] * h_air_in[i]^2 + c_COP_h[6] *
DELTAT_hw[i]^2
    "For ar-water CO2 HP"

    // COP_h_CV[i] = COP_h_CV_AW[i]                    " Comment when WW mode is solved "
    COP_h_CV[i] = COP_h_CV_WW[i]                      " Comment when AW mode is solved "

   " Determine the various errors "
    ERR_COP_h[i] = ( COP_h[i] -COP_h_CV[i] )^2         " Determine square of the error "
    ERR_COP_h%[i] = ( COP_h[i] -COP_h_CV[i] ) / COP_h[i] * 100[%]      " Determine the error
percentage "
    ABS_ERR_COP_h[i] = ABS ( COP_h[i] -COP_h_CV[i] )
    " Determine absolute error "


    "  Determine the curve fit mass flow of the hot water"
    "-------------------------------------------------------------------------"
    m_dot_hw_CV_WW[i] = c_m_hw[1] + c_m_hw[2] * T_cw_in[i]   + c_m_hw[3] * DELTAT_hw[i] +
c_m_hw[4] * T_cw_in[i] * DELTAT_hw[i] + c_m_hw[5] * T_cw_in[i]^2 + c_m_hw[6] * DELTAT_hw[i]^2
    "For water-water CO2 HP "
    m_dot_hw_CV_AW[i]  = c_m_hw[1] + c_m_hw[2] * h_air_in[i]   + c_m_hw[3] * DELTAT_hw[i] +
c_m_hw[4] * h_air_in[i] * DELTAT_hw[i] + c_m_hw[5] * h_air_in[i]^2 + c_m_hw[6] * DELTAT_hw[i]^2
    " For ar-water CO2 HP"

    // m_dot_hw_CV[i] = m_dot_hw_CV_AW[i]              " Comment when WW mode is solved "
    m_dot_hw_CV[i] = m_dot_hw_CV_WW[i]                " Comment when AW mode is solved "


    " Determine the various errors "
    ERR_m_hw[i] = ( m_dot_hw[i] - m_dot_hw_CV[i] )^2  " Determine square of the error "
    ERR_m_hw%[i] = ( m_dot_hw[i] - m_dot_hw_CV[i] ) / m_dot_hw[i] * 100[%]           " Determine the
error percentage "
    ABS_ERR_m_hw[i] = ABS ( m_dot_hw[i] - m_dot_hw_CV[i]  )      " Determine absolute error "


    "  Determine the curve fit COP cooling"
    "----------------------------------------------------"
    COP_c_CV_WW[i] = c_COP_c[1] + c_COP_c[2] * T_cw_in[i] + c_COP_c[3] * DELTAT_hw[i] +
c_COP_c[4] * T_cw_in[i] * DELTAT_hw[i] + c_COP_c[5] * T_cw_in[i]^2 + c_COP_c[6] *
DELTAT_hw[i]^2                                        " FOR WATER-WATER  - NO AIR-WATER
OPTION"

    COP_c_CV[i] = COP_c_CV_WW[i]

    " Determine the various errors "
    ERR_COP_c[i] = ( COP_c[i] - COP_c_CV[i] )^2         " Determine square of the error "
    ERR_COP_c%[i] = ( COP_c[i] - COP_c_CV[i] ) / COP_c[i] * 100[%]          " Determine the error
percentage "
    ABS_ERR_COP_c[i] = ABS ( COP_c[i] - COP_c_CV[i]  )      " Determine absolute error "



    "  Determine the curve fit mass flow of the chilled water"
    "--------------------------------------------------------------------------"
    m_dot_cw_CV[i] = c_m_cw[1] + c_m_cw[2] * T_cw_in[i] + c_m_cw[3] * DELTAT_hw[i] +
c_m_cw[4] * T_cw_in[i] * DELTAT_hw[i] + c_m_cw[5] * T_cw_in[i]^2 + c_m_cw[6] * DELTAT_hw[i]^2
    " For water-water -no air water option"
```

```
    " Determine the various errors "
    ERR_m_CW[i] = ( m_dot_cw[i] - m_dot_cw_CV[i] )^2     " Determine square of the error "
    ERR_m_CW%[i] = ( m_dot_cw[i] - m_dot_cw_CV[i] ) / m_dot_cw[i] * 100[%]     " Determine the 
error percentage "
    ABS_ERR_CW[i] = ABS ( m_dot_cw[i] - m_dot_cw_CV[i] )     " Determine absolute error "

    "  Determine the curve fit mass flow of the brine-chilled water"
    m_dot_bcw_CV[i] = c_m_bcw[1] + c_m_bcw[2] * T_cw_in[i] + c_m_bcw[3] * DELTAT_hw[i] + 
c_m_bcw[4] * T_cw_in[i] * DELTAT_hw[i] + c_m_bcw[5] * T_cw_in[i]^2 + c_m_bcw[6] * 
DELTAT_hw[i]^2                                        " For water-water -no air water option"

    " Determine the various errors "
    ERR_m_BCW[i] = ( m_dot_bcw[i] - m_dot_bcw_CV[i] )^2    " Determine square of the error "
    ERR_m_BCW%[i] = ( m_dot_bcw[i] - m_dot_bcw_CV[i] ) / m_dot_bcw[i] * 100[%]     " Determine 
the error percentage "
    ABS_ERR_BCWCW[i] = ABS ( m_dot_bcw[i] - m_dot_bcw_CV[i] )     " Determine absolute error "


End

"------------------- Determine the sum of the errors -------------------"

SUM_ERR_Q_c = sum(ERR_Q_c[1..n])
// SUM_ERR_Q_h = sum(ERR_Q_h[1..n])
// SUM_ERR_COP_h = sum(ERR_COP_h[1..n])
// SUM_ERR_m_HW = sum(ERR_m_HW[1..n])
// SUM_ERR_COP_c = sum(ERR_COP_c[1..n])
// SUM_ERR_m_CW = sum(ERR_m_CW[1..n])
// SUM_ERR_m_BCW = sum(ERR_m_BCW[1..n])



//SUM_ERR_TOT = SUM_ERR_COP_h + SUM_ERR_COP_c
// SUM_ERR_TOT = SUM_ERR_m_BCW
// SUM_ERR_TOT = SUM_ERR_m_HW
// SUM_ERR_TOT = SUM_ERR_COP_c
// SUM_ERR_TOT = SUM_ERR_COP_h
// SUM_ERR_TOT = SUM_ERR_Q_h
SUM_ERR_TOT = SUM_ERR_Q_c
```

Appendix H Minimum mass flow of the CO_2 HP

Table 49: Minimum mass flow for the CO_2 HP

Zone	Minimum CW mass flow [kg/s]	Minimum CW mass flow in water-water mode at 65 °C [kg/s]	Minimum CW mass flow in water-water mode at 65 °C [kg/s]	Minimum water mass flow at 65 °C [kg/s]	Minimum water mass flow 65 °C in water-water mode [kg/s]	Minimum water mass flow 65 °C in air-water mode [kg/s]	Minimum water mass flow at 90 °C [kg/s]	Minimum water mass flow 90 °C in the water-water mode [kg/s]	Minimum water mass flow 90 °C in the air-water mode [kg/s]
Zone 01	2.00	2.00	2.04	0.21	0.21	0.22	0.13	0.13	0.14
Zone 02	2.00	2.00	2.04	0.22	0.24	0.22	0.14	0.16	0.14
Zone 03	2.00	2.00	2.04	0.22	0.25	0.22	0.14	0.17	0.14
Zone 04	2.00	2.00	2.04	0.22	0.26	0.22	0.14	0.18	0.14
Zone 05	2.00	2.00	2.04	0.22	0.26	0.22	0.14	0.18	0.14
Zone 06	2.00	2.00	2.04	0.22	0.22	0.22	0.14	0.14	0.14
Minimum	**2.00**	**2.00**	**2.04**	**0.21**	**0.21**	**0.22**	**0.13**	**0.13**	**0.14**

Appendix I Detail EES code to determine the detail time it takes to chill the water tank.

```
---------------------------------------------------------------------------------------------------------------------"
"| PROGRAM TO DETERMINE THE TIME TO COOL DOWN CHILLED WATER TANK                    |"
"| WRITTEN BY WH KAISER                                                              |"
"---------------------------------------------------------------------------------------------------------------------"

"------------------- INPUT VALUES -------------------"
"-----------------------------------------------------------"


"-----------HX VALUES--------"

BRINE$ = 'PG'                          " Brine used in heat pump (Propylene Glycol-
Water)"

CTRN = 50 [%]                          " Brine Concentration "

m_dot_\HP = 2 [kg/s]                   " Minimum mass flow per HP "

N_HP = 5                               " Number of HP "

DELTAT_HX = 5 [°C]

P_HX_in = 200 [kPa]                    " Assume HX inlet pressure "

T_HX_in = 0.5[°C]                      " Temperature from original program "


"-----------FEED WATER VALUES--------"

P_fw = 200 [kPa]                       " Feed water pressure "

T_FW = 10 [°C]                         " Feed water temperature "


T_CW_in = 15[°C]

T_CW_out = 4[°C]

"-----------TANK VALUES--------"

m_Tank = 30000 [kg]

DELTA_time_min = 2 [min]

h_tank = 2.35 [m]

D_tank_out = 1 [m]

t_ins = 0.1 [m]                        " Thicknes of the insulation "

k_ins = 0.036 [W/m-K]                  " k value of the insulation "
```

```
 "-----------TANK COOLDOWN VALUES--------"

SF_time_min = 45 [min]                                " Safety factor for cool down time "

SF_time_min = SF_time * convert ( s, min)

 "-------------------- CALCULATIONS --------------------"
"----------------------------------------------------------------"

"-----------HX VALUES--------"

m_dot_HX_tot = m_dot_\HP * N_HP                      " Mass flow through the HX "

"-----------HX VALUES--------"

p_0[372] = P_HX_in

T_0[372] = T_HX_in

T_0[373] = T_0[372] + DELTAT_HX

"-------------------- Component characteristics ----------"
alpha_E[372] = 0

"--------------------Fluid properties ----------"

h_0[372] = ENTHALPY ( BRINE$, T = T_0[372], C = CTRN, p = p_0[372] )

h_0[373] = ENTHALPY ( BRINE$, T = T_0[373], C = CTRN, p = p_0[373] )


"-------------------- Conservation equations ----------"

m_dot[372] = m_dot_HX_tot
     " Conservation of mass "

// - DELTAp_E[372] = alpha_E[372] * average( p_0[373], p_0[372] )
     " Pressure drop for the HX "
p_0[373] = p_0[372]

Q[372] = m_dot[372] * ( h_0[373] - h_0[372] )
     " Heat transfer for the HX "


"----------- UA THE TANK -----------"

A_tank_top = Pi * D_tank_out^2 /4

A_tank_side = 2* Pi * D_tank_out * h_tank

A_tank = A_tank_top + A_tank_side

R_tank_side = ln ( r_2 / r_1 ) / 2 * pi * h_tank * k_ins

r_1 = r_2 - t_ins

r_2 = D_tank_out / 2
```

```
"----------- INPUT VALUES FOR COOL DOWN OF THE TANK -----------"

DELTA_time = DELTA_time_min * CONVERT ( min, s )
    " Times step "

Q_in_HX = -Q[372]
    " Heat transfer size "

p_0_Tank = P_FW
    " Tank pressure "

T_0[1] = T_FW
    " Initial tank temperature "

T_0_K[1] = CONVERTTEMP (C, K, T_0[1] )
    " Initial tank temperature in K "



"--------------------Fluid properties ----------"

c_p[1] = CP ( Water, T = T_0[1], p = p_0_tank )

t_s_CW[1] = 1

n = 45


"----------- DETERMINE HOW THE TANK COOLS DOWN -----------"

Duplicate i = 1, n

    T_0_K[i+1] = T_0_K[i] + 1 / ( m_Tank * c_p[i] ) * ( Q_in[i] ) * DELTA_time

    c_p[i+1] = CP ( Water, T = T_0[i+1], p = p_0_tank )

    T_0_K[i+1] = CONVERTTEMP (C, K, T_0[i+1] )

    t_s_CW[i+1] = if ( T_0[i], 4, t_s_CW[i], t_s_CW[i], i + 1 )

    Q_in[i] = Q_in_HX

End

"----------- DETERMINE STEPS TO COOL DOWN THE TANK -----------"

STEPS = t_s_CW[n]

t_s_CW = STEPS * DELTA_time + SF_time

t_s_CW_hr# = t_s_CW_hr

t_s_CW_min = t_s_CW * convert ( s, min)

t_s_CW_hr = t_s_CW * convert ( s, hr)
```

Appendix J Standard tank sizes

Table 50: Standard Heat transfer engineering tank sizes. Source: HTE (2008)

Model	Capacity [l]	Model	Capacity [l]
HT450S	450	HT2700S	2700
HT500S	500	HT2500S	2500
HT600S	600	HT3000S	3000
HT700S	700	HT3600S	3600
HT800S	800	HT4000S	4000
HT1000S	1000	HT4500S	4500
HT1200S	1200	HT5000S	5000
HT1400S	1400	HT6000S	6000
HT1500S	1500	HT7500S	7500
HT1600S	1600	HT10000S	10000
HT1800S	1800	HT12000S	12000
HT2000S	2000	HT15000S	15000
HT2300S	2300	HT20000S	20000

Table 51: Number tanks needed for poultry abattoir

	Chilled water	Hot water at 65 °C	Hot water at 90 °C
Rounded to standard tank size [m^3]	30.0	40.0	2.0
Standard tank size [m^3]	1.50	20.00	2.00
Number of tanks	20	2	1

Appendix K Calorific values of fuel

Table 52: Calorific value for the various LPG and Paraffin. Source: DoE SA (2018); Steyn and Minnitt (2010), IPCC (2006), and Carbon Tax Act 15 (2019)

Carrier	**LPG [MJ/kg]**	**Paraffin [MJ/kg]**
South Energy Digest 2009 and Energy Price Report 2018	49.44	46.30
Carbon Tax Act	47.30	43.80
IPCC	47.30	40.20
IPCC Lower value	44.80	33.70
IPCC upper value	52.20	48.20
Calorific value	48.21	43.43
Uncertainty	2.48	5.12

Table 53: Calorific value for the various fuel sources. Source: DoE SA (2018); Steyn and Minnitt (2010), IPCC (2006); and Carbon Tax Act 15 (2019)

Carrier	**Coal [MJ/kg]**
South Energy Digest 2009 and Energy Price Report 2018	24.30
Carbon Tax Act	24.30
Coal A grade	27.50
Coal B grade	26.50
Coal C grade	25.50
Coal D grade	24.50
IPCC	25.80
IPCC Lower value	19.90
IPCC upper value	30.50
Calorific value	25.42
Uncertainty	2.69

Appendix L Fuel prices

L.1 Price of coal

Table 54: Monthly Price of coal for 2019. Source: Quantec data (2019a)

Period	Month price [R/tonne] (VAT excluded)	Month price [R/tonne] (VAT included)
Jan	422.00	485.30
Feb	448.00	515.20
Mar	442.00	508.30
Apr	440.00	506.00
May	420.00	483.00
Jun	445.00	511.75
Jul	437.00	502.55
Aug	444.00	510.60
Sep	442.00	508.30
Oct	445.00	511.75
Nov	447.00	514.05
Dec	491.00	564.65
Average	443.58	510.12
Uncertainty	16.75	19.26

L.2 Price of paraffin

Table 55: Monthly price of paraffin for 2019 in cents per litre. Source: Data from Quantec data (2019b)

Period	**Coast [R/litre] (VAT included)**	**Gauteng (inland) [R/litre] (VAT included)**
January	8.83	9.53
February	8.78	9.47
March	9.65	10.35
April	10.30	11.07
May	10.33	11.11
June	10.42	11.20
July	9.77	10.54
August	9.75	10.52
September	10.02	10.79
October	10.31	11.08
November	10.05	10.82
December	9.84	10.61
Average	9.84	10.59
Uncertainty	0.52	0.55

L.3 LPG price

Table 56: Monthly price of LPG for 2019. Source: Data from Quantec data (2019b)

Period	Coast [R/kg] (VAT included)	Gauteng (inland) [R/kg] (VAT included)
January	24.22	26.67
February	24.09	26.54
March	25.25	27.70
April	27.22	29.67
May	28.19	30.64
June	28.09	30.56
July	26.57	29.03
August	26.93	29.38
September	26.75	29.20
October	26.94	29.39
November	26.60	29.05
December	27.63	30.22
Average	26.54	29.00
Uncertainty	1.30	1.31

L.4 Electricity price

Table 57: Eskom Business rating for 2018/2019: Source: Eskom (2018)

Energy charge [c/kWh]	Ancillary service charge [c/kWh]	Network demand charge [c/kWh]	Total [c/kwh]	VAT
100.28	0.39	14.16	114.83	Excluded
115.32	0.45	16.28	132.05	Included

Table 58 Eskom Business rating for 2019/2020: Source: Eskom (2019)

Energy charge [c/kWh]	Ancillary service charge [c/kWh]	Network demand charge [c/kWh]	Total [c/kwh]	VAT
118.84	0.45	16.47	135.76	Excluded
136.67	0.52	18.94	156.12	Included

Appendix M Default emissions values

M.1 Coal, LPG and Paraffin emissions

Table 59: Default emissions factor for stationary combustion in the energy industries (kg of greenhouse gas per TJ on a Net Calorific Basis): Source: IPCC (2006)

Emissions	Description	Unit	Coal (Other Bituminous Coal)	LPG	Paraffin
CO_2	Chosen value	[kg/TJ]	94600	63100	71900
	Uncertainty	[kg/TJ]	4164	1500	1100
	Standard deviation	[kg/TJ]	4164	1650	1195
	Default	[kg/TJ]	94600	63100	71900
	Lower limit	[kg/TJ]	89500	61600	70800
	Upper limit	[kg/TJ]	99700	65600	73700
CH_4	Chosen value	[kg/TJ]	1.43	1.43	4.67
	Uncertainty	[kg/TJ]	0.70	0.70	2.00
	Standard deviation	[kg/TJ]	1.14	1.14	3.86
	Default	[kg/TJ]	1.00	1.00	3.00
	Lower limit	[kg/TJ]	0.30	0.30	1.00
	Upper limit	[kg/TJ]	3.00	3.00	10.00
N_2O	Chosen value	[kg/TJ]	2.33	0.14	0.93
	Uncertainty	[kg/TJ]	1.00	0.07	0.40
	Standard deviation	[kg/TJ]	1.93	0.11	0.77
	Default	[kg/TJ]	1.50	0.10	0.60
	Lower limit	[kg/TJ]	0.50	0.03	0.20
	Upper limit	[kg/TJ]	5.00	0.30	2.00

M.2 Electricity emissions values

Table 60: Default emissions factor for stationary combustion in the energy. Based on Energy send out: Source: Eskom (2016)

Description	Unit	Average	Uncer-tainty	2017/18	2016/17	2015/16	2014/15	2013/14	2012/13	2011/12	2010/11	2009/10	2008/09
CO_2 emissions	[kg/kWh]	0.972	0.020	0.926	0.959	0.980	0.987	1.009	0.979	0.977	0.970	0.965	0.968
Sox (SO4) emissions	[g/kWh]	8.000	0.250	8.119	8.021	7.723	8.104	8.545	7.918	7.792	7.623	7.972	8.185
N_2O emissions	[g/kWh]	0.0124	0.0004	0.0119	0.0126	0.0125	0.0129	0.0117	0.0128	0.0125	0.0122	0.0121	0.0122
NOx emissions	[g/kWh]	4.090	0.085	3.870	4.020	4.059	4.141	4.128	4.146	4.117	4.115	4.119	4.180
Particulate emissions	[g/kWh]	0.321	0.043	0.257	0.296	0.356	0.364	0.341	0.347	0.305	0.319	0.379	0.243
Water use	[l/kWh]	1.369	0.042	1.300	1.420	1.440	1.380	1.350	1.420	1.340	1.350	1.340	1.350
Ash produced	[g/kWh]	151.38	4.34	142.61	148.12	148.15	152.05	151.30	151.67	152.60	152.55	154.67	160.13
Coal use	[kg/kWh]	0.525	0.004	0.520	0.516	0.522	0.527	0.530	0.528	0.528	0.525	0.527	0.529

Appendix N Inflation rates.

N.1 Prime lending rate

Table 61: Prime lending rate from 2010 – 2019. Source South African Reserve bank (2020)

Year	Prime lending rate [%]
2010	9.9
2011	9.0
2012	8.8
2013	8.5
2014	9.1
2015	9.4
2016	10.4
2017	10.4
2018	10.1
2019	10.1
Chosen value	**9.6**

N.2 Consumer price index.

Table 62: Consumer price index from 2009 – 2019. Source Statistics South Africa (2019b)

Year	Consumer price index	Increase
2009	67.8	
2010	70.7	4.3%
2011	74.2	5.0%
2012	78.4	5.7%
2013	82.9	5.7%
2014	88.0	6.2%
2015	92.0	4.5%
2016	97.8	6.3%
2017	103.0	5.3%
2018	107.8	4.7%
2019	112.2	4.1%
Chosen value		**9.9%**

N.3 Coal inflation rate

Table 63: Coal price from 2010 – 2019. Source: Quantec data (2019a)

Year	Rand/tonne]	Increase
2010	187.4	
2011	209.8	12.0%
2012	236.6	12.7%
2013	270.1	14.2%
2014	299.9	11.0%
2015	315.8	5.3%
2016	338.8	7.3%
2017	381.2	12.5%
2018	405.4	6.4%
2019	436.8	7.7%
Chosen value		**9.9%**

N.4 LPG inflation rate

Table 64: LPG price from 2010 – 2019. Source: Quantec data (2019b)

Year	Price [c/kg]	Increase
2010	1603.33	
2011	1857.33	15.8%
2012	2033.42	9.5%
2013	2181.25	7.3%
2014	2286.00	4.8%
2015	1900.42	-16.9%
2016	1903.08	0.1%
2017	2023.00	6.3%
2018	2280.67	12.7%
2019	2307.92	1.2%
Chosen value		**4.5%**

N.5 Paraffin inflation rate

Table 65: Paraffin price from 2010 – 2019. Source Quantec data (2019b)

Year	Price [c/kg]	Increase
2010	504.18	
2011	665.90	32.1%
2012	772.31	16.0%
2013	871.99	12.9%
2014	926.54	6.3%
2015	670.49	-27.6%
2016	618.61	-7.7%
2017	684.91	10.7%
2018	853.95	24.7%
2019	855.41	0.2%
Chosen value		**7.5%**

N.6 Electric inflation rate

Table 66: Electric inflation price from 2008 – 2017 for the industrial sector. Source: DoE SA (2018), DoE SA (2016b)

Year	Price [c/kg]	Increase
2007/2008	17.28	
2008/2009	21.69	25.5%
2009/2010	27.03	24.6%
2010/2011	34.34	27.0%
2011/2012	42.13	22.7%
2012/2013	45.56	8.1%
2013/2014	51.79	13.7%
2014/2015	56.81	9.7%
2015/2016	62.64	10.3%
2016/2017	67.71	8.1%
2017/2018	70.02	3.4%
Chosen value		**14.2%**

Appendix O Detail calculations on the abattoir sizes

Table 67: Detail calculations on the abattoir sizes (Part A)

Site no	Abattoir	Site	Climatic zone	Number of CO_2 HP A A = B / Birds per heat pump	Birds\min B B = C / hours per week	Birds per week based 2015 data C C = G x D	Percentage of abattoir per producer total D D = E/ SUM (producer in E)
1	Astral	Olifantsfontein	1	40	198	1109510	26.2%
2	Astral	Durban	5	6	27	153210	3.6%
3	Astral	Standerton	1	57	283	1588090	37.5%
4	Astral	Cape Town	4	50	247	1385810	32.7%
5	CBH	Bloemfontein	1	5	25	141220	10.5%
6	CBH	Tigane	1	22	108	603400	44.8%
7	CBH	Mafikeng	2	22	108	603400	44.8%
8	Daybreak	Delmas	1	18	86	481430	50.0%
9	Daybreak	Sundra	1	18	86	481430	50.0%
10	Fouries poultry	Potchefstroom	1	36	178	999460	86.5%
11	Fouries poultry	Potchefstroom	1	6	28	155980	13.5%
12	RCL	Durban	5	45	223	1253440	27.1%
13	RCL	Tzaneen	2	13	64	360990	7.8%
14	RCL	Rustenburg	2	84	420	2356470	51.0%
15	RCL	Worcester	2	24	116	650880	14.1%
16	Sovereignfoods -Rocklands	Uitenhage	4	35	172	962870	100.0%
17	Sovereignfoods - Tydstroom	Hartebeespoort	2	42	206	1155440	100.0%
Total				**523**	**2575**	**14443030**	

Table 68: Detail calculations on the abattoir sizes (Part B)

Site no	Abattoir	Site	Birds per week 2015	Data	Bird per week based on the total producer percentage 2015 data	Percentage per producer (Based on SAPA data)	Percentage per province (Based on SAPA data)	Percentage assumed
			E[16]	F	G	H	I	J
			E = G x I or E = G x J		G = H x I			
1	Astral	Olifantsfontein	[17]1289000	Actual	4236644	22.0%		
2	Astral	Durban	[17]178000	Actual				
3	Astral	Standerton	[17]1845000	Actual				
4	Astral	Cape Town	[17]1610000	Actual				
5	CBH	Bloemfontein	141220	Estimated	1348023	7.0%	5.5%	
6	CBH	Tigane	603400	Estimated			23.5%	
7	CBH	Mafikeng	603400	Estimated			23.5%	
8	Daybreak	Delmas	481436	Estimated	962873	5.0%		50.0%
9	Daybreak	Sundra	481436	Estimated				50.0%
10	Fouries poultry	Potchefstroom	999462	Estimated	1155448	6.0%		86.5%
11	Fouries poultry	Potchefstroom	155985	Estimated				13.5%
12	RCL	Durban	577724	Estimated	4621794	24.0%	12.5%	
13	RCL	Tzaneen	166384	Estimated			3.6%	
14	RCL	Rustenburg	1086121	Estimated			23.5%	
15	RCL	Worcester	300000	Estimated				14.1%
16	Sovereignfoods -Rocklands	Uitenhage	962873	Actual	962873	5.0%		
17	Sovereignfoods - Tydstroom	Hartebeespoort	1155448	Actual	1155448	6.0%		
					14443103	75%		

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[16] If the abattoir sites are in the same province, an assumption must made on the percentage per site.

[17] For Astral actual figure of 2015 were used