Development and verification of a TRNSYS energy system simulation model for a combined heat and power dual-fuel system

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Mini-Dissertation submitted in partial fulfilment of the requirements for the degree *Masters of Engineering in Development and Management Engineering* at the Potchefstroom Campus of the North West University

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Examination: May 2018

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ACKNOWLEDGEMENTS

This study would not have been possible had it not been for the endeavour of many individuals. I wish to express my deepest gratitude towards the following people and institutions:

Prof JH Wichers, my supervisor, for his support and encouragement.

Dr GG Jacobs, my co-supervisor, for taking the time to provide valuable inputs and advice.

Hanyani Makhuvele, Kabelo Mamadisa, Vhukhudo Matidza, my colleagues, for their invaluable assistance with the calculations required for the TRNSYS model.

The Skills Development Department at Vaal University of Technology for the payment of my study fees.

Lovell Emslie, from Pegasus, for initiating and advising on the Skills for Green Jobs project.

Cape Advanced Engineering (Pty) Ltd. (CAE) for accommodating the team whilst assembling the CHP demonstrator and for providing the data from the various components of the CHP dual fuel demonstrator.

Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ) that enabled this study, encouraged international collaboration and provided the funding for training and international fact-finding trips.

Professor Lars Kühl from Ostfalia University, an expert in CHP within the food processing industry and TRNSYS, for his expertise throughout the early stages of the Skills for Green Jobs project.

Dr JJ AC Smit for editing the text.

My wife, Noreen, without whose love, support and encouragement this study would not have been possible.

ABSTRACT

Key terms: Dual-fuel system, combined heat and power (CHP) system, energy system, energy simulation model, energy efficiency, CO_2 emissions, biogas, TRNSYS, CHP dual fuel demonstrator

Many companies suffer economic losses due to unannounced, interrupted power supply caused by electricity cuts. These companies then purchase electricity generator units to supply electricity during these times. This however, is a costly exercise as diesel is expensive, CO_2 emissions are high and heat energy is wasted. An alternative, permanent, constant energy supply system, such as a CHP dual-fuel system thus needed to be properly investigated.

The aim of this study was to develop and verify an energy system simulation model known as TRNSYS, as a means to identify an appropriate CHP dual fuel system that could replace traditional power generators and suppliers.

The literature study revealed the importance of energy management with reference to the South African context. The use of CHP dual fuel systems as an alternative energy source were confirmed and the crucial components of CHP systems were described. Dual fuel, including the use of bio-gas, as an alternative energy source for CHP systems was emphasised.

Based on the components installed in the CHP dual fuel demonstrator used for this study, the input data requirements for each library component TYPE, selected for modelling purposes, were entered into the TRNSYS model and output values were then generated. The TRNSYS output values were compared to the measured and calculated values obtained for the CHP dual fuel demonstrator in use at Uilenkraal farm.

The TRNSYS model produced similar outputs, within a 15% deviation, to that of the CHP dual fuel demonstrator for the majority of the components selected.

It was concluded that the TRNSYS energy system simulation model could be used to identify a suitable CHP dual fuel system that could provide an alternative, permanent and constant energy supply and could lead to a reduction in CO_2 emissions, efficiency gains and cost saving. Recommendations were made to use TRNSYS as a modelling tool, prior to the manufacturing and installation of a CHP dual fuel system. It was also recommended that TRNSYS be refined to improve the predictive validity of the TRNSYS model outputs.

GLOSSARY OF TERMS

Biogas;	Type of biofuel that is naturally produced from the decomposition of organic waste such as animal manure, food scraps, waste water and sewage.
Bio digester:	System that uses the process of fermentation to break down organic matter to produce biogas in an anaerobic environment.
CHP dual fuel demonstrator:	Mobile unit built as a technology demonstrator to showcase the advantages of CHP dual fuel systems.
CHP dual fuel system:	Combined heat and power system that uses two fuel types, typically diesel and gas, to generate electricity and thermal energy.
Combined heat and power;	Integrated system that generates electricity and useful thermal energy.
Control system;	System that manages, commands, directs, or regulates the behaviour of other devices, instruments or systems.
Dual Fuel system:	Internal combustion engine capable of running on two fuels such as diesel and gas.
Emissions:	Release into the earth's atmosphere of any gases.
Energy efficiency:	Measures the ratio between benefit gained and the energy used to produce that gain.
Energy intensity;	Primary energy demand per unit of gross domestic product.
Energy management:	Efficient and effective use of energy through the minimisation of costs and the maximisation of profits.
Energy productivity; consumed.	Production of more Gross Domestic Product for each unit of energy.
Generator:	Machine for converting mechanical energy into electricity.
Heat exchanger:	Component designed to efficiently transfer or "exchange" heat from one matter to another.
Internal combustion engine:	Engine in which the ignition and combustion of fuel occurs within the engine itself, which generates motive power by burning fuel (petrol, oil, diesel, natural gas).
Modelling:	Using a computer program version of a mathematical model for a physical system.
Natural gas:	Fossil fuel that consists mainly of methane found deep beneath the earth’s surface.
Prime mover:	Machine (or component of a machine) that converts energy from a source energy, into mechanical energy, such as an engine.
Thermal energy:	Energy produced by heat.

Transient System Simulation Tool (TRNSYS):	Flexible software tool used to simulate and assess the performance of thermal energy systems.
TYPE:	Component models available in the TRNSYS library.

ABBREVIATIONS

CAE	Cape Advanced Engineering (Pty) Ltd.
CHP	Combined Heat and Power
CH_4	Methane
CO_2	Carbon Dioxide
DLL	Dynamic Link Library
GIZ	Deutsche Gesellschaft für Internationale Zusammenarbeit
GHG	Greenhouse gas
GDP	Gross Domestic Product
HRSG	Heat Recovery Steam Generator
HVAC	Heating, ventilation and air conditioning
IEA	International Energy Agency
IPP	Independent Power Producer
ISO	International Standards Organisation
NO_x	Nitrogen Oxides
OEM	Original Equipment Manufacturer
OPEC	Organisation of Petroleum Exporting Countries
SANEDI	South African National Energy Development Institution
S4GJ	Skills for Green Jobs
SO_2	Sulphur dioxide
TESS	Thermal Energy System Specialists
TRNSYS	Transient System Simulation Tool
TS	Technology Station
VUT	Vaal University of Technology

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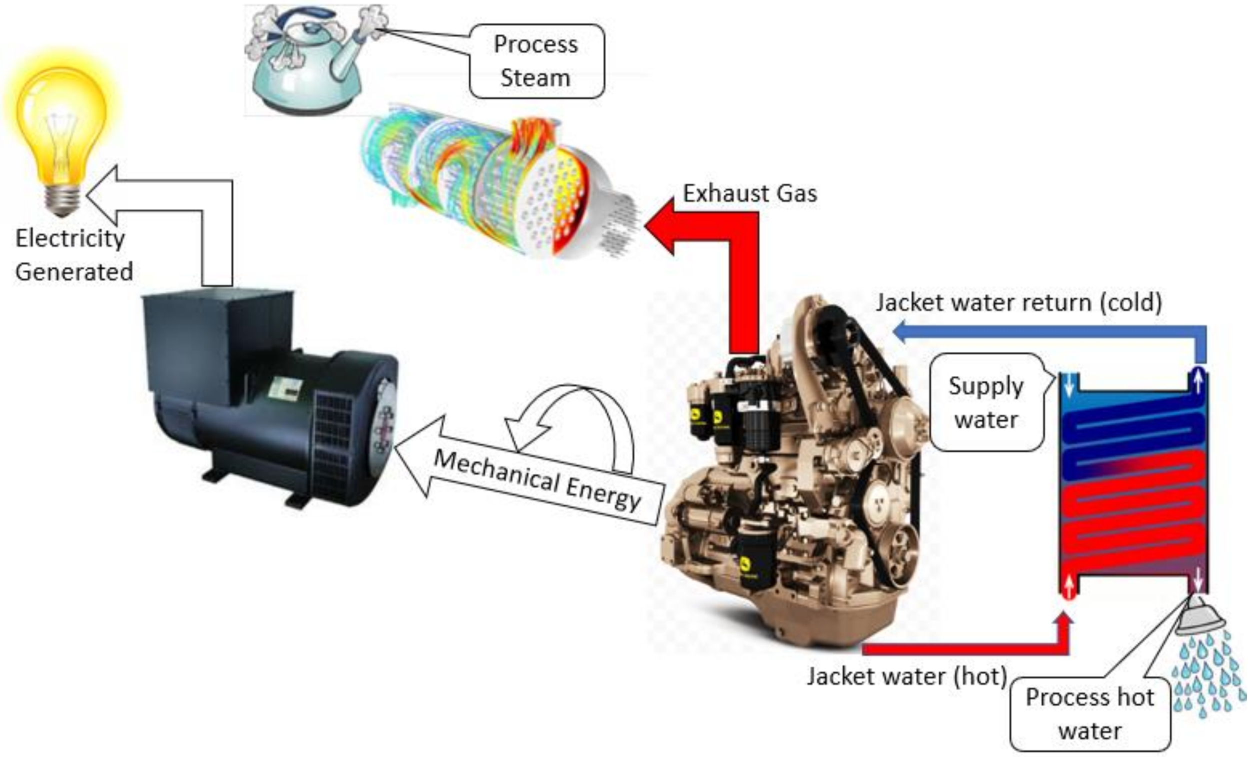
CHAPTER 1: INTRODUCTION

1.1 Background

Cogeneration means the simultaneous production of more than one type of energy from a single fuel source. The production of heat and power at the same time is also known as combined heat and power (CHP) (SANEDI, 2016).

CHP generates electricity whilst also capturing the usable heat that is produced during this process, as shown in Figure 1.1 below. This contrasts with conventional ways of generating electricity where vast amounts of heat, as a by-product of electricity generation, is wasted (Cogen Europe, 2013).



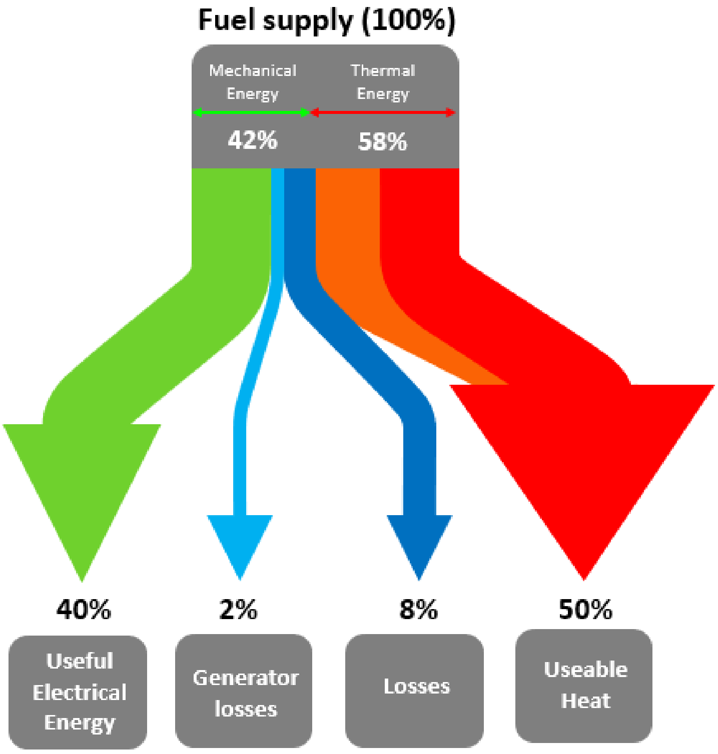
Source: Adapted from (Educogen, 2001)

Figure 1.1: CHP process

Waste heat is heat that is produced by a machine, or other processes that use energy, as a by-product of doing work. All such processes give off some waste heat as a fundamental result of the laws of thermodynamics and often that heat is transferred into the surrounding atmosphere and disperses to such an extent that it becomes very difficult to do anything useful with it (Andersson & Hagg, 2008).

By using wasted heat, CHP plants can reach efficiency values in excess of 80% (Cogen Europe, 2013). The combined generation of heat and power can deliver up to 35% of overall energy savings and a reduction in CO_2 emissions, depending on application. At the same time cogeneration has the potential to strengthen companies' power independence and competitiveness (SANEDI, 2016).

APROVIS, a German company that manufactures CHP units, outlines the benefits of CHP in Figure 1.2 below.



Source: Adapted from (APROVIS, 2016)

Figure 1.2: Energy distribution through CHP

Depending on the systems installed, the initial investment in a cogeneration project can be quite high but a payback period of between 3-5 years can be expected (Educogen, 2001).

It should be noted that although the purpose of a cogeneration project is to produce cheaper electricity, the success of cogeneration systems depends on using recovered heat productively, thus a prime criterion is a suitable heat requirement (Educogen, 2001), (Patill , et al., 2008).

In a conventional CHP process the prime mover is a diesel engine (Darraw, et al., 2017). To reduce carbon emissions that result from the internal combustion process associated with using diesel, the focus is now on dual-fuel technology.

Utilising this technology, diesel engines can run on up to 85% natural gas, with the gas being introduced through the air intake (Acosta, 2015).

A dual-fuel engine is an internal combustion engine in which the primary fuel (usually natural gas) is mixed more or less homogeneously with the air in the cylinder. Unlike a spark-ignition engine, however, the air/fuel mixture is ignited by injecting a small amount of diesel fuel (the "pilot") as the piston approaches the top of the compression stroke. This diesel pilot fuel rapidly undergoes pre-flame reactions and ignites due to the heat of compression, just as it would in a diesel engine. The combustion of the diesel pilot then ignites the air-fuel mixture in the rest of the cylinder (Turner & Weaver, 1994).

Turner and Weaver also state that one of the advantages of dual-fuel engines is that in most cases, they can be designed to operate interchangeably on natural gas with a diesel pilot, or on 100% diesel fuel. This makes them especially valuable in circumstances where the use of natural gas is desired for environmental or economic reasons, but where the gas supply may not be fully reliable. Another advantage of dual-fuel engines is the ease with which most existing diesel engines can be converted to dual-fuel operation.

Dual-fuel systems can save operators up to 50% on fuel costs, based upon the cost of diesel relative to natural gas, plus the fact that they render diesel engines more environmentally friendly (Acosta, 2015).

To date only a few CHP dual-fuel systems have been implemented in South Africa (SANEDI, 2016). The ABSA Campus in central Johannesburg with four 3MW CHP units which operate in parallel with City Power, is one of South Africa's leading examples (Gafner, 2012).

Skills for Green Jobs (S4GJ), a collaboration project between the Vaal University of Technology (VUT), Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ) and Pegasus, an independent private organisation, initiated a project to determine the viability of a CHP dual-fuel system using the Transient System Simulation Tool (TRNSYS) as a modelling tool.

The outputs of this project will demonstrate:

- The potential energy efficiency gain when utilising a dual fuel system,
- cost saving over time and
- environmental effects such as reduced carbon dioxide (CO_2) emissions.

The data generated from this project will be used to develop and verify an energy system simulation model (TRNSYS) for a CHP dual-fuel system.

1.2 Problem statement

Many companies suffer economic losses, lose production time and experience substantial amounts of product loss due to unannounced, interrupted power supply caused by loss of electricity supply (van der Nest, 2015). These companies purchase electricity generator units to supply electricity during these power cuts. This however, is a costly exercise as diesel is expensive, CO_2 emissions are high and heat energy is wasted. An alternative, permanent, constant energy supply system, such as a CHP dual-fuel system thus needs to be properly investigated, analysed and verified using an energy system simulation model in the form of TRNSYS.

1.3 Research questions

The following research questions are addressed during this study:

- Using a TRNSYS energy system simulation model, can a CHP dual fuel system be identified that will provide an alternative, permanent, constant energy supply system that will be more cost-effective, lead to a reduction in CO_2 emissions and reduce heat waste?

- Do the data collected from a CHP dual fuel demonstrator correlate with the predicted data obtained from the TRNSYS Model?

- How accurate is the TRNSYS Model when applied to the selection of a CHP dual fuel system?

1.4 Research aim and objectives

This research is divided into a general research objective and associated specific objectives as outlined below.

1.4.1 Research aim

To develop and verify a TRNSYS simulation model that can be applied to the selection of a CHP dual-fuel system.

1.4.2 Research objectives

The specific theoretical objectives of this study are to:

- Emphasise the importance of energy management within a South African Context.
- Provide an overview of CHP and dual fuel systems.

- Describe the need to analyse CHP systems through the use of the TRNSYS energy system simulation model.

The specific empirical objectives of this study are to:

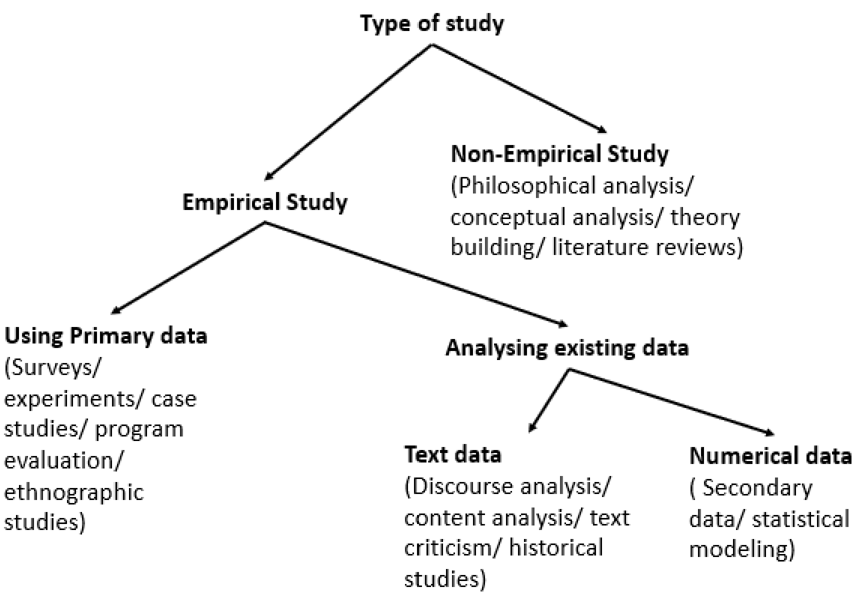
- Develop an energy system simulation model in TRNSYS for the selection of a CHP dual-fuel system that would be suitable for application in South Africa.
- Verify that the data obtained from the TRNSYS energy system simulation model correlates with the measured data obtained from a CHP dual fuel demonstrator.
- Analyse the energy efficiency gains, cost saving and CO_2 emissions when using a CHP dual fuel system.

1.1 Research methodology

1.5.1 Study design

This research project will consist of both a literature review and an empirical study in order to develop and verify a TRNSYS energy system simulation model of a dual-fuel CHP system.

The two research methods that will be used to achieve the objectives of this study are outlined in Figure 1.3.



Source: Adapted from (Babbie & Mouton, 2010)

Figure 1.3: Research methods

A literature review should clearly show how previous studies in the specific field of research, relate to one another and how the proposed research ties in with them. This is often referred to as the golden thread (Welman, et al., 2010). Thus, the first part of this study comprises of a literature review.

The second contributing factor to undertaking postgraduate research is through an empirical study to provide better insight and understanding of the basic methodological techniques and methods used during the study, how it was applied and what purpose it played, in obtaining the relevant data. An empiricist attempts to describe, explain and make predictions through observation (Cooper & Schnidler, 2014).

The second part of this study will thus comprise of an empirical study whereby data are collected to develop a simulation model to verify the use of a CHP dual-fuel system.

1.5.2 Research procedure

Table 1.1 outlines the procedure to be followed during the empirical study.

Table 1.1: Research procedure

Step	Description
1	The key physical elements of a generic CHP dual fuel system are identified through the literature review.
2	The key physical elements of the CHP dual fuel demonstrator to be used in this study will be selected.
3	TRNSYS sub-routine models (types) are selected from the TRNSYS TESS (Thermal Energy System Specialists) library to best represent the key physical elements of the CHP dual fuel demonstrator.
4	Select suitable thermal energy load elements from the TRNSYS TESS library to simulate the process energy demand of the consumer.
5	Develop a TRNSYS energy simulation system model through connecting the TRNSYS selected elements to represent the elements of the CHP dual fuel demonstrator.
6	Collect actual input values from the CHP dual fuel demonstrator and enter these values into the TRNSYS model.
7	Compare the TRNSYS output values to the CHP dual fuel demonstrator output values to verify the authenticity of the TRNSYS energy simulation model.

1.2 Delimitations of the study

The following delimitations of the study should be noted:

- Weather data to be used for the TRNSYS energy simulation model will be obtained from the TRNSYS Regional Data Weather File.

- CHP dual fuel demonstrator engine specifications will be obtained from the original equipment manufacturer (OEM).
- CHP dual fuel demonstrator engine operating data is obtained from Cape Advanced Engineering (Pty) Ltd. (CAE).
- Heat exchanger design calculations are not included in this study. This data will be generated through a separate study that is currently underway at VUT.
- A bio digester will be simulated as a thermal storage unit in the TRNSYS energy simulation model.

1.7 Expected contribution of the study

This research will contribute to the field of science, engineering and technology in the manner outlined below.

- *Individuals:* Implementation of CHP technology leads to a reduction in CO_2 emissions which leads to a healthier environment for all. This research, through the development of a simulation model, serves as an aid towards this goal.
- *Literature:* One article on the research presented in this dissertation will be submitted to accredited journals on successful completion of the study.
- *Organisation:* The expected outcome of this research is an energy simulation model that will predict energy usage based on the integration of a CHP dual-fuel system. This model could then be used as a predictive tool when organisations consider moving towards a more energy efficient system thus contributing to the field of alternative energy. The reduction in CO_2 emissions and the carbon footprint as a result of the integration of CHP dual-fuel systems can contribute towards the green energy movement.

1.8 Ethical considerations

The following ethical considerations apply:

- *Permission and informed consent:* Permission has been obtained from all companies that participated in this research, prior to the collection and publication of data.

1.9 Chapter division

The chapters are presented as outlined below:

Chapter 1: Introduction: This chapter begins with the background to the research problem, the formulation of the research questions and the research objectives. The delimitations of the study are explained, the nature of the study is described and the research procedure to be followed is outlined. The intended value of the research is discussed and ethical considerations are mentioned.

Chapter 2: Literature review: This chapter describes the benefits of energy management and provides an overview of CHP systems. CHP dual fuel systems are also discussed and the use of biogas as a fuel source is discussed in the South African context. The literature also refers to the issues of CO_2 emissions and carbon footprint reduction. The need for modelling CHP systems is motivated.

Chapter 3: Methodology: This chapter describes the origins of S4GJ project which forms the basis for this research project. The objectives of the research are outlined and the methodology to be followed is described. The key physical elements of the CHP dual fuel demonstrator are explained and the library components for the TRNSYS model are selected to achieve the project outputs.

Chapter 4: Modelling a CHP dual fuel system using TRYNSYS: Chapter 4 provides an overview of the TRNSYS model used specifically for comparison against the CHP dual fuel demonstrator. The selection of the specific input values and parameters for each component is described, followed by the verification of the resultant outputs from the TRNSYS model versus measured and calculated values obtained from the CHP dual fuel demonstrator. The CO_2 emissions, efficiency gains and cost savings derived from the use of a CHP system will also be indicated. **Chapter 5: Conclusions and recommendations:** In this chapter, an overview of the study is provided, final conclusions are drawn and recommendations are made. The limitations of the study and possible avenues for future research are mentioned and the chapter is concluded with a summary of the value of this research study.

1.10 Summary

In this chapter, the background to the research and the statement of the research problem was provided. The research questions and objectives were formulated, the delimitations and nature of the study were described and the research procedure was outlined. The intended value of the research and the ethical considerations were also described.

The following chapter provides a review of the literature that underpins this research project.

CHAPTER 2 - LITERATURE STUDY

2.1 Introduction

This chapter will discuss the importance of energy management in a South African context. Thereafter, the origins and definition of combined heat and power (CHP), the uses and types of CHP systems and the advantages and disadvantages of CHP will be described. Dual Fuel technology will be explained and the key elements of CHP dual fuel systems will be identified. The use of biogas as a fuel source is discussed in the South African context and the need to reduce CO_2 emissions.

The Transient System Simulation Tool (TRNSYS) which will be used to model a CHP dual fuel system will be described in the latter part of this chapter.

2.2 Energy management

Energy management is described as the efficient and effective use of energy through the minimisation of costs and the maximisation of profits (Capehart, et al., 2007).

Driven by policy and financial incentives the application of energy management systems, which provide a structure to monitor energy consumption and identify opportunities to improve efficiency, is growing. The number of certifications for ISO 50001, a global standard for energy management, developed in 2011, grew to nearly 12 000 in 2015. Evidence suggests that companies that implement ISO 50001 or similar standards can achieve annual energy and financial savings of over 10% (International Energy Agency, 2017a).

To manage energy, the practices that arise from adherence to energy related standards include the following (Department of Energy, 2016):

- eliminating waste by ensuring that energy is used at the highest possible efficiency,
- maximising efficiency through the utilisation of the most appropriate technology to meet organisational needs and
- optimising supply by purchasing or supplying energy at the lowest possible cost.

Energy management takes many different forms. Simple maintenance and operational activities can ensure that equipment and systems use energy efficiently and effectively. Alternatively, capital intensive installation of new, more efficient technology could also lead to efficiency gains. Energy management may also involve "fuel switching" to energy sources that are inherently more economical for a given application, such as the use of CHP dual fuel systems (Department of Energy, 2016).

Some of the objectives of energy management programs include (Capehart, et al., 2007):

- improving energy efficiency;
- reducing energy use;
- reducing costs;
- reducing greenhouse emissions;
- improving air quality;
- developing and maintaining effective monitoring, reporting and management strategies for energy usage and
- finding new and better ways to increase returns from energy investments through research and development opportunities such as modelling energy efficiency.

It can be seen from the above that 3 key areas of energy management encompass the investigation of:

- potential energy efficiency gains through the use of alternate energy sources;
- cost saving over time to determine the viability of capital investment in more efficient energy systems and
- environmental effects such as reduced CO_2 emissions.

2.2.1 Potential energy efficiency gains

Effectiveness measures the degree to which the objectives of an activity are achieved, while efficiency refers to the ratio of benefits to expenses. Energy efficiency, therefore, measures the ratio between benefit gained and the energy used (Irrek, et al., 2008).

Energy efficiency reduces energy use worldwide. From a global perspective, energy efficiency has improved by 13% between 2000 and 2016. Energy savings from efficiency improvements in International Energy Agency (IEA) member countries make up nearly half of this global total, with the major emerging economies accounting for around 40%. Without this improvement, final energy use at global level, in 2016 would have been 12% higher – equivalent to adding the annual final energy use of the European Union to the global energy market (International Energy Agency, 2017a).

Based on a recent study by the IEA (International Energy Agency, 2017a) the following global energy efficiency trends and indicators were documented:

- Primary energy demand per unit of gross domestic product (GDP) known as global energy intensity, fell by 1.8% in 2016. Since 2010, intensity has declined at an average rate of 2.1% per year, which is a significant increase from the average rate of 1.3% between 1970 and 2010. The fall in global energy intensity means that the world is able to produce more GDP for each unit of energy consumed. This is known as an energy productivity bonus.

- Falling energy intensity is the main factor behind the flattening of global energy-related greenhouse gas (GHG) emissions since 2014, offsetting three-quarters of the impact of GDP growth. An increase in the share of renewable energy and other low-emission fuels was responsible for offsetting the other quarter. Improvements in energy efficiency are the biggest contributor to reduced energy use and emissions, more than double the impact of the shift in economic activity towards less energy-intensive sectors.

- In emerging economies, energy efficiency gains have limited the increase in energy use associated with rapid economic growth. Without efficiency, total energy use among the member countries of the IEA would still be increasing.

- Energy security is the uninterrupted availability of energy sources at an affordable price. Energy efficiency has made a significant contribution to the strengthening of energy security in IEA member countries and emerging economies, in particular with regard to natural gas and oil as energy sources (International Energy Agency, 2017a).

Based on this data, many governments are emphasising energy efficiency opportunities as a way to stimulate their economies. By investing in energy efficiency initiatives, governments can reduce dependence on fossil fuels and reduce carbon emissions (McKinsey & Company, 2010).

CHP systems are viewed as highly efficient energy production processes as CHP requires less fuel to produce a given energy output. This contributes towards energy productivity, falling energy intensity and improved energy security (US Environmental Protection Agency, 2017a).

2.2.2 Economic impact of energy management

In economic terms, energy efficiency encompasses all changes that result in decreasing the amount of energy used to produce one unit of economic activity for example, the energy used per unit of GDP. Energy efficiency is then associated with economic efficiency and includes technological, behavioural and economic changes (World Energy Council, 2004).

Energy efficiency can be seen as a tool for economic growth as energy efficiency is the most cost-effective means to reduce the need for capital investment in new power supplies (Raphulu, 2017).

Within an organisation any new activity can only be justified if it is cost effective. Thus, the result of any new technology or changes to existing systems must show a profit improvement or cost reduction greater than the cost of the activity (Capehart, et al., 2007).

The introduction of energy management has proven to be cost effective over time as savings of 5-15% can be achieved with little or no capital outlay. Over time as much as 70% savings can be obtained by retrofitting the energy system, however this will require a capital investment (Capehart, et al., 2007), (McManus & O'Mara, 2010), (McKinsey & Company, 2010).

Secure, reliable, consistent and affordable energy supply is fundamental to economic stability and development (International Energy Agency, 2008).

CHP systems, which can lead to cost savings based on the fuel sources selected, can be used to increase energy production efficiency and to provide sustainable energy alternatives (Akorede, et al., 2010), (Cakir, et al., 2012), (Mago, et al., 2009).

CHP systems are based upon an efficient, integrated system that combines electricity production and a heat recovery system and generally converts 75-80% of the fuel source into useful energy. Some CHP plants can reach efficiencies of 90% or more thus leading to significant cost savings. CHP plants also reduce power network losses as they are sited near the end user thus reducing infrastructure costs (International Energy Agency, 2008).

2.2.3 Environmental impact of energy management

Energy efficiency represents about 40% of the greenhouse gas reduction potential worldwide. Energy efficiency initiatives can pay for themselves over time while providing the added benefits of reducing the cost of energy and increasing the energy productivity of the economy (McKinsey & Company, 2010).

Greenhouse gas (GHG) emissions savings from energy efficiency improvements on a global level since 2000 have led to a reduction in GHG emissions of just over 4 billion tonnes of carbon dioxide in 2016. Without these efficiency improvements, emissions in 2016 would have been 12.5% higher (International Energy Agency, 2017a).

CHP systems can reduce CO_2 emissions arising from energy generation systems by up to 10%. CHP can, therefore, make a meaningful contribution towards the achievement of emissions stabilisation, necessary to avoid major climate disruption (International Energy Agency, 2008).

2.3 Combined heat and power (CHP)

2.3.1 Origins of CHP

CHP technology, also referred to as cogeneration, is not a new concept. The first indications of electricity were described in 600 B.C. when Thales of Miletus discovered what we now know as static electricity, when he discovered that amber gets charged when rubbed (Hellström, 1998).

In 1752 Benjamin Franklin invented the lightning rod and demonstrated that lightning was electricity (Franklin Insitute, 2017). The principles of electromagnetic induction, generation and transmission was discovered by Michael Faraday in 1831 (Deffree, 2017). This led to electricity and electricity generation as we know it today.

Thomas Edison's Pearl Street Station was the world's first commercially viable power plant, which opened on 4 September 1882 in lower Manhattan (Astrum People, 2016). Mechanical rotational movement was used to generate the electricity from this plant (Deziel, 2018) . Mechanical rotational movement can be induced in a number of ways, however a disadvantage of this process is that heat, as a by-product, is often lost into the atmosphere (Hanania, et al., 2015).

Edison's plant was probably the first instance of energy recycling as it produced electricity and thermal energy. The thermal energy (produced as waste) was used to heat neighbouring buildings. As a result, Edison's plant was able to achieve 50% efficiency (Zanzalari, 2015) Thus the concept of CHP systems was born.

Prior to 1973, the oil and natural gas price, at under a dollar per barrel, led to energy waste and little thought was given to the efficient use of energy around the world (History.com Staff, 2010). In 1973 with the Organisation of Petroleum Exporting Countries (OPEC) energy crisis, the awareness to conserve energy and to seek alternative energy sources became a reality (US Department of State, 2016).

Today, it is imperative that alternative energy sources be developed and implemented as the economic and environmental impact of energy emissions and wasted energy is being felt all over the world (Cheng, et al., 2013).

CHP systems are one method of addressing this crisis.

2.3.2 Definition of CHP

CHP or cogeneration is defined as:

"Combined heat and power (CHP) systems, also known as cogeneration, generate electricity and useful thermal energy in a single, integrated system" (American Council for an Energy Efficient Economy, 2015)

"Combined heat and power is a system in which steam produced in a power station as a by-product of electricity generation is used to heat nearby buildings" (HarperCollins, 1979).

"The simplest definition of Cogeneration is defined as the simultaneous production of more than one type of energy from a single fuel source" (Goth, 2014).

For the purpose of this study, CHP will be defined as:

An integrated system for generating electricity and useful thermal energy.

2.3.3 Applications of CHP

From the internal combustion engine in a CHP unit, hot water with a temperature in the region of 60ºC and wet steam with a temperature in the region of 200ºC-400ºC is available for use in certain processes (US Department of Energy, 2016a).

Hot water for central heating in office blocks, apartment buildings, hotels and shops is generally the most common use of the heat energy collected from a CHP system (UK Department of the Environment, Transport and the Regions, 2000).

Besides the other advantages of CHP, proper central heating provided for the tenants of buildings, cheaper heat and hot water, CHP also reduces condensation and mould (UK Department of the Environment, Transport and the Regions, 2000) (US Environmental protection Agency, 2012).

As South Africa has a hot and mostly arid climate and central heating systems are not used, (Goth, 2014) the application of CHP lends itself more to other uses such as (US Environmental Protection Agency, 2017) (SANEDI, 2016):

- heating, ventilation and air conditioning (HVAC) of commercial buildings, residential buildings and institution buildings such as hospitals, prisons and military bases;
- heating for municipal uses which include wastewater treatment facilities and bio digesters and
- providing thermal energy in manufacturing industries for example, chemical, refining, ethanol, pulp and paper, food processing and glass manufacturing.

2.3.4 Industries most suitable for CHP systems

Industries that could benefit from CHP are mainly industries that require vast amounts of hot water or steam (US Department of Energy, 2016a). Typical examples of these are listed below:

- food & beverage;
- textiles;
- lumber and wood;
- furniture;
- paper;
- printing/publishing;
- chemicals;

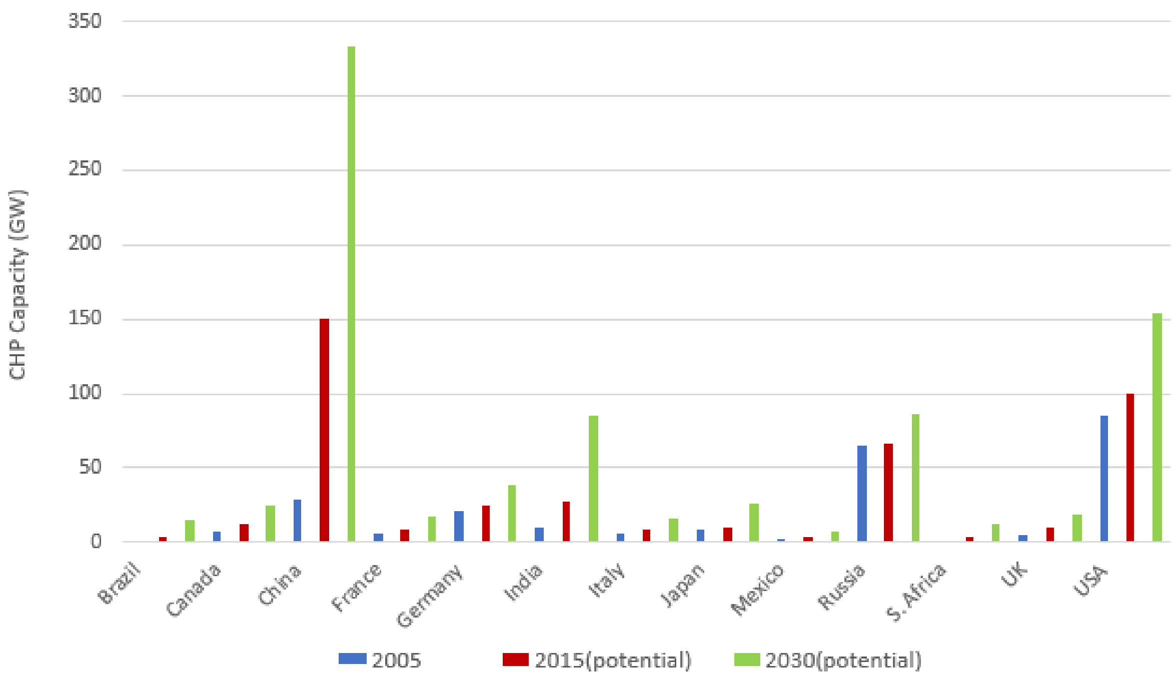
- petroleum refining;
- rubber/miscellaneous plastics;
- stone/clay/glass;
- primary metals;
- fabricated metals;
- machinery/computer equipment;
- transportation equipment;
- instruments;
- miscellaneous manufacturing and
- gas processing.

2.3.5 The potential for CHP systems in South Africa

According to the U.S. Department of Energy there is still a lot of potential for development and growth in the global CHP field (US Department of Energy, 2016a). The IEA states that the heating and cooling demand in the industrial, commercial and residential sectors of a country influence the development of CHP systems in that country (International Energy Agency, 2017b).

In a study conducted by the IEA (International Energy Agency, 2017b), this demand was used to analyse CHP potential in G13 countries. The heating and cooling demands required to meet current and future demands were considered to best estimate the potential for CHP systems.

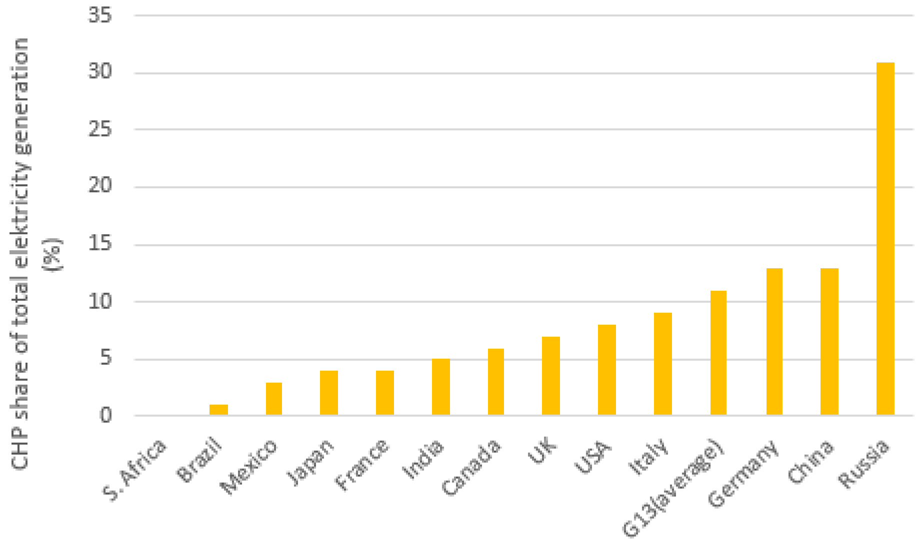
Taking this information into consideration, Figure 2.1 depicts the expected rise in CHP capacity in the G13 countries over a 25-year period. A small increase in CHP capacity between 2005 and 2015 is indicated in Figure 2.1, with a much larger growth expected by 2030 as green policies are widely implemented (International Energy Agency, 2017b).



Source: Adapted from IEA, 2017

Figure 2.1: G13 Countries – Expected rise in CHP capacity

With reference to Figure 2.2, it is clear that South Africa is significantly behind in terms of using CHP systems for power generation in comparison to the rest of the word (International Energy Agency, 2017b).



Source: Adapted from IEA, 2017

Figure 2.2: CHP share of total electricity generation (%)

In 2015, South Africa's Department of Energy requested bids under the cogeneration (CoGen) Independent Power Producer (IPP) procurement programme. The aim of the Cogeneration IPP procurement programme is to procure energy through three technologies (Department of Energy, 2015):

- waste to energy;
- combined heat and power (CHP) and
- industrial biomass.

The Cogeneration IPP procurement programme has two main requirements:

- the fuel and/or energy source should originate from an underlying industrial process and
- the cogeneration facility is coupled to the industrial process of a host plant (Department of Energy, 2015).

This program aims to produce approximately 800MW of new generation capacity from industrial cogeneration facilities (Gaille & Freehills, 2016).

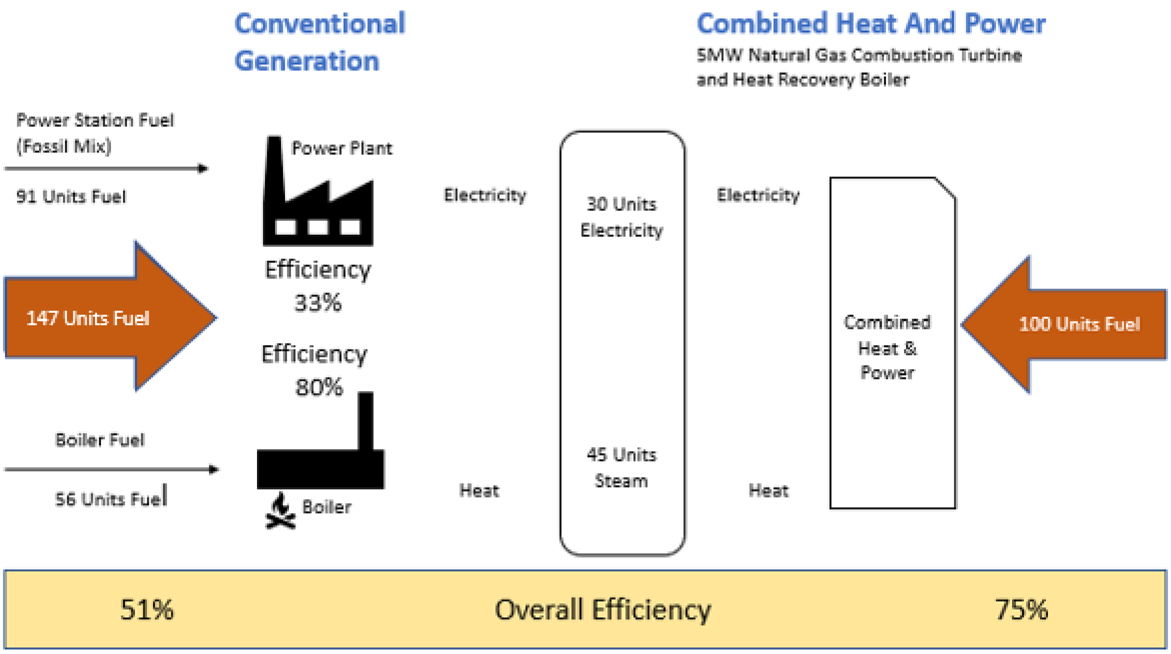
In addition, South Africa has the opportunity to install CHP plants in rural areas and for farm applications using biogas as a fuel source. Biogas is easily produced through agricultural waste and is a cost-effective fuel source (Griffiths, 2013). The use of biogas in South Africa is discussed in more detail in Section 2.4.5.3 in this Chapter.

2.3.6 Advantages of CHP

2.3.6.1 Efficiency benefits

An efficiency of about 33% can be expected from most fossil-fuel burning power plants. Two thirds of the potential energy are discharged into the atmosphere in the form of heat. By recovering this wasted heat in a CHP system, the total efficiency of the system can increase to between 60% and 90%, depending on the specific system used (US Environmental Protection Agency, 2016) (Siemens, 2017).

Figure 2.3 demonstrates the efficiency gains of a 5 megawatt (MW) natural gas-fired combustion turbine CHP system compared to the conventional production of electricity and useful thermal energy. It can be seen from Figure 2.3 that overall efficiency when using a CHP system increases from 51% to 75%.



Source: Adapted from US EPA, 2016

Figure 2.3: Conventional electricity generation vs. CHP: Overall efficiency

2.3.6.2 Environmental benefits

Thousands of people and organisations in South Africa currently own generators. Many of these generators stand idle when the electricity supply is constant. If these generators could be converted into CHP units, a reduction in the emissions that are released into the atmosphere could be significant and more usable energy can be produced with the same amount of fuel consumed (US Energy Information Administration, 2017).

In traditional coal burning power stations approximately 40% more CO_2 is released into the atmosphere compared to a natural gas burning CHP unit for the same amount of electricity generated (US Energy Information Administration, 2017).

According to the Carbon Trust, by installing CHP systems, 14.76 million tons of CO_2 was saved during 2007 in the United Kingdom alone (Carbon Trust, 2010) (Siemens, 2017).

Caused by the efficiency benefits of CHP, less fuel is burned for the same energy output, thus less emissions. A natural gas burning CHP unit has reduced emissions of GHG such as carbon dioxide (CO_2), nitrogen oxides (NO_x) and sulphur dioxide (SO_2) (US Environmental Protection Agency, 2016).

2.3.6.3 Economic benefits

The high efficiency of CHP directly impacts on the cost of producing energy. The use of natural gas also has an economic impact in that in most cases, natural gas is less expensive causing electricity to be cheaper (Siemens, 2017).

The economic benefits of CHP are dependent on the electricity rates, initial equipment costs and the overall CHP system design. The user‘s process needs, and goals also have an impact on the economic benefits of CHP (Siemens, 2017), (US Environmental Protection Agency, 2016).

2.3.6.4 Reliability benefits

The interruption of electricity supply could lead to health, safety and business risks. CHP systems can be designed to supply uninterrupted electricity. A properly designed and configured CHP system can provide better protection against loss of electricity supply (US Environmental Protection Agency, 2016).

2.3.7 Disadvantages of CHP

The following disadvantages of CHP systems should be noted:

- CHP is still a fossil-fuel based energy generation method and cannot be viewed as a long-term solution as fossil fuels are viewed as non-renewable (Howarth, 2015) (Savin, 2017);
- CO_2 and other green-house gasses are still emitted into the atmosphere albeit in smaller quantities (Intergovernmental Panel on Climate Change, 2007);
- overrated efficiency frequently claims that CHP is one of the largest potential solutions for our energy crisis (Watts, 2015) and
- CHP is only suitable where heat and electricity are required (Apunda & Nyangoye, 2017).

2.4 The CHP system

Apunda and Nyangoye (2017) state that a CHP system mainly consists of 4 key elements:

- a driving system (prime mover);
- generator for electricity production;
- a heat recovery system and
- a control system.

CHP units are classified according to the fuel they use and the type of prime mover that is driving the electricity generator (Apunda & Nyangoye, 2017).

2.4.1 Driving system (Prime movers)

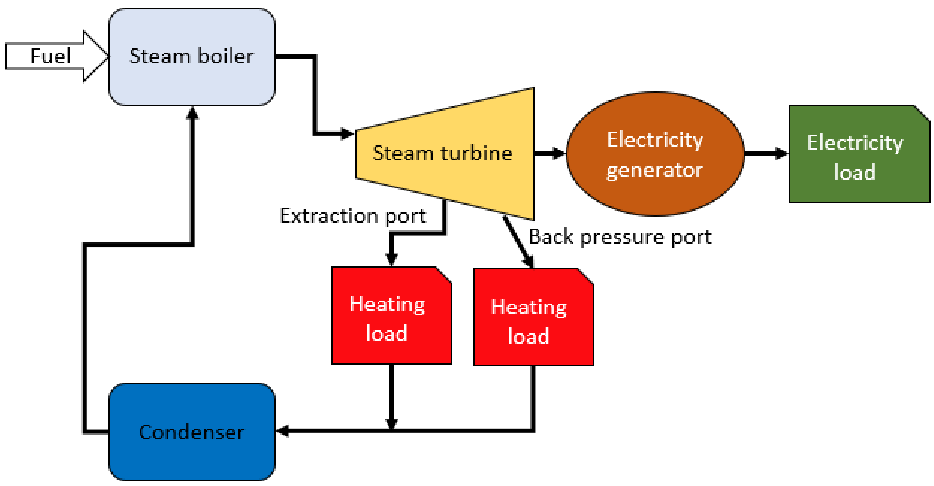
Mechanical rotational movement can be induced by water wheel, steam turbine, steam engine, wind generator or internal combustion engines (Lewitt, 1965), (Alternative Energy , 2015).

In the process of creating rotation using a steam turbine, coal must be burned, or a nuclear reaction needs to take place. Both these processes have heat as a by-product that is released into the atmosphere (Lewitt, 1965), (Alternative Energy , 2015). In addition, if an internal combustion engine is used to create rotational movement, 60% of the energy generated by the combustion process is released into the atmosphere via the exhaust in the form of heat (US Environmental Protection Agency, 2016).

Types of prime movers, which provide mechanical rotational movement, are briefly explained in the following sections:

2.4.1.1 Steam turbine

A steam turbine is mostly found in industry where cheaper fuel such as wood chips, coal or other biomass solid wastes are available to burn. The exhaust steam from the turbine is directly used for the heating demand and the electricity is absorbed by the plant (Apunda & Nyangoye, 2017) (US Environmental Protection Agency, 2015). This process is illustrated in Figure 2.4 below.



Source: Adapted from (Apunda & Nyangoye, 2017)

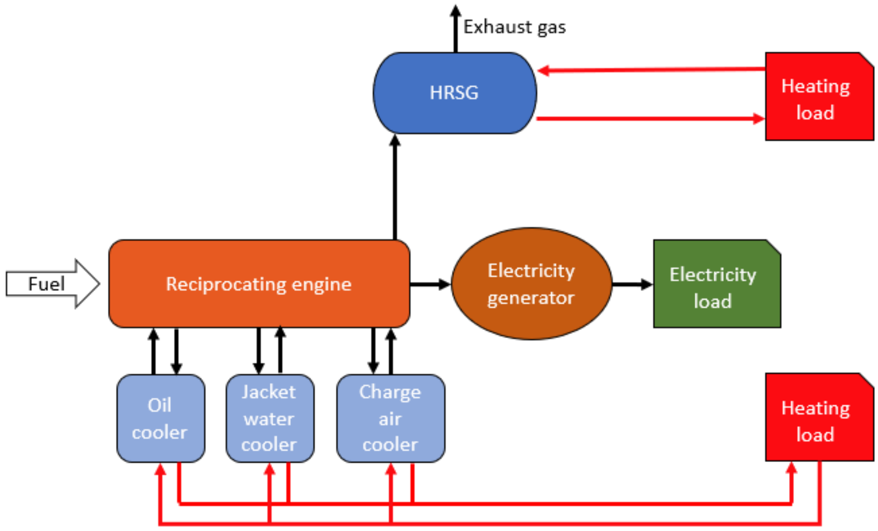
Figure 2.4: Steam turbine in a CHP

2.4.1.2 Reciprocating engines

Reciprocating engines are the most common type of CHP prime mover and are used in trucks, trains and emergency power systems.

Reciprocating engines can range from small portable units to multi story units.

The exhaust heat available from reciprocating engines is ideal for producing hot water as an output for a CHP system as shown in Figure 2.5 (Apunda & Nyangoye, 2017) (US Environmental Protection Agency, 2015).



Source: Adapted from (Apunda & Nyangoye, 2017)

Figure 2.5: Reciprocating engine in a CHP system

2.4.1.2.1 Internal combustion engines

The most common form of reciprocating engine is an internal combustion engine (University of Calgary, 2015).

Combustion is the basic chemical process of releasing energy from a fuel and air mixture. In an internal combustion engine, the ignition and combustion of the fuel occurs within the engine itself. The engine then partially converts the energy generated from the combustion into power. The engine consists of a fixed cylinder and a moving piston. The expanding combustion gases push the piston, which in turn rotates the crankshaft (US Department of Energy, 2013a).

There are two kinds of internal combustion engines currently in production:

- the spark ignition gasoline engine and
- the compression ignition diesel engine.

Most of these are four-stroke cycle engines, meaning four piston strokes are needed to complete a cycle. The cycle includes four distinct processes:

- intake;

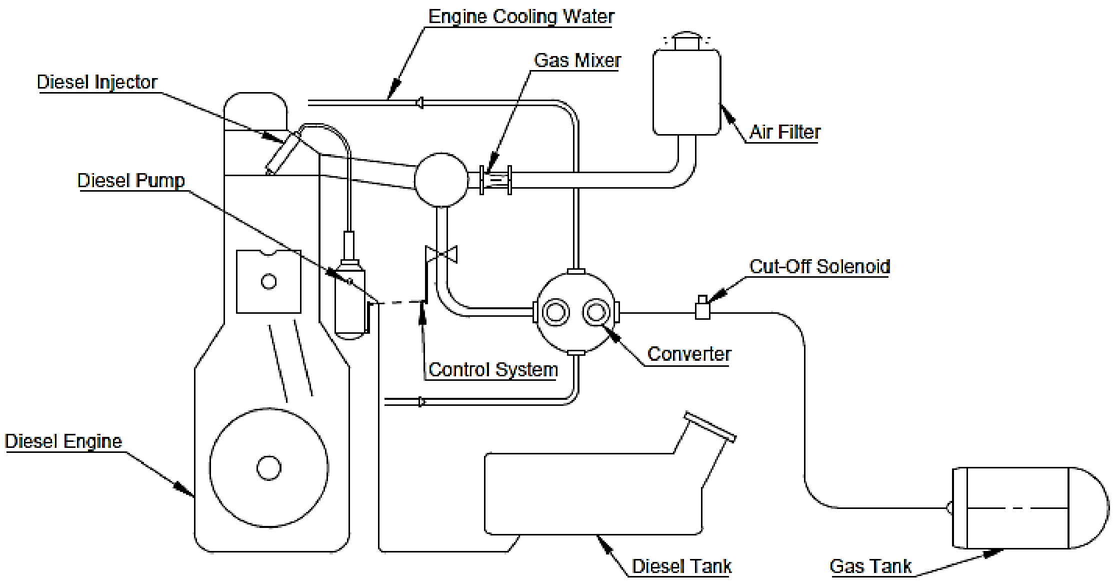
- compression;
- combustion and power stroke and
- exhaust.

In a spark ignition engine, the fuel is mixed with air and then inducted into the cylinder during the intake process. After the piston compresses the fuel-air mixture, the spark ignites it, causing combustion. The expansion of the combustion gases pushes the piston during the power stroke. In a diesel engine, only air is inducted into the engine and then compressed. Diesel engines then spray the fuel into the hot compressed air at a suitable, measured rate, causing it to ignite (US Department of Energy, 2013a).

2.4.1.2.2 Dual fuel engines

A normal diesel engine will only run on natural gas if a pilot flame is present to start combustion. This pilot flame is achieved by introducing between 5% and 15% diesel to the combustion process. Thus, the name dual-fuel.

Normally a dual-fuel prime mover is a compression ignition engine run by blending two fuels simultaneously, usually a mixture of 85% - 95% compressed natural gas (CNG) and 5% - 15% diesel. Fumigation takes place before pilot diesel ignition when the gas and air is mixed. Ignition is triggered upon the injection of a small amount of diesel at the required timing of the specific engine. This arrangement can be seen in figure 2.6 (Papagannakis, et al., 2007).

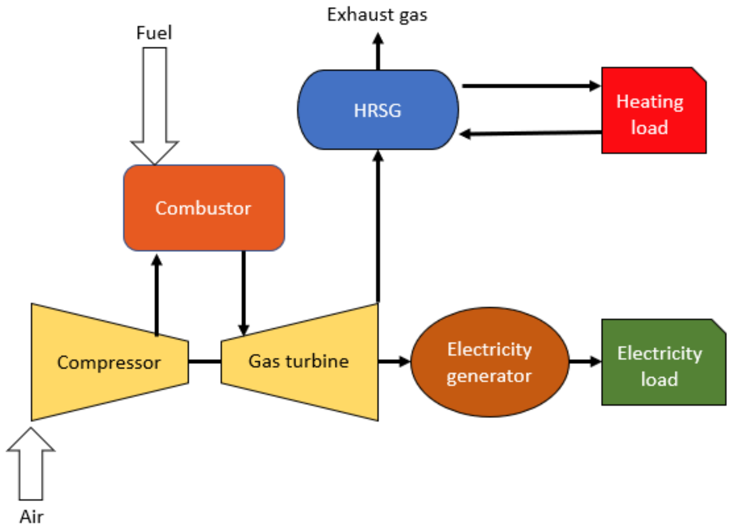


Source: Adapted from (Bergman & Busenthur, 1986)

Figure 2.6: Dual-fuel engine layout

2.4.1.3 Gas turbines

Gas turbines use the same technology that is used in jet aircraft. For CHP application, using gas turbines, the most economic arrangement is for CHP systems greater than 5MW. The high temperature generated at the exhaust side of the turbine is ideal for producing high pressure steam as an output for a CHP unit as shown in Figure 2.7 (Apunda & Nyangoye, 2017) (US Environmental Protection Agency, 2015).

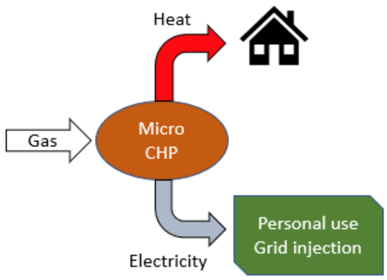


Source: Adapted from (Apunda & Nyangoye, 2017)

Figure 2.7: Gas turbine CHP

2.4.1.4 Micro turbines

Micro turbines are housed in very compact units which are mainly developed for residential houses and are clean burning. They are available in capacities ranging from 30kW to 250kW and are set up as illustrated in Figure 2.8 (Apunda & Nyangoye, 2017) (US Environmental Protection Agency, 2015).

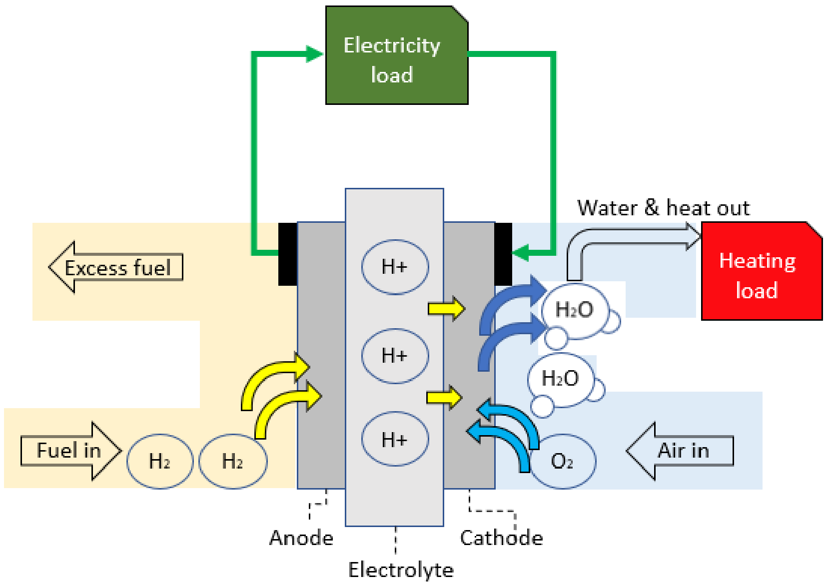


Source: Adapted from (Apunda & Nyangoye, 2017)

Figure 2.8: Micro turbine CHP

2.4.1.5 Fuel cells

Fuel cells are not a prime mover but in the process of converting the chemical energy of hydrogen into water and electricity, waste heat is created. Heat is recovered from hot water or low-pressure steam depending on the type of fuel cell as shown in Figure 2.9. Fuel cells are still very expensive but are ideal for low noise application (Apunda & Nyangoye, 2017) (US Environmental Protection Agency, 2015).



Source: Adapted from (Apunda & Nyangoye, 2017)

Figure 2.9: Fuel cell CHP

2.4.2 Generator for electricity production

An electricity generator is a device that converts mechanical energy (rotation) from an external source, such as a dual fuel engine, into electrical energy as output (Halliday & Resnick, 1988).

Electromagnetic induction discovered by Michael Faraday in 1831 is the main principle upon which modern day generators produce electricity. The flow of electric charge is induced by moving an electrical conductor in a magnetic field, which creates a potential difference (volts) over the ends of the electric conductor which causes electric charge to flow (current) (Energy Information Administration, 2017a).

2.4.3 Heat recovery system

The capturing of the thermal energy in the heat recovery system of a CHP system determines the efficiency of the CHP system. In a CHP dual fuel system exhaust gas from the prime mover (internal combustion engine) is directed into a heat recovery steam generator (HRSG) where thermal energy is extracted from the exhaust gas of the engine at a temperature of between 400 ˚C – 700 ˚C.

The HRSG is essentially a fire tube boiler. Shell and tube heat exchangers are used to capture the wasted engine water jacket thermal energy and the oil thermal energy. These heat exchangers are designed mostly using the Delaware method to suit the specifications of the prime mover (dual-fuel engine) for temperature and flowrates (Kozman, et al., 2009).

2.4.4 Control system

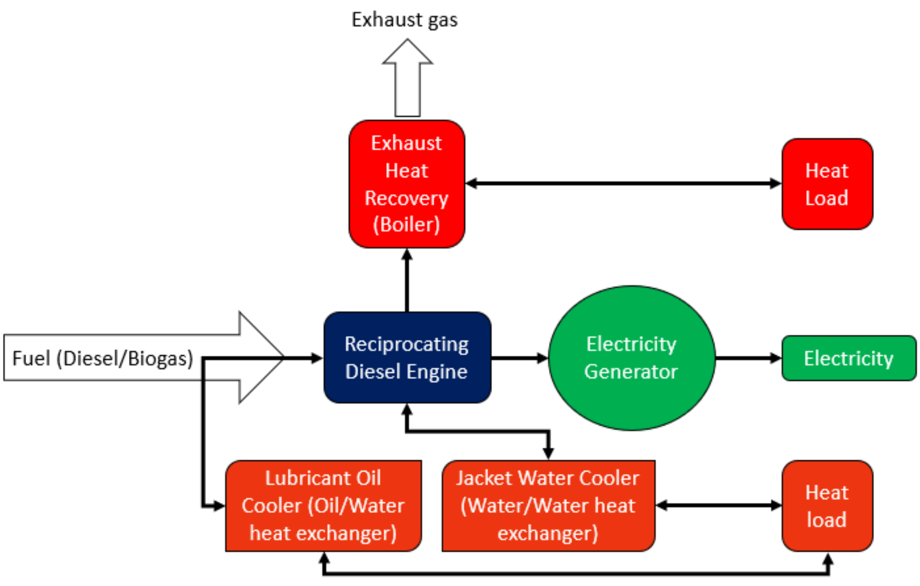
For efficient CHP systems control is essential. CHP systems can be controlled for:

- heat lead (HL) where the heat demand is the controlling factor, or
- electricity lead (EL) where electricity demand is the controlling factor.

Various algorithms can be applied by electronic control units to satisfy the predetermined control factors determined by the specific application of the CHP system (Gu, et al., 2015).

2.5 CHP dual fuel systems

A CHP dual-fuel system generally consists of a prime mover (diesel internal combustion engine), an electricity generator, lubricating oil heat exchanger, water jacket heat exchanger and an exhaust gas heat recovery system (Chartered Institution of Building Engineers, 2012), (Apunda & Nyangoye, 2017). Figure 2.10 illustrates the relationship between these components.



Source: Adapted from (Chartered Institution of Building Engineers, 2012)

Figure 2.10: CHP dual-fuel system diagram

This prime mover is typically a reciprocating engine that has been converted into a dual-fuel engine running on both gas and diesel.

It should however be noted that dual fuel engines have both associated disadvantages and advantages.

2.5.1 Disadvantages of dual fuel engines

Disadvantages of dual-fuel engines include (Turner & Weaver, 1994) (Jensen, 2006):

- initial (older) dual-fuel converted engines show an increase in carbon monoxide (CO) and hydrocarbons (HC) emissions under part load. This is mainly due to un-throttled air intake;
- expensive engine management control systems are required to address the above-mentioned problem. By managing the air intake much improved emissions can be achieved;
- two fuel system are required, gas and diesel;
- maintenance on two fuel systems can be costly and
- converting diesel engines to dual-fuel in most cases has an impact on the engine warranty.

It should be noted that when internal combustion engines are used to generate electricity they not only generate heat but in the combustion process CO_2 and NO_x are released into the atmosphere (Pisupati, 2017) (Low, 1965). However, use of the energy recovered through a heat recovery system linked to a dual fuel engine, can lead to a reduction of emissions per energy unit.

2.5.2 Advantages of dual fuel engines

The advantages of dual-fuel engines include (Weaver & Turner, 1994) (Renner, 2005):

- the biggest advantage of dual-fuel engines is their ability to run on 100% diesel or on a diesel-gas mixture. This is especially important when intermittent or unreliable gas supply occurs;
- decrease in partial matter(soot) emissions;
- diesel like efficiency;
- lower emission of CO_2 and NO_x than that produced by conventional electricity generation methods;
- increase of performance on full load application;
- no internal alterations are needed inside the diesel engine to convert it into a dual-fuel engine and
- very long service intervals compared to spark ignition gas engines (Jensen, 2006).

Based on the above, it is felt that the increased performance and the reduced emissions at full load application makes dual-fuel an ideal application for CHP systems (Renner, 2005).

2.5.4 CHP dual fuel: natural gas versus biogas as an alternative fuel source

Electricity generation worldwide is using our resources at an alarming rate thus there is a need to identify alternative fuel sources (EcoMetrix Africa , 2016) such as gas.

For the reduction of harmful gas emissions, natural gas can be used as a fuel source in conjunction with conventional diesel, thus reducing the amount of diesel used in a four-stroke internal combustion diesel engine. Burning natural gas instead of diesel reduces the CO_2 emissions significantly (Papagannakis, et al., 2007).

2.5.4.1 Natural gas

Natural gas is a fossil fuel that consists mainly of methane, a compound with one carbon atom and four hydrogen atoms (CH_4) and is found deep beneath the earth's surface. The use of natural gas has become more and more popular as it can be used for commercial, industrial, electric power generation and residential applications (Energy Information Administration, 2017b).

Natural gas is cheaper and cleaner than petrol or diesel and produces less greenhouse emissions than its counterparts. It burns completely and can be safely stored (Howarth, 2015).

There are however some disadvantages associated with the use of natural gas (Howarth, 2015) (Savin, 2017):

- Natural gas can be considered as a non-renewable energy source as its true reliability cannot be quantified. While huge natural gas discoveries have been announced over the past few years, they will ultimately become depleted. In terms of renewable sources of energy, natural gas does not come close to wind and solar energy.

- Increasingly, conventional sources of natural gas are being depleted and shale gas (natural gas obtained from shale formations using high-volume hydraulic fracturing and precision horizontal drilling) is rapidly growing in importance. Using hydraulic fracturing for natural gas extraction can lead to soil and water contamination and fracking can also cause small quakes in the area of the well, all of which are potentially harmful to the environment.

- Natural gas emits some quantities of GHG, in the form of CO_2 into the atmosphere, which contributes to climate change and global warming. While it is true that less CO_2 is emitted per unit of energy released when burning natural gas compared to coal or oil, natural gas is composed largely of methane, which itself is an extremely potent GHG. Methane is far more effective at trapping heat in the atmosphere than is carbon dioxide and so even small rates of methane emission can have a large influence on the GHG footprints (GHGs) of natural gas use.

Natural gas can be replaced with bio gas for further cost saving and lower GHG emissions.

2.5.4.2 Biogas

With rising concern over global warming issues more and more countries have now moved towards the generation of cleaner and greener energy as an alternative energy source. One example of green energy that can be used is biogas as it is both relatively cheap and more environmentally friendly than natural gas (Mel, et al., 2016).

Biogas is a type of biofuel that is naturally produced from the decomposition of organic waste such as animal manure, food scraps, waste water and sewage (Benzaken, 2015).

When organic matter is broken down in an environment absent of oxygen, known as an anaerobic environment, they release a blend of gases, primarily methane (CH_4) and carbon-dioxide (CO_2) along with some trace gases such as water vapour, hydrogen sulphide (H_2S), nitrogen, hydrogen and oxygen.

CO_2 and trace gases such as water vapour and H_2S must be removed before the biogas can be used in internal combustion engines (Benzaken, 2015), (Enviro Business, 2015), (Mel, et al., 2016) due to the fact that:

- H_2S gas is corrosive;
- water vapour may cause corrosion when combined with H_2S on metal surfaces and reduce the heating value of the heat recovery system and
- the presence of CO_2 may affect the performance of biogas thus CO_2 is also removed.

The process of producing biogas is known as anaerobic digestion, a natural form of waste-to-energy that uses the process of fermentation to break down organic matter (Benzaken, 2015). This process is similar to the digestive system of a cow, in that for fermentation to take place a temperature of between 35˚C and 42˚C should be maintained (Uzodinma, et al., 2007). This temperature is higher than ambient temperature, thus, an external energy source is required for an anaerobic bio digester. This external energy source can be supplied by the heat recovery system of a CHP dual fuel system (Kozman, et al., 2009).

Biogas produced by anaerobic digestion is an alternative and renewable fuel source for internal combustion (IC) engines. Biogas can replace conventional fossil fuels such as natural gas and lead to a reduction in diesel consumption. The use of biogas also allows exhaust nitrogen oxides (NOx) emissions to be reduced substantially. In addition, biogas plants significantly curb the greenhouse effect as a biogas plant lowers methane emission by capturing this harmful gas and using it as fuel (Mostafi, et al., 2006).

2.5.4.3 Biogas production in South Africa

In 1957 John Fry installed the world's first commercial anaerobic bio digester on a pig farm in South Africa, using pig manure. In 1958 electricity was produced to power the pumps on the farm using biogas from the anaerobic digester (ESI Africa, 2016) (Mutungwazi, et al., 2017)

Unfortunately, since the introduction of biogas in South Africa, limited advances in the biogas market have been made. In 2013, approximately 1000 commercial biogas plants were built per year in Germany, there were 12 million biogas plants in India alone and 600 in Uganda. At that time South Africa only had 300 (Munganga, 2013).

South Africa is, thus, not utilising its biogas potential. Reasons for this could include:

- the relatively cheap cost of electricity from other sources such as fossil fuels;
- limited grants or government incentives to support biogas technology and
- unavailability of local biogas technology providers (ESI Africa, 2016).

In 2005, the Central Energy Fund (CEF) developed a bio-energy programme for South Africa, based on the introduction of:

- a regulatory framework promoting renewable energy;
- appropriation of green funding and incentives;
- unreliable power grid supply and ever-increasing electricity tariffs;
- availability of unused biogas feedstock sources such as biomass and landfill sites that were fast reaching their capacity;
- the need to treat wastewater at a lower cost and
- the government's commitment to cleaner energy sources (ESI Africa, 2016), (Mutungwazi, et al., 2017).

Between 2005 and 2017 more biogas digesters have been installed across South Africa. Table 2.1 provides a list of biogas digesters installed in different parts of South Africa, the substrates used and the power output generated. In addition, many small domestic scale digesters have also been installed but no individual record of their numbers has yet been published (Mutungwazi, et al., 2017).

Table 2.1: Biogas digesters installed in South Africa

Area	Substrate input (where available)	Power output (Where available)
Alice, Eastern Cape	4000 m^3 of dairy and piggery manure	2 × 132 kVa electricity generators
Alrode brewery	400 t of organic waste per day	-
Bela-Bela Limpopo	-	-
Belville	Waste water treatment plant	-
Bonnievale	> 5 t bovine manure	-
Bredasdorp	4 t abattoir waste per day	100 kW
Cavalter	20 t abattoir waste per day	190 kW-500 kW
Darling Uilenkraal	Bovine manure	600 kW
Darling GrootPost	Bovine manure	
Durban	3500–5000 refuse per day	6 MW
Durban	550–850 t per day	1.5 MW
Grabouw	> 5 t of fruit waste per day	500 kW
Jan Kempdorp	5.5 t abattoir waste per day	135 kW
Jacobsdale	-	150 kW
Johannesburg	Sewage sludge	1.2 MW
Johannesburg	-	19 MW
Klipheuwel	700 t organic waste per day	-
Klipheuwel (Zandam)	> 5 t of manure per day	600–700 kW
Mossel Bay	Refinery waste water	4.2 MW
Newlands	4500 m^3 of wastewater per day	10% of the plant's energy demand
Paarl	-	14 MW
Pretoria	Manure	4.6 MW
Queenstown	42 t mixed waste from a piggery per day	
Riverdale	4 t abattoir waste per day	100 kW -150 kW
Springs	Slaughter waste and organic waste	0.4 MW
Stellenbosch	1000 m^3 wastewater per day	
Stellenbosch Franschhoek	35 kg per day (testing feedstock) Sewage, silage, manure Sewage, silage, manure Sewage, silage, agricultural waste	0.5 MW 1 MW
Table view	0.6–1 t of food waste per day	
KZN	Manure from 2+ cows, school organic and sewage waste	Rural cooking fuel
KZN	Manure from 2+ cows, school organic and sewage waste	Rural cooking fuel
EC (Alice, Fort Corx and Melani villages), WC (Phillipi), KZN	Manure from 2+ cows, school organic and sewage waste	Rural cooking fuel
Gauteng	Vegetable pulp + silage plant	7200 m^3 methane

Source: Adapted from (Mutungwazi, et al., 2017)

It can be seen from Table 2.1 that the substrate inputs and the power outputs of biogas digesters can lead to significant energy cost savings in the waste-to energy field in South Africa.

Energy generation using CHP saves valuable natural resources and driving the CHP system with biogas makes this configuration renewable (US Environmental Protection Agency, 2011) (EcoMetrix Africa , 2016).

2.6 Modelling CHP dual-fuel systems

Modelling CHP dual-fuel systems saves valuable resources, time and money (Hebert, 2015).

The modelling of a CHP plant is useful to develop a technical and economic analysis of both electrical and thermal energy production. Using a CHP model, it is possible to estimate and to forecast energy production, based on weather and operative conditions (Deneux, et al., 2013).

The ability to establish or estimate maximum generated energy provides the user with an advantage on the energy market and can lead to a faster maximisation of profits. Moreover, since it is possible to estimate some values that are not measured directly and others which vary quickly, or change due to failures, a model can provide a faster analysis of energy performance. A good model can also forecast the behaviour of an entire CHP system and be used to predict the technical and/or economic possibilities of installing different combinations of the elements that make up a CHP system (McDaniel & Kosanovic, 2016).

2.6.1 Transient System Simulation Tool (TRNSYS)

TRNSYS (Transient System Simulation Tool) is a flexible software tool used to simulate and assess the performance of thermal energy systems (TRNSYS, 2017).

It is used by engineers and researchers around the world to verify new energy concepts, from simple domestic hot water systems to the design and simulation of alternative energy systems (TRNSYS, 2017).

This program was designed 35 year ago by Duffy Beckman to simulate:

- solar thermal systems;
- photovoltaic systems;
- low energy buildings with advanced design features (natural ventilation, slab heating/cooling, double façade and so forth.);
- thermal industrial systems;
- renewable energy systems;
- cogeneration and
- fuel cells.

In TRNSYS, the Dynamic Link Library (DLL)-based architecture allows users and third-party developers to easily add custom component models, using common programming languages such as C, C++, Pascal and FORTRAN. In addition, TRNSYS can be easily connected to many other applications such as Microsoft Excel and Matlab, for pre- or post-processing or through interactive calls during the simulation () (TRNSYS, 2017), (Solar Energy Laboratory, 2007).

TRNSYS is made up of two parts (Solar Energy Laboratory, 2007):

- The TRNSYS simulation engine (called the kernel) that reads and processes an input file, iteratively solves the system, determines convergence, and plots system variables. The kernel also provides utilities that determine thermo-physical properties, invert matrices, perform linear regressions and interpolate external data files.

  The simulation engine is programmed in FORTRAN and the source is distributed. The engine is compiled into a Windows DLL, named TRNDll. The TRNSYS kernel reads all the information on the simulation (which components are used and how they are connected) in the TRNSYS input file. It also opens additional input files such as weather data and creates output files.

  The simulation engine is called by an executable program, which also implements the online plotter, a useful tool that allows the user to view dozens of output variables during a simulation.

- The second part of TRNSYS is an extensive library of components, each of which models the performance of one part of the system chosen. The standard library includes approximately 150 models ranging from pumps to multi-zone buildings, wind turbines to electrolysers, weather data processors to economics routines and basic HVAC equipment to cutting edge emerging technologies.

Models are constructed in such a way that users can modify existing components or write their own, extending the capabilities of the environment. Thus, TRNSYS is ideal for the simulation of CHP integration into industrial thermal processes (Goldade, 2017).

2.7 Summary

This chapter described the benefits of energy management and provided an overview of CHP systems. CHP dual fuel systems were also discussed and the use of biogas as a fuel source was discussed in the South African context. The literature also referred to the issues of CO_2 emissions and carbon footprint reduction. The need for modelling CHP systems was also motivated.

In the following chapter the research methodology will be described, the key physical components of the CHP dual-fuel demonstrator will be identified and the TRNSYS components to be used in the model will be identified.

CHAPTER 3 – METHODOLOGY

3.1 Introduction

This chapter describes the origins of Skills for Green Jobs project which forms the basis for this research project. The objectives of the research are outlined and the methodology to be followed is described. The key physical elements of the CHP dual fuel demonstrator are explained and the library components for the TRNSYS model are selected to achieve the project outputs.

3.2 The origin of the research project

In 2016, the Technology Station of the Vaal University of Technology (VUT), and Pegasus (Pty) Ltd. tendered for the project, Skills for Green Jobs (S4GJ) and both were awarded the tender.

S4GJ is a technology transfer project in the green energy field that was initiated by the *Deutsche Gesellschaft für Internationale Zusammenarbeit* (GIZ) as a collaborative project between academic institutions and industry partners in South Africa.

The S4GJ project had 3 main aims (Council for Scientific and Industrial Research, 2015):

- in the first place the project was aimed at developing the skills of both staff and students from an academic institution within the field of sustainable energy;
- the second aim was to develop a CHP dual fuel model, using TRNSYS, to demonstrate the energy cost savings associated with the use of CHP dual fuel systems and
- the third aim was to build a CHP dual fuel demonstrator, in conjunction with Pegasus and CAE that would showcase CHP dual fuel technology and verify the TRNSYS model.

In this project, the academic institution selected was VUT and the industry partner is represented by Pegasus. In association with Pegasus, Cape Advanced Engineering (Pty) Ltd., an engineering and manufacturing organisation that specialises in the installation of machinery and equipment used in the renewable energy and biogas field, was selected to build the CHP dual fuel demonstrator used in the project.

Each of the 3 parties involved in the project are discussed in more detail in the following sections.

3.2.1 The Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ)

The GIZ, also known as the German Society for International Cooperation is a German development agency, head quartered in Bonn and Eschborn that provides services in the field of international development cooperation (Deutsche Gesellschaft für Internationale Zusammenarbeit, 2014).

One of the 8 main product areas in which GIZ specialises is that of sustainable infrastructure. For the purpose of the S4GJ project, the key focus areas include:

- basic energy supply services;
- renewable energy and
- energy efficiency.

The GIZ global agenda includes South African cooperation, which focuses on both:

- bilateral cooperation between developing countries and emerging economies and
- triangular cooperation between developing countries as beneficiaries, emerging economies as "new donors" and traditional donors, for example, Germany, as contributors of expertise (Deutsche Gesellschaft für Internationale Zusammenarbeit, 2014).

In terms of the S4GJ project, GIZ provided:

- Expertise, in that 3 staff members from the Technology Station at VUT were provided with the opportunity to liaise with and visit academic institutions in Germany. The institutions visited included Hamburg Technical University, where the Technology Centre known as TuTech, specialises in CHP technology and transfer and the Energy Research Centre in Goslar. Arrangements were also made to visit organisations in Germany that utilise CHP using both natural gas and biogas. Organisations visited included APROVIS and AGO. In addition, Professor Lars Kühl from Ostfalia University, an expert in CHP within the food processing industry and TRNSYS, provided his expertise throughout the early stages of the S4GJ project.

- Funding was provided for the above-mentioned visits, and funding for 5 Technology Station staff members for the Certified Energy Management Training Programme, Certified Energy Audit Training Programme, Heat Exchanger Design Training Programme, Steam Handling and Boiler Maintenance Training Programme and the TRNSYS webinar. Funding was also provided for the manufacturing of the CHP Demonstrator used for this research project.

3.2.2 Vaal University of Technology

The VUT S4GJ project team originally consisted of:

- 1 academic partner from the Faculty of Engineering, who later resigned from the university and thus withdrew from the project;
- 3 staff members from the Technology Station at VUT and

- 5 Bachelor of Technology (B.Tech) students, 2 of whom withdrew from the project, during the early stages.

As part of GIZ's commitment to the project, major emphasis was placed on the skills development of the selected project team members.

The 2 remaining Technology Station staff members and the 3 B.Tech students completed the training programmes mentioned in 3.2.1 above. In addition, all 3 students successfully completed the B.Tech in Mechanical engineering and 1 staff member (the researcher) enrolled for the M.Eng in Engineering Management at North West University. The result of this investment in skills development led to the establishment of the Energy Optimisation Unit within the Technology Station at VUT on completion of the S4GJ project.

The VUT project team contributed to the project through:

- the theoretical design of the heat exchanger components for the CHP dual fuel demonstrator to be used later in the project;
- modelling of the CHP dual fuel system using TRNSYS and
- assisting with the assembly, installation and commissioning of the CHP dual fuel demonstrator.

3.2.3 Pegasus (Pty) Ltd and Cape Advanced Engineering (Pty) Ltd (CAE)

Cape Advanced Engineering (Pty) Ltd (CAE) was established as a Centre of Excellence in engine and fuel technology at Stellenbosch University in 1993 and in 1999 was privatised as a commercially sustainable enterprise.

CAE has thus operated as a private company since 1999 and the majority of CAE's projects have been related to engine and fuel technology. The company also has a close relationship with local fuel companies and major fuel additive companies, for whom CAE has undertaken significant bench testing and fleet trial evaluation programmes (Emslie, 2014)

CAE has successfully completed a number of vehicle conversions to liquid petroleum gas (LPG) and has run numerous fleet trials for various clients in the automotive and other sectors. CAE's latest fleet trial, conducted in 2012/2013 for the Industrial Development Corporation (IDC) of South Africa, investigated the use of compressed natural gas and compressed bio-methane as a vehicle fuel locally, particularly in buses and minibus taxis for public transport. During the IDC investigation, a number of diesel dual fuel conversion systems were identified and studied. A Volkswagen diesel dual fuel vehicle's performance was evaluated and the best and least intrusive diesel dual fuel conversion system available in the market today was identified (Emslie, 2014).

In 2007, following the publication of the 2003 White Paper on Renewable Energy and as well as invitations from government to the private sector to participate in the development of renewable power generation, CAE recruited a dedicated team and commenced with the development of local knowledge in the construction and operation of bio-gas power generation plants.

CAE established Pegasus to facilitate the entry of a broader spectrum of individuals and start-up enterprises into the renewable energy sector within South Africa and Namibia (Emslie, 2014).

In December 2013, Pegasus, in collaboration with VUT, also initiated a diesel dual fuel demonstration project for the City of Johannesburg Metrobus, using dual fuel technology.

With regard to the S4GJ project, Pegasus was responsible for the identification, sourcing and funding of the equipment required for the CHP dual fuel demonstrator, based on the design outcomes of the VUT project team. In collaboration with CAE, Pegasus developed the geometrical design for the CHP dual fuel demonstrator and subsequently CAE manufactured and assembled the demonstrator.

3.3 The purpose of this research project

The data generated from the S4GJ project, will be used to develop and verify an energy system simulation model for a CHP dual-fuel system. This entails:

- developing an energy system simulation model in TRNSYS for the selection of a CHP dual-fuel system that would be suitable for application in South Africa;
- verifying that the data obtained from the TRNSYS energy system simulation model correlates with the measured data obtained from a CHP dual fuel demonstrator and
- analysing the energy efficiency gains, cost saving and CO_2 emissions when using a CHP dual fuel system.

3.4 Research Methodology

The key physical elements of a generic CHP dual fuel system were identified through the literature review in Chapter 2.

In order to achieve the objectives of this study, the empirical procedure to be followed includes the selection of the:

- key physical elements of the CHP dual fuel demonstrator used in this study;
- TRNSYS sub-routine models(TYPES) from the TRNSYS TESS library to best represent the key physical elements of the CHP dual fuel demonstrator and
- suitable thermal energy load elements from the TRNSYS TESS library to simulate the process energy demand of the consumer.

This will be followed by the:

- development of a TRNSYS energy simulation system model through connecting the TRNSYS selected elements to represent the elements of the CHP dual fuel demonstrator;
- collection of actual input values from the CHP dual fuel demonstrator and entering these values into the TRNSYS model and
- comparison of the TRNSYS output values to the CHP dual fuel demonstrator output values to verify the authenticity of the TRNSYS energy simulation model.

3.5 The CHP dual fuel demonstrator

The design criteria for the CHP dual fuel system used in this project required that a mobile demonstrator be built for VUT for the purpose of validating the TRNSYS model, presenting technical demonstrations regarding the capabilities and benefits of a CHP dual fuel system and for further research in the field.

3.5.1 Specifications of the CHP dual fuel demonstrator

The CHP dual fuel demonstrator was manufactured by CAE in 2017.

The CHP dual fuel demonstrator was built exclusively as a technology demonstrator to showcase the advantages of CHP as identified in the literature. The CHP dual fuel demonstrator, as shown in Figure 3.1, is a mobile unit and cannot function as a standby energy supply unit.

Figure 3.1: Mobile CHP dual fuel demonstrator

The CHP dual fuel system was built on a 1.5-ton trailer fitted with a 50 kW Mercedes Benz OM 346 C dual fuel engine that drives a 75kVA (max) generator. The CHP dual fuel demonstrator delivers steam at a temperature of 168˚C and steam pressure of 11.4 bar. Hot water at 70˚C is also produced for external use. This unit can only be integrated into an existing system where thermal energy and electricity is required. It also has the capability to tie into the existing electricity supply. An energy balance can then be set up to illustrate the benefits of using CHP.

For this research, however, the thermal values and available power generated from the CHP dual fuel demonstrator were measured in order to be compared against the corresponding values from the TRNSYS system model.

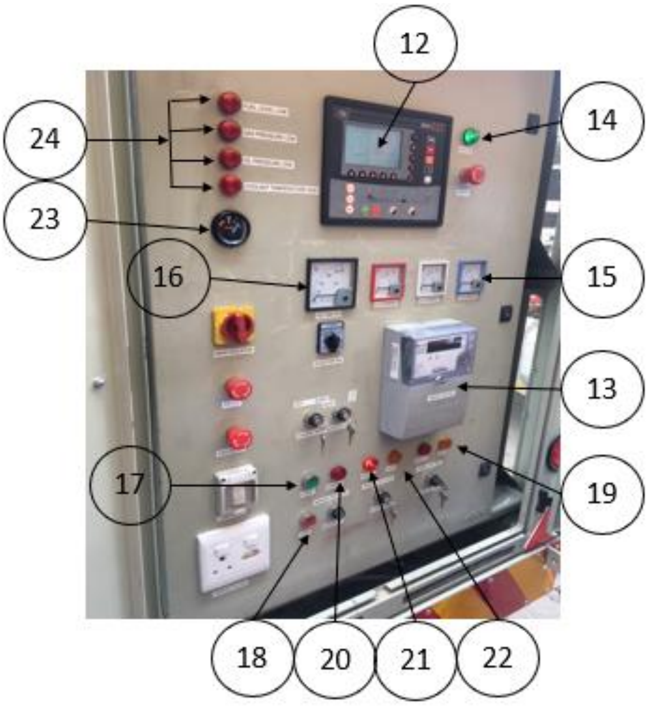
The advantage of dual fuel is the ability to operate on either diesel or a diesel-gas mixture. This unit enables demonstrations of the uses of both.

Figure 3.2: Quick couplings and connections

Easy access to quick coupling devices is one of the features that make this unit ideal for demonstration purposes. Some of the couplings can be seen in Figure 3.2 above.

A user-friendly control panel enables ease of use and visible fault-finding capability as shown in Figure 3.3 and 3.4 below.

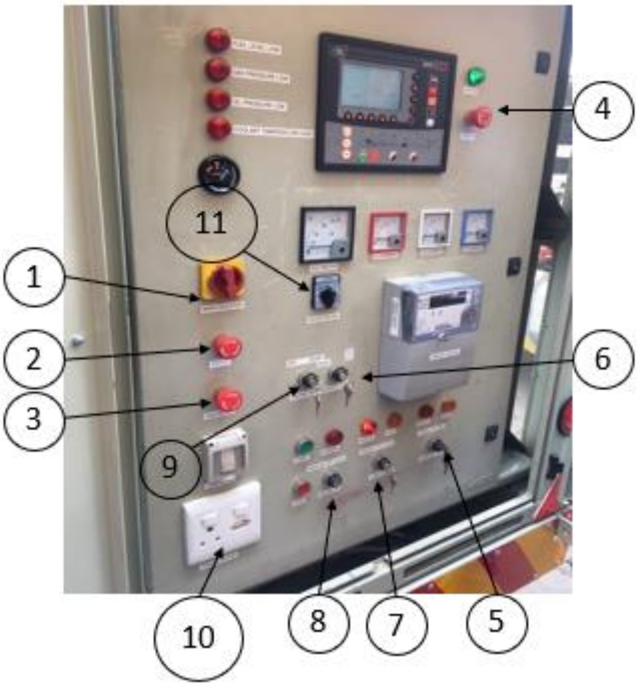
	Indicator Name	**Indicator Description**
12	RDM 2.0	Human Machine Interface (HMI) screen for the generator controller
13	Power Monitor	Display the power and energy consumption from the system
14	24V Power	Indicate battery circuit connection
15	Ammeter	Display current supplied to the plant



16	Voltmeter	Display voltage supplied to the plant
17	Start	Start boiler water pump
18	Stop	Stop boiler water pump
19	DDF mode	Indicate whether the system is in DDF mode
20	Boiler status	Indicate boiler status
21	Radiator status (manual)	Indicate that the fan is in manual mode
22	Radiator status (automatic)	Indicate that the fan is in automatic mode
23	Fuel gauge	Indicates the level of the diesel fuel
24	Alarm warning lights	Indicates: low diesel alarm, low gas pressure alarm, low oil pressure alarm and high coolant temperature alarm

Source: (Pegasus, 2018)

Figure 3.3: Control panel indicators



	Control Name	**Control Description**
1	Panel Isolator	Switch main power to the panel
2	Boiler Emergency Stop	Partialy switches off control circuit
3	Gas Emergency Stop	Partialy switches off control circuit
4	Main Emergency Stop	Switches off all control systems
5	Diesel Dual Fuel (DDF) Switch	Fuel mode selection switch ON → Diesel and gas OFF → Diesel only
6	Load switch	Select the load set point (25kW / 50 kW)
7	Rariator fan switch	Switch fan on / off
8	Boiler switch	Switch boiler on / off
9	Ignition switch	Enables engine to start or switch off
10	Plug	220V external singele-phase load connection
11	Voltmeter switch	Phase selection switch for voltmeter

Source: (Pegasus, 2018)

Figure 3.4: Control panel controls

The GENSYS 2.0 is a control panel, as seen in Figure 3.5, designed specifically for generators. The following functions are combined in this one unit (Cretechnology, 2017):

- three phases mains failure;
- engine start/stop and protections;
- alternator control and protections;
- mechanical parameters display;
- electrical parameters display;
- genset synchronisation;
- load sharing and kW control and
- load sharing and kVAR control.

Figure 3.5: GENSYS 2.0 display screen

The GENSYS 2.0 can be configured using the front panel or with a personal computer with Cretechnology configuration software. It has an embedded web site which is password protected. The GENSYS 2.0 controller has analogue load sharing lines and is compatible with most types of analogue load sharing modules. (Cretechnology, 2017)

The built-in wireless capability of the GENSYS 2.0 generator controller makes data acquisition easy and data can also be accessed remotely.

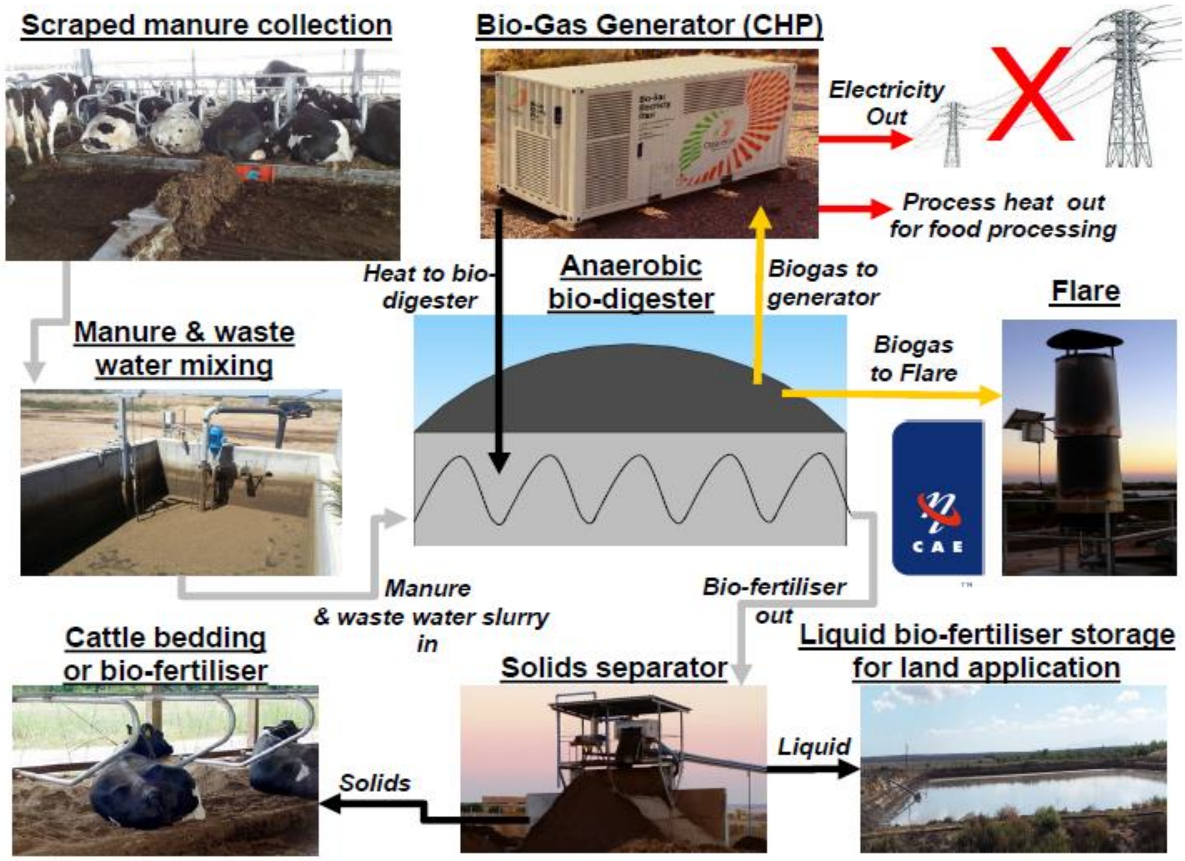
3.5.2 Installation of the CHP dual fuel demonstrator

A dairy farm “Uilenkraal“, situated in the Western Cape, was identified as the ideal place to test the CHP dual fuel demonstrator as the farm already has an extensive anaerobic bio-digester, shown in Figure 3.6 that produces bio gas used in the generation of electricity.

Source: (Taylor, 2015)

Figure 3.6: Uilenkraal Bio-gas digester

Uilenkraal farm milks more than 1500 lactating cows producing approximately 60000 litres of milk per day. The cows each produce, on average 60kg of waste per day, totalling 90 000kg that is used in the production of biogas using the anaerobic bio-digester. The biogas is scrubbed to remove impurities such as CO_2 and water vapour and then used to fuel the CHP biogas generator, the output of which is in the region of 600kW. The process is demonstrated in Figure 3.7.



Source: (Taylor, 2015)

Figure 3.7: Process flow of Uilenkraal

Nutrikor a large-scale commercial feed mill is also operated by Uilenkraal and consumes in the region of 350kVA of electricity produced by Uilenkraal.

Uilenkraal and CAE have been in collaboration since 2008 working towards the advancement of bio-gas, power generation and combined heat and power generation technology (Taylor, 2015).

CAE suggested that Uilenkraal would be the most suitable site for the commissioning and piloting of the CHP demonstrator as a constant supply of scrubbed biogas is available and the farm is situated close to CAE, thus access to expertise and problem-solving capability related to the CHP dual fuel demonstrator is close at hand.

To control secondary variance, the researcher agreed that Uilenkraal would be ideal, as the impact of an interrupted supply of biogas would have a negative effect on the outcome of the TRNSYS model in comparison to the outputs of the CHP dual fuel demonstrator.

The energy generated by the CHP dual fuel demonstrator during the pilot stage will be used on the farm to help meet daily electricity demand for the farm and the heat generated will be used to heat the bio-digester for greater efficiency.

3.5.2 Key physical elements of the CHP dual fuel demonstrator

For the purpose of this research the key physical elements of the CHP demonstrator that will be used in the TRNSYS model are discussed below,

3.5.2.1 Prime mover

A four-cylinder reciprocating, four stroke Mercedes Benz 3.9L turbocharged compression ignition engine was used. The engine was run at 1500rpm with an output power of 50kW to meet the required electricity output frequency of 50Hz.

A brief description of the engine is provided in Table 3.1. Figure 3.8 illustrates the actual Mercedes Benz OM 346 C engine used in the CHP demonstrator.

Table 3.1: Prime mover specifications

Specifications	Values
Engine Model	Mercedes Benz OM 346 C
No. of cylinders	4
Bore	97.5mm
Stroke	103 mm
Volumetric capacity	3.972 cubic meters
Compression ratio	17.75
Specific fuel consumption	0.217 kg/kWh
Torque	320N.m @ 1500rpm
Max power	50kW @ 1500 rpm
Exhaust temperature	480˚C
Coolant temperature, In	75˚C
Coolant temperature, Out	85˚C

Source: adapted from (Emslie, 2014)

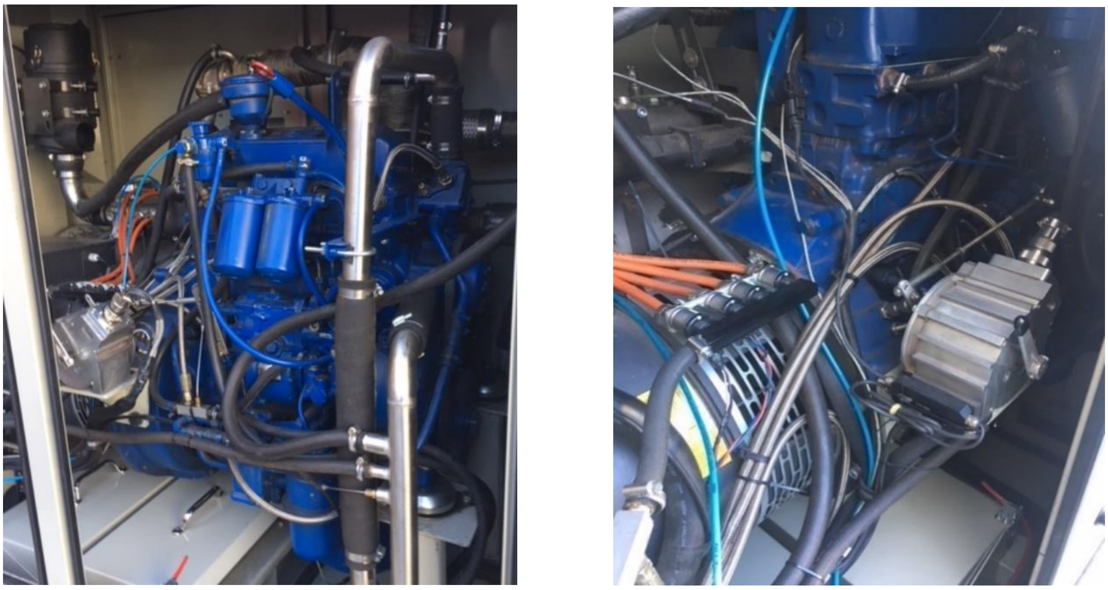


Figure 3.8: Mercedes Benz OM 346 C engine in the CHP demonstrator

The engine was run using a dual fuel mixture of scrubbed biogas, obtained from the anaerobic biogas digester plant on the Uilenkraal farm and diesel. The ratio for the dual fuel mixture was 85:15 where biogas was used as the main fuel source.

The researcher will measure the following engine outputs of the CHP dual fuel demonstrator in real time using the GENSYS 2.0 generator controller and data acquisition system for TRNSYS modelling purposes:

- power output /load (kW to be measured using GENSYS 2.0);
- revolutions per minute (rpm to be measured using GENSYS 2.0);
- water jacket temperature (˚C to be measured using a k-type thermal couple);
- engine oil temperature (˚C to be measured using a k-type thermal couple);
- exhaust temperature (˚C to be measured using a k-type thermal couple);
- atmospheric pressure (kPa to be measured using a pressure transducer) and
- boost pressure (kPa to be measured using a pressure transducer).

CAE conducted a separate dyno meter engine test to establish the oil and water flow rates used in this research. See Annexure 1 for the data sheet.

3.5.2.2 Generator

A FLD224F16 generator, as shown in Figure 3.9, was selected to best suit the power produced by the Mercedes Benz OM 346 C engine. Table 3.2 lists the specifications of the generator used. The function of the generator is to optimally use the available mechanical power supplied by the engine and convert it into electricity (Jiangsu Farrand Alternator Technology Co.,Ltd, 2017).

Table 3.2: The generator specifications;

Specifications	Values
Operating RPM	1500/1800 r/min
Phases	3
Voltage	380 V
Power factor	0.8
Frequency	50Hz
Power output	75 kVA at 40˚C 78 kVA at 28˚C

Source: adapted from (Jiangsu Farrand Alternator Technology Co.,Ltd, 2017)

Figure 3.9: Electricity Generator

For TRNSYS modelling, the electric power generated (kW) by the CHP dual fuel demonstrator will be measured using GENSYS 2.0.

3.5.2.3 Heat recovery system

Two cross-flow shell and tube heat exchangers were used in the CHP dual fuel demonstrator.

The heat exchanger shown in Figure 3.10 was used to harvest the engine oil heat and the heat exchanger shown in Figure 3.11 was used to harvest the water jacket heat.

Source: (EXERGY Heat Transfer Solutions, 2017)

Figure 3.10: Engine oil heat exchanger

Source: (InKorr, 2014)

Figure 3.11: Water jacket heat exchanger

The size of the cross-flow heat exchangers was determined from the measured temperatures and flowrates of the water jacket and the engine oil lubricant used for the Mercedes Benz OM 346 C engine. Based on the measurements taken, Table 3.3 lists the sizes of the water jacket heat exchanger required and Table 3.4 lists the required sizes of the engine oil heat exchanger. Off-the-shelf heat exchangers were bought from a heat exchanger supplier, with near perfect correlating sizes. These are listed next to the calculated values in Table 3.3 and Table 3.4.

Table 3.3: Water jacket heat exchanger properties

Property	Calculated or measured	InKorr BCF actual
Shell diameter	153mm	160mm
Tube inside diameter	13.6mm	13.5mm
Tube outside diameter	16mm	16mm
Tube length	460mm	480mm
Overall length	550mm	580mm
Number of tubes	40	40
Heat transfer coefficient	688W/m^{2}K	-
Mass flow rate hot(tube) side	0.6kg/s	-
Mass flow rate cold(shell) side	0.133kg/s	-
Tube inlet temperature	358.15K (85 ˚C)	-
Tube outlet temperature	348.15K (75 ˚C)	-
Shell side inlet temperature	298.15K (25 ˚C)	-
Shell side outlet temperature	343.15K (70 ˚C)	-
Tube side design pressure	-	1MPa
Shell side design pressure	-	20MPa
Design temperature max.	-	150˚C
Tube material	Copper	Copper
Shell material	Copper	Brass

Source: (InKorr, 2014)

Table 3.4: Engine oil heat exchanger properties

Property	Calculated or measured	EXERGY actual
Shell diameter	50mm	64mm
Tube inside diameter	5.2mm	4.8mm
Tube outside diameter	6.3mm	6mm
Tube length	900mm	1000mm
Overall length	1000mm	1100mm
Number of tubes	48	50
Heat transfer coefficient	152W/m^{2}K	-
Mass flow rate hot(tube) side	0.33kg/s	-
Mass flow rate cold(shell) side	0.97kg/s	-
Tube inlet temperature	358.15K (85 ˚C)	-
Tube outlet temperature	348.15K (75 ˚C)	-
Shell side inlet temperature	298.15K (25 ˚C)	-
Shell side outlet temperature	343.15K (70 ˚C)	-
Tube side design pressure	-	1MPa
Shell side design pressure	-	20MPa
Design temperature max.	-	150˚C
Tube material	Copper	Copper
Shell material	Copper	Copper

Source: adapted from (EXERGY Heat Transfer Solutions, 2017)

The fluid properties, flowing in the heat exchangers, as required by TRNSYS, are indicated in Table 3.5

Table 3.5: Fluid properties required for heat exchangers

Description	Abbreviation	Unit
Specific heat capacity	Cp	kJ/kgK
Dynamic Viscosity	µ	Pa.s
Thermal conductivity	K	W/mK
Density	ρ	Kg/m^3
Prandtl number	Pr	

Source: Adapted from (Engineering ToolBox, 2003)

For TRNSYS modelling the following data will be obtained from the cross-flow heat exchangers for both engine oil and water jacket:

- heat transfer coefficient (W/m^2K to be calculated);
- mass flow rate hot(tube) side (kg/s obtained from CAE dyno meter test data – Annexure 1);
- mass flow rate cold(shell) side (kg/s to be calculated);
- tube inlet temperature (˚C to be measured using a k-type thermal couple);
- tube outlet temperature (˚C to be measured using a k-type thermal couple);
- shell side inlet temperature (˚C to be measured using a k-type thermal couple) and
- shell side outlet temperature (˚C to be measured using a k-type thermal couple).

The Heat Recovery Steam Generator (HRSG) was designed by an external accredited pressure vessel design company, ProTherm Systems (Pty) Ltd. as shown in Figure 3.12. CAE manufactured, tested and certified the HRSG. 316L Stainless Steel was used for the HRSG. The specifications of the HRSG are listed in Table 3.6.

Table 3.6: Specifications for the boiler

Property	**Calculated value**
Mass flow tube side (exhaust gas)	195kg/h
Mass flow shell side	30kg/h
Tube side inlet temperature	485˚C
Tube side outlet temperature	220˚C
Shell side inlet temperature (feed water)	20˚C
Shell side outlet temperature	185.7˚C
Shell side pressure (steam)	1140kPa
Tube side pressure (flue gas)	85kPa
Tube outside diameter	10mm
Number of tubes	80
Tube length	900mm
Overall length	1402mm
Shell outside diameter	324mm

Source: adapted from (ProTherm, 2018)

Figure 3.12: Heat Recovery Steam Generator

The following data will be obtained from the HRSG for the TRNSYS model:

- mass flow tube side (exhaust gas) (kg/s to be calculated);
- mass flow shell side (kg/s obtained from ProTherm Systems (Pty) Ltd.);
- tube side inlet temperature (˚C to be measured using a k-type thermal couple);
- tube side outlet temperature (˚C to be measured using a k-type thermal couple);
- shell side inlet temperature (feed water) (˚C to be measured using a k-type thermal couple);
- shell side outlet temperature (˚C to be measured using a k-type thermal couple);
- shell side pressure (steam) (kPa to be measured using a pressure transducer) and
- tube side pressure (flue gas) (kPa to be measured using a pressure transducer).

3.5.2.4 Data Acquisition and Control System

To acquire the data for TRNSYS modelling, various instruments were installed on the CHP dual fuel demonstrator. Data from these instruments is accessible through the GENSYS 2.0 data acquisition and control system.

K-type thermo-couples, as shown in Figure 3.13, were installed in all relevant fluid lines to measure temperature.

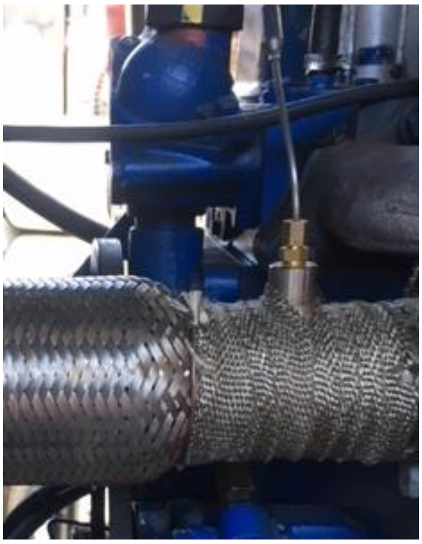


Figure 3.13: K-Type thermo-couple installed in the exhaust

The K-type thermo-couples were used to measure the following:

For the engine oil heat exchanger:

- engine oil temperature, tube inlet (˚C);
- engine oil temperature, tube outlet (˚C);
- shell side inlet temperature, water (˚C) and
- shell side outlet temperature, water (˚C).

For the water jacket heat exchanger:

- tube inlet temperature, Ethylene Glycol Water mix (˚C);
- tube outlet temperature, Ethylene Glycol Water mix (˚C);
- shell side inlet temperature, water (˚C) and
- shell side outlet temperature, water (˚C).

For the HRSG:

- exhaust gas tube inlet temperature(˚C);
- exhaust gas tube outlet temperature (˚C);
- feed water shell inlet temperature (˚C) and
- steam shell outlet temperature (˚C).

WIKA model S-20 electronic pressure transducers as shown in Figure 3.14, were used in the demonstrator to measure:

- Bio/Natural gas pressure (kPa);
- engine oil pressure (kPa);
- atmospheric pressure (kPa);
- boost pressure (kPa) and
- steam pressure (kPa).

Source: (WIKA Instruments (Pty) Ltd., 2013)

Figure 3.14: S20 Electronic pressure transducer

The measured temperature and pressure electronic sensors were then connected to the GENSYS 2.0 control unit where the data could be displayed or stored for later recovery.

3.6 TRNSYS Model Components

The TRNSYS program consists of two main components, the first component is the kernel or engine that reads and processes input files, interactively solves systems, determines any convergences and plots variables. The kernel also determines thermo-physical properties, invert matrices, calculates linear regressions and interpolates external data files. The second component of TRNSYS is an extensive library that consists out of component models called TYPES (TRNSYS, 2018).

All the elements of a CHP dual fuel system are represented in the TRNSYS standard library as standard plug and play parts known as "TYPES" (Solar Energy Labratory, 2017).

For the purpose of this research the TRNSYS library component TYPES to be used for modelling the CHP dual fuel system are briefly explained below.

3.6.1 Prime Mover TYPE

For TRNSYS modelling, the prime mover, an internal combustion engine generator, was selected from the Tess Library component list. This engine generator is known as TYPE -907.

To calculate efficiency, air flowrate and heat transfer data as a function of inlet temperature and part power load ratio (power over rated power) of the prime mover are used for modelling. The input values required for TYPE-907 are indicated in Figure 3.15. This input data can be read from an external data file (TESS, 2017) or by manual input.

All	Inputs	Outputs	Parameters	Derivatives

	Name	Role	Dimension	Unit
1	Intake Air Temper	input	Temperat	C
2	Desired Output P	input	Power	kJ/hr
3	Jacket Fluid Tem	input	Temperat	C
4	Jacket Fluid Flow	input	Flow Rate	kg/hr
5	Oil Cooler Fluid T	input	Temperat	C
6	Oil Cooler Fluid Fl	input	Flow Rate	kg/hr
7	Aftercooler Fluid	input	Temperat	C
8	Aftercooler Fluid	input	Flow Rate	kg/hr

Source: (TRNSYS Simulation Model, 2018)

Figure 3.15: TYPE-907 input values

When using TYPE-907 for modelling, the output values in Figure 3.16 can be used as input values for other library component TYPES such as the heat exchanger, condenser and pumps.

All	Inputs	Outputs	Parameters	Derivatives

	Name	Role	Dimension	Unit
1	Exhaust Tempera	output	Temperat	C
2	Exhaust Flowrat	output	Flow Rate	kg/hr
3	Jacket Water Out	output	Temperat	C
4	Jacket Water Flo	output	Flow Rate	kg/hr
5	Oil Cooler Outlet	output	Temperat	C
6	Oil Cooler Flowra	output	Flow Rate	kg/hr
7	Aftercooler Outle	output	Temperat	C
8	Aftercooler Flow	output	Flow Rate	kg/hr
9	Electrical Power	output	Power	kJ/hr
10	Shaft Power	output	Power	kJ/hr
11	Required Heat In	output	Power	kJ/hr
12	Mechanical Effici	output	Percentag	Fracti
13	Electrical Efficien	output	Percentag	Fracti
14	Part Load Ratio	output	Percentag	Fracti
15	Exhaust Heat Rat	output	Power	kJ/hr
16	Jacket Water He	output	Power	kJ/hr
17	Oil Cooler Heat R	output	Power	kJ/hr
18	Aftercooler Heat	output	Power	kJ/hr
19	Environment Heat	output	Power	kJ/hr

Source: (TRNSYS Simulation Model, 2018)

Figure 3.16: TYPE-907 Output values

3.6.2 Heat Exchanger TYPE

For the lubricant oil heat exchanger and the water jacket heat exchanger, a shell and tube TESS library component was used, known as TYPE-5 - Hydronics\Heat Exchangers\Shell and Tube.

This is a heat exchanger model with zero capacitance and modelled in a shell and tube configuration. The given parameters are the side inlet temperature and flow rates. The model calculates effectiveness for a fixed overall heat transfer coefficient (TESS, 2017).

For the CHP dual-fuel model two TYPE-5 models were used, one with parameters for water and engine coolant and the other with parameter values for engine oil and water.

Typical input values used for the TYPE-5 heat exchangers are shown in Figure 3.17. Input values are determined from the output values obtained from TYPE-907.

er | Input | Output | Derivative | Special Cards | External Files | Comment

	Name	Value	Unit
1	Source side inlet temperature	85	C
2	Source side flow rate	1200	kg/hr
3	Load side inlet temperature	20.0	C
4	Load side flow rate	2000	kg/hr
5	Overall heat transfer coefficient of exchanger	1000	W/K

Source: (TRNSYS Simulation Model, 2018)

Figure 3.17: TYPE-5 input values

Figure 3.18 shows typical calculated output values for the TYPE-5 heat exchanger model.

er | Input | Output | Derivative | Special Cards | External Files | Cor

	Name	Value	Unit
1	Source side outlet temperature	0	C
2	Source side flow rate	0	kg/hr
3	Load side outlet temperature	0	C
4	Load side flow rate	0	kg/hr
5	Heat transfer rate	0	kJ/hr
6	Effectiveness	0	-

Source: (TRNSYS Simulation Model, 2018)

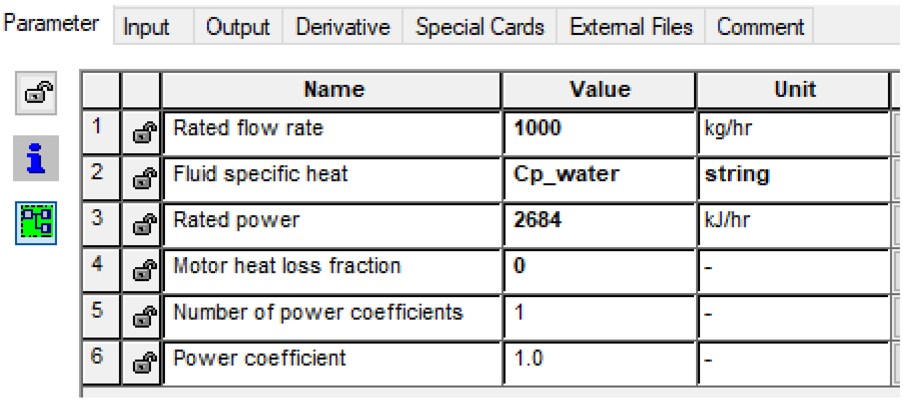
Figure 3.18: TYPE-5 output values

3.6.3 Pump TYPE

To achieve the required flow through for the load side of the water jacket heat exchanger and the engine oil heat exchanger, the HRSG and the HRSG feed water, a pump model, TYPE-110 was selected from the TESS library.

TYPE-110 – Hydronics\Pumps\variable speed represents a variable speed pump that can maintain a mass flow rate from zero up to a set value. For this TYPE the mass flowrate varies linearly to the set values. A polynomial is used to model the power drawn by the pump (TESS, 2017).

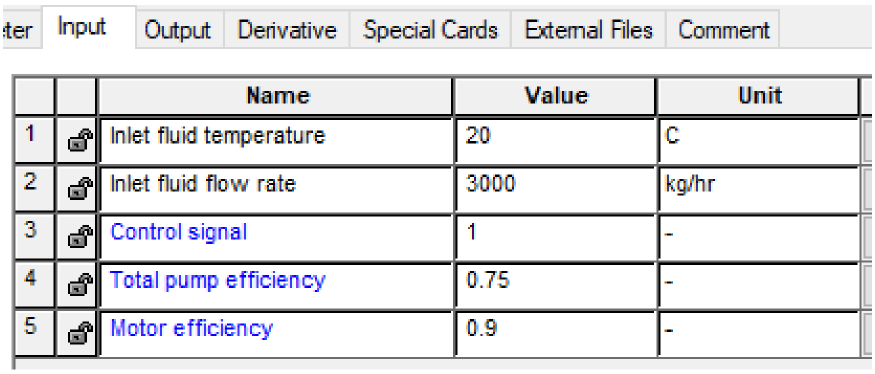
The parameter values to be used for TYPE-110 will differ for each pump application in the TRNSYS model. Input values for TYPE-110 will be obtained from the TYPE-5 output values. Typical parameter values are shown in Figure 3.19 and input values used for TYPE-110 modelling are shown in Figure 3.20.



	Name	Value	Unit
1	Rated flow rate	1000	kg/hr
2	Fluid specific heat	Cp_water	string
3	Rated power	2684	kJ/hr
4	Motor heat loss fraction	0	-
5	Number of power coefficients	1	-
6	Power coefficient	1.0	-

Source: (TRNSYS Simulation Model, 2018)

Figure 3.19: Parameter values for TYPE-110



	Name	Value	Unit
1	Inlet fluid temperature	20	C
2	Inlet fluid flow rate	3000	kg/hr
3	Control signal	1	-
4	Total pump efficiency	0.75	-
5	Motor efficiency	0.9	-

Source: (TRNSYS Simulation Model, 2018)

Figure 3.20: Input values for TYPE 110

For the condensate pump a TYPE-597 from the TESS library was used in the TRNSYS model. This component models a steam condensate pump. The user specifies the inlet steam condensate conditions and the desired outlet pressure. The model calculates the theoretical power from a compressed liquid calculation (specific volume times pressure differential). The actual power is found by dividing the theoretical power by the overall pump efficiency. This model sets the flowrate for the steam loop by multiplying the rated pump flowrate by the input control signal.

From the TESS library, TYPE–14 Time Dependent Forcing Function: Water Draw, will be used to simulate the behaviour characterised by a repeated pattern. This TYPE uses kg/hr to be more readily useful for creating water draw forcing functions (TESS, 2017).

Forcing functions will be utilised in the TRNSYS model to control the pumps for the load side of the heat exchangers.

3.6.4 Weather data TYPE

The weather plays a role in a CHP dual-fuel system as weather conditions can adversely affect the engine air intake temperature and the external skin temperature of the thermal storage tank, which could influence the energy required to maintain set temperatures required for the CHP dual fuel system. As a result, the atmospheric conditions need to be used as input values for the TRNSYS model. TYPE-15 – Weather data reading\standard format\metronome was selected from the TESS library. TYPE-15-6 was selected to read the weather data for the region from weather data files and convert it to input values for the TRNSYS model.

From an external file weather data is read at regular time intervals and made available to other TRNSYS components by the TYPE 15-6 (TESS, 2017). Figure 3.21 shows some of the typical output values provided by TYPE-15-6.

ter | Input | Output | Derivative | Special Cards | External Files | Com

	Name	Value	Unit
1	Dry bulb temperature	0	C
2	Dew point temperature	0	C
3	Wet bulb temperature	10.0	C
4	Effective sky temperature	0	C
5	Mains water temperature	10.0	C
6	Humidity ratio	0	-
7	Percent relative humidity	0	-
8	Wind velocity	0	m/s
9	Wind direction	0	degrees
10	Atmospheric pressure	0	atm
32	Latitude	0	degrees
33	Longitude	0	degrees

Source: (TRNSYS Simulation Model, 2018)

Figure 3.21: Output values for TYPE-15-6

3.6.5 Thermal storage TYPE

The thermal load was simulated by incorporating a water storage tank in the TRNSYS model for each of the heat exchangers. This storage tank represents the role of the bio digester for modelling purposes.

Type-534 - Cylindrical Storage Tank was selected from the TESS library: A vertical tank with constant volume and immersed heat exchangers will be modelled by a subroutine within TYPE-534. Isothermal nodes divide the tank; the degree of stratification can be controlled through the specification of the number of nodes. The nodes are assumed to be isothermal and interact with the surrounding nodes. Four different immersed heat exchangers can be specified, horizontal tubes, vertical tubes serpentine tubes or coiled tubes. The model considers temperature dependent fluid properties for pure water or a propylene glycol water solution. The environmental losses from the top, bottom and edges of the tank are also considered in the model (TESS, 2017).

Input values will be read from the heat exchanger models (TYPE-5) and the input flow rate will be provided by the pump model (TYPE-110). The weather data from TYPE 15-6 will provide the external conditions of the storage tank. Typical input values for TYPE-534 are shown in Figure 3.22.

ter | Input | Output | Derivative | Special Cards | External Files | Comment

		Name	Value	Unit
1		Inlet Temperature for Port-1	20.0	C
2		Inlet Flowrate for Port-1	2400	kg/hr
3		Inlet Temperature for Port-2	70	C
4		Inlet Flowrate for Port-2	1200	kg/hr
5		Top Loss Temperature	20.0	C
6		Edge Loss Temperature for Node-1	20.0	C
7		Edge Loss Temperature for Node-2	20.0	C
8		Edge Loss Temperature for Node-3	20.0	C
9		Edge Loss Temperature for Node-4	20.0	C
10		Edge Loss Temperature for Node-5	20.0	C
11		Bottom Loss Temperature	20.0	C
12		Gas Flue Temperature	20.0	C
13		Inversion Mixing Flowrate	-100	kg/hr
14		Auxiliary Heat Input for Node-1	0.0	kJ/hr

Source: (TRNSYS Simulation Model, 2018)

Figure 3.22: Input values for TYPE-534

The output values from the immersed heat exchangers from the storage tanks will be used to plot the available thermal energy available from the CHP dual fuel system. Examples of typical output values are shown in Figure 3.23.

		Name	Value	Unit
1		Temperature at Outlet-1	20.0	C
2		Flowrate at Outlet-1	0.0	kg/hr
3		Temperature at Outlet-2	20.0	C
4		Flowrate at Outlet-2	0.0	kg/hr
5		Average Tank Temperature	20.0	C
6		Energy Delivery Rate	0.0	kJ/hr
7		Energy Delivered to Flow -1	0	kJ/hr
8		Energy Delivered to Flow -2	0	kJ/hr
9		Top Losses	0.0	kJ/hr
10		Edge Losses	0.0	kJ/hr
11		Bottom Losses	0.0	kJ/hr
12		Gas Flue Losses	0	kJ/hr
13		Auxiliary Heating Rate	0.0	kJ/hr
14		Miscellaneous Energy	0	kJ/hr
15		Tank Energy Storage Rate	0.0	kJ/hr
16		HX Heat Transfer Rate	0.0	kJ/hr

Source: (TRNSYS Simulation Model, 2018)

Figure 3.23: Output values for TYPE-534

3.6.6 Heat recovery steam generator TYPE

TYPE-637 models a heat recovery steam generator (HRSG), a device which uses high-temperature waste heat to heat a steam flow. The model relies on the pinch-point temperature difference approach to check for unrealistic heat exchange conditions.

The pinch-point temperature difference is the minimum temperature difference between the hot-source fluid and the steam that allows for heat transfer between the fluids. This TYPE will be configured as a counter-flow. (TESS, 2017).

Figure 3.24 shows the typical input values for TYPE-637 and typical output values are indicated in Figure 3.25.

ter | Input | Output | Derivative | Special Cards | External Files | Comme

		Name	Value	U
1		Source Fluid Inlet Temperature	480	C
2		Source Fluid Inlet Flowrate	600	kg/hr
3		Steam Inlet Temperature	95	C
4		Steam Inlet Flowrate	1200	kg/hr
5		Steam Inlet Pressure	1000.0	kPa
6		Steam Inlet Enthalpy	720	kJ/kg
7		Desired Steam Enthalpy	2900	kJ/kg

Source: (TRNSYS Simulation Model, 2018)

Figure 3.24: Input values for TYPE-637

ter | Input | Output | Derivative | Special Cards | External Files | Com

		Name	Value	Unit
1		Source Fluid Outlet Temperature	*250.0*	C
2		Source Fluid Flowrate	*0.0*	kg/hr
3		Steam Outlet Temperature	*240.0*	C
4		Steam Flowrate	*0*	kg/hr
5		Steam Pressure	*1554.0*	kPa
6		Steam Enthalpy	*2803.8*	kJ/kg
7		Heat Transfer Rate	*0*	kJ/hr

Source: (TRNSYS Simulation Model, 2018)

Figure 3.25: Output values for TYPE-637

3.6.7 Steam condenser TYPE

TYPE- 598 was selected from the TESS library. This component models a condenser for steam applications where the condensing pressure is known and provided to the model as an input as indicated in Figure 3.26.

This model calculates the resultant heat transfer and outlet steam conditions when provided with the desired degrees of sub-cooling leaving the condenser (TESS, 2017) as shown in Figure 3.27.

ter | Input | Output | Derivative | Special Cards | External Files | Comment

		Name	Value	Unit
1		Steam Inlet Temperature	179.9	C
2		Steam Inlet Flowrate	1000.0	kg/hr
3		Steam Inlet Pressure	1000.0	kPa
4		Steam Inlet Enthalpy	2778.0	kJ/kg
5		Steam Condensing Pressure	20.0	kPa
6		Degrees of Subcooling	5.0	deltaC

Source: (TRNSYS Simulation Model, 2018)

Figure 3.26: Input values for TYPE-598

ter | Input | Output | Derivative | Special Cards | External Files | Con

		Name	Value	Unit
1		Condensate Outlet Temperature	*240.0*	C
2		Condensate Flowrate	*0*	kg/hr
3		Condensate Pressure	*1554.0*	kPa
4		Condensate Enthalpy	*2803.8*	kJ/kg
5		Heat Transfer Rate	*0*	kJ/hr

Source: (TRNSYS Simulation Model, 2018)

Figure 3.27: Output values for TYPE-598

3.3 Summary

In this chapter the different components of the CHP dual-fuel demonstrator were identified. The TRNSYS library components and the integration of these components (types) into the TRNSYS model were described.

The following chapter will focus on the verification of the outputs obtained from the TRNSYS model in relation to the outputs, measured and calculated, for the CHP dual fuel demonstrator.

CHAPTER 4: MODELLING A CHP DUAL FUEL SYSTEM USING TRYNSYS

4.1 Introduction

Based on the TRNSYS model TYPES selected in the previous chapter to simulate the CHP dual fuel demonstrator's critical components, this chapter begins with the development of the TRNSYS model. The selection of the specific input values and parameters for each component TYPE is described, followed by the verification of the resultant outputs from the TRNSYS model versus measured and calculated values obtained from the CHP dual fuel demonstrator.

The correlations are shown and the findings are discussed. The CO_2 emissions, efficiency gains and cost savings derived from the use of a CHP system are also indicated.

4.2 Developing a TRNSYS energy simulation system model

The TRNSYS model was developed to replicate the components of the actual CP dual fuel demonstrator installed at Uilenkraal Farm. The process flow diagram, as shown in Figure 4.1, represents the actual configuration of the components of the CHP dual fuel demonstrator.

A fuel source either diesel (diesel tank) or diesel and gas (gas cylinder) mixture serves as the energy source for the CHP system. The internal combustion dual fuel engine uses the fuel and converts it into mechanical energy. In the process of converting fuel (chemical energy) to mechanical energy, heat was generated. This heat is absorbed by the water jacket and the engine oil and transferred to the heat exchangers, thus harvesting this energy. The mechanical energy from the engine is converted into 3-Phase 380V electricity by the generator and fed into the local electricity grid. Heat harvested by the heat exchangers is pumped with two pumps to two bio digesters.

Heat emitted by the exhaust of the engine is captured by the HRSG and steam is then generated. The steam passes through a condenser and is converted back into water. The heat released by the condenser is also measured.

All the recovered heat energy is channelled into the bio-digester to improve the digester efficiency.

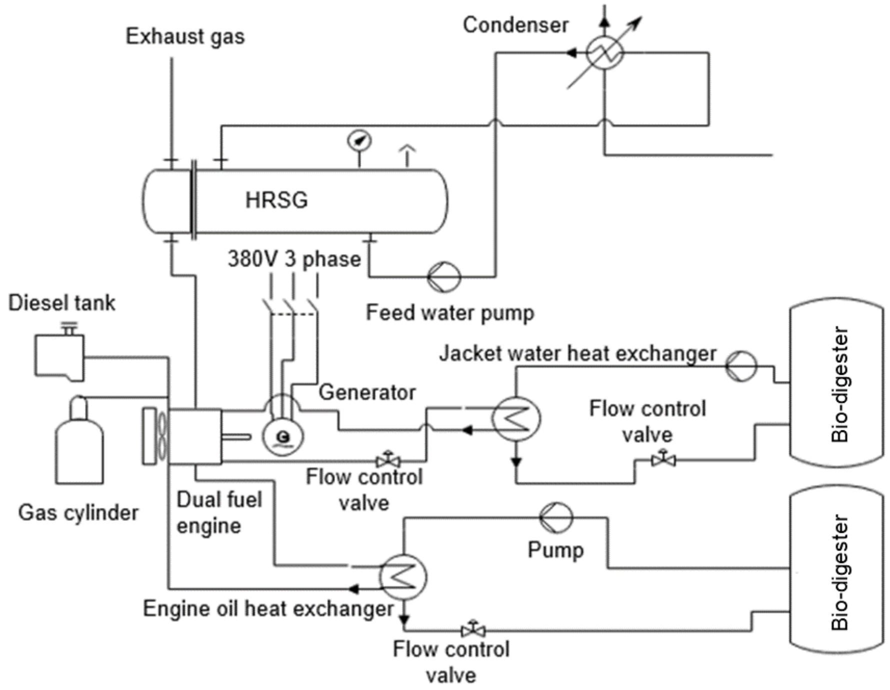


Figure 4.1 Process flow diagram of the CHP system

The entire process described above, is represented in Figure 2.4 with the TESS components that were selected from the TRNSYS library, representing the elements of the CHP dual fuel demonstrator.

This serves as the basis for the TRNSYS simulation.

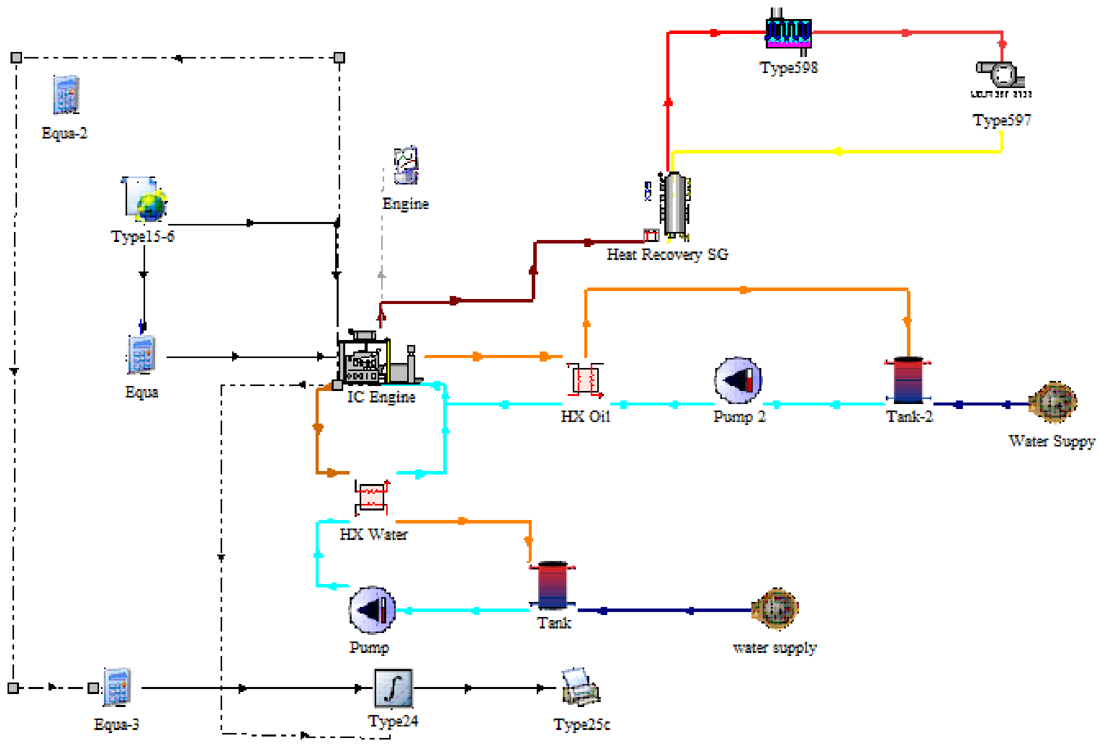


Figure 4.2 TRNSYS model of the CHP dual fuel demonstrator

It should be noted in Figure 4.2 that the bio digester linked to the CHP dual fuel demonstrator is represented by thermal storage tanks in TRNSYS. Tank 1 and tank 2 were selected with identical sizes (200l) to represent the bio digester in the model.

4.3 TRNSYS model inputs

The input data was sourced from the TESS library in TRNSYS, CAE (Pty) Ltd., ProTherm Systems (Pty) Ltd., the VUT S4GJ team and various calculations. The input data for the TRNSYS model are described in the following sections.

4.3.1 Weather data TYPE 15-6 input values

Weather data to be used in TYPE 15-6 were selected from the standard TESS library. As Uilenkraal is in the Western Cape, the weather data for Cape Town, as the closest region to the farm were selected. This weather data were provided with the TESS library and represents the last 30 years of data for the region (TESS, 2017).

The most significant weather data used as input values for the TRNSYS model are dry bulb temperature and atmospheric pressure. However, TRNSYS is a transient system and actual weather data varies from second to second, thus actual values used for modelling were generated by TRNSYS over the time period in which data were collected from the CHP dual fuel demonstrator.

4.3.2 Engine and generator TYPE-907 input values

The following assumptions were made during modelling for the internal combustion engine and the generator represented by TYPE-907 in TRNSYS:

- temperature distribution remains constant across any sub-system of the model;
- heat transfer coefficients remain constant throughout the model and
- the thermal properties of the materials used on the components remain constant.

For modelling, TYPE- 907, the engine component, an external file data file (2D performance map) that produces output data, was used by the TRNSYS model. The file contains an engine performance map with engine performance parameters (TRNSYS, 2018).

The simulation in this project used a map that correlated to some extent with the actual engine, but deviations can be expected. Table 4.1 shows the 2D performance map used.

Table 4.1 2D Performance map used in TYPE-907

```
File   Edit   Format   View   Help
0       100
0.400   0.500   0.600   0.700   0.750   0.800   0.900   1.000
0.400   0.338   0.921   0.311   0.070   0.532   0.000   0.087   0.528
0.500   0.350   0.932   0.314   0.071   0.526   0.013   0.076   0.600
0.600   0.359   0.936   0.314   0.071   0.521   0.026   0.068   0.678
0.700   0.365   0.939   0.314   0.070   0.517   0.037   0.061   0.759
0.750   0.367   0.939   0.313   0.070   0.515   0.043   0.059   0.800
0.800   0.368   0.939   0.313   0.070   0.513   0.048   0.056   0.841
0.900   0.368   0.939   0.310   0.069   0.512   0.057   0.052   0.919
1.000   0.364   0.939   0.307   0.068   0.514   0.065   0.047   1.000
0.400   0.338   0.921   0.311   0.070   0.532   0.000   0.087   0.528
0.500   0.350   0.932   0.314   0.071   0.526   0.013   0.076   0.600
0.600   0.359   0.936   0.314   0.071   0.521   0.026   0.068   0.678
0.700   0.365   0.939   0.314   0.070   0.517   0.037   0.061   0.759
0.750   0.367   0.939   0.313   0.070   0.515   0.043   0.059   0.800
0.800   0.368   0.939   0.313   0.070   0.513   0.048   0.056   0.841
0.900   0.368   0.939   0.310   0.069   0.512   0.057   0.052   0.919
1.000   0.364   0.939   0.307   0.068   0.514   0.065   0.047   1.000

!Row 1 = Intake Temperatures in Degrees C
!Row 2 = Part Load Ratio (Electrical Output / Rated Electrical Output )
!Column 1 = Part Load Ratio (Electrical Output / Rated Electrical Output )
!Column 2 = Mechanical Efficiency (Electrical Output / Rated Electrical Output )
!Column 3 = Electrical Efficiency (Electrical Output / Shaft Power )
```

Source: Adapted from (TRNSYS Simulation Model, 2018)

Other input values and parameters required by TYPE-907 for modeling are listed in Table 4.2. The sources of the data are also indicated in the table.

Table 4.2: Input values and parameters required by TYPE-907

Input values		
Description	**Value**	**Source**
Power	50kW	CAE data (Annexure 1)
Jacket water temperature	82˚C	CAE data (Annexure 1)
Jacket water flowrate	1200kg/hr	CAE data (Annexure 1)
Oil temperature	92˚C	CAE data (Annexure 1)
Oil flowrate	900kg/hr	CAE data (Annexure 1)
Parameters		
Description	**Value**	**Source**
Cp Coolant water	3.62 kJ/kgK	(Incropera, 2007)
Cp Engine oil	2.1 kJ/kgK	(Incropera, 2007)
Cp Exhaust gas	1.063 kJ/kgK	(Incropera, 2007)
Exhaust gas flowrate	280kg/hr	CAE data (Annexure 1)

The generator was also represented by TYPE-907, as it was included in TRNSYS as part of the engine TYPE. The power factor value of the generator was the only input required by TRNSYS for modelling. Most manufacturers use a generator efficiency value of 0.9, which was used in the model (Zenatix, 2015).

4.3.3 Heat exchanger TYPE-5 input values

A TYPE 5 library component was selected to model the water jacket heat exchanger. The input values for the TRNSYS model for the tube(hot) side of the heat exchanger are shown in Table 4.3. A 50% Ethylene Glycol and water mix and an average fluid temperature of 80 ˚C were used as property selection criteria for TRNSYS modelling.

Table 4.3: Water jacket properties for the tube (hot) side of the heat exchanger

Description	Abbreviation	Value	Unit
Specific heat capacity	Cp	4.1975	kJ/kgK
Dynamic Viscosity	µ	0.000351	Pa.s
Thermal conductivity	K	0.669	W/mK
Density	ρ	971.8	Kg/m^3
Prandtl number	Pr	2.1955	

Source: Adapted from (Engineering ToolBox, 2003) (Incropera, 2007)

The TYPE-5 library component was also used to simulate the engine oil heat exchanger. The input values for the TRNSYS model for the tube (hot) side of the heat exchanger are shown in Table 4.4. Engine oil type 15W40 and an average oil temperature of 80 ˚C were used as property selection criteria for TRNSYS modelling.

Table 4.4. Engine oil properties for the tube (hot) side of the heat exchanger

Description	Abbreviation	Value	Unit
Specific heat capacity	Cp	2.1	kJ/kgK
Dynamic Viscosity	µ	0.019358	Pa.s
Thermal conductivity	K	0.0138	W/mK
Density	ρ	841.4	Kg/m^3
Prandtl number	Pr	546	

Source: Adapted from (Paar, 2018) (Engineering ToolBox, 2003) (Incropera, 2007)

In addition, the following variables were calculated for the TRNSYS model:

- t_{in} = 85 ˚C, inlet temperature as measured by CAE (Annexure 1);
- t_{out} = 75 ˚C, outlet temperature as calculated by the VUT S4GJ team (Annexure 2 for engine oil heat exchanger and Annexure 3 for water jacket heat exchanger);
- $\dot{m}_{hot} = 0.6kg/s$ water jacket flowrate as measured by CAE (Annexure 1) and
- $\dot{m}_{hot} = 0.25kg/s$ engine oil flowrate as measured by CAE (Annexure 1).

4.3.4 Pump TYPE-110 and thermal storage TYPE-534 input values

For the lubricant oil heat exchanger and the water jacket heat exchanger, a shell and tube TESS library component was used, known as TYPE-5 - Hydronics\Heat Exchangers\Shell and Tube, thus, necessitating the need for differing input values for the water jacket heat exchanger and the engine oil heat exchanger.

The thermal storage tanks, represented by tank 1 and tank 2 in Figure 4.2, were selected with identical sizes (200l) to represent the bio digester (which does not form part of the TRNSYS model).

For this research, the temperature of the thermal storage water exiting the heat exchangers was kept at 70 ˚C. This was achieved by calculating the required flowrate through the heat exchangers:

$Q = \dot{m}_{hot} * cp_{hot} * (T_{hot_{in}} - T_{hot_{out}})$ (Incropera, 2007)

= 0.6kg/s x 4.197Pa.s x (85 ˚C - 75 ˚C)

=25.182kW

$Q_{hot} = Q_{cold}$

$\dot{m}_{cold}$ =0.133884kg/s

The mass flow of the water, as calculated above, is received by the hot water storage tank connected to the water jacket heat exchanger. This value is used as the input value for the heat exchanger, TYPE-5, and thermal storage tank 1, TYPE 534.

This mass flow was also used as the input flowrate for the pump, TYPE 110, creating flow for the hot water storage circuit for the water jacket heat exchanger linked to thermal storage tank 1.

Table 4.5 includes the properties of storage water at an average of 47.5 ˚C and the associated input values for both heat exchangers for the shell (cold) side to be used in the TRNSYS model.

Table 4.5: Storage water properties

Description	Abbreviation	Value	Unit
Specific heat capacity	Cp	4.18026	kJ/kgK
Dynamic Viscosity	µ	0.000571	Pa.s
Thermal conductivity	K	0.640	W/mK
Density	ρ	989.125	Kg/m^3
Prandtl number	Pr	3.7245	

Source: Adapted from (Engineering ToolBox, 2003) (Incropera, 2007)

The shell side flow rate (Kg/s) for the engine oil heat exchanger is given by:

$Q = \dot{m}_{hot} * cp_{hot} * (T_{hot_{in}} - T_{hot_{out}})$ (Incropera, 2007)

= 0.2523kg/s x 2.1Pa.s x (85 ˚C - 75 ˚C)

=5.29kW

$Q_{hot} = Q_{cold}$

$\dot{m}_{cold}$ =0.0281kg/s

This is the mass flow of the water received by the hot water storage tank, represented by tank 2 in Figure 4.2, connected to the engine oil heat exchanger. This value is used as the input value for TYPE-5 (heat exchanger) and TYPE 534 (thermal storage tank 2) connected to the engine oil heat exchanger. This mass flow was also used as the input flowrate for the pump, TYPE-110, creating flow for the hot water storage circuit for the engine oil heat exchanger.

4.3.5 HRSG TYPE-637 input values

The HRSG, also referred to as the boiler, was designed by ProTherm Systems (Pty) Ltd. Input values and parameters for the HRSG, TYPE-637, were selected from the design specifications provided by ProTherm Systems (Pty) Ltd. (ProTherm, 2018) and data measured by CAE for the engine as shown in Annexure 1.

Table 4.6 outlines the input values and parameters used for the HRSG TYPE-637.

Table 4.6: Input values and parameters required by TYPE-637

Input values		
Description	**Value**	**Source**
Exhaust temperature in	485˚C	CAE data (Annexure 1)
Exhaust gas flowrate	280kg/hr	CAE data (Annexure 1)
Condensate input temperature	185.6˚C	ProTherm Systems (Pty) Ltd
Steam flowrate	30kg/hr	ProTherm Systems (Pty) Ltd
Steam pressure (feed pump pressure)	11.4bar	ProTherm Systems (Pty) Ltd
Steam inlet Enthalpy	720kJ/kg	(Incropera, 2007)
Parameters		
Description	**Value**	**Source**
Delta T (Δ˚C)	15˚C	ProTherm Systems (Pty) Ltd
Cp exhaust gas	1.063kJ/kgK	(Incropera, 2007)

4.3.6 Steam condenser TYPE-598 input values

The condenser was supplied by ProTherm Systems (Pty) Ltd to best suit the designed boiler (HRSG). The input values and parameters for TYPE- 598 were the specification values provided by ProTherm Systems (Pty) Ltd. (ProTherm, 2018) and CAE. The values are shown in Table 4.7

Table 4.7: Input values and parameters required by TYPE-598

Input values		
Description	**Value**	**Source**
Cooling fluid temperature in	25˚C	CAE data (Annexure 1)
Cooling fluid flowrate	900kg/hr	ProTherm Systems (Pty) Ltd
Steam inlet temperature	185.6˚C	ProTherm Systems (Pty) Ltd
Steam flowrate	30.54kg/hr	ProTherm Systems (Pty) Ltd
Steam pressure (feed pump pressure)	11.4bar	ProTherm Systems (Pty) Ltd
Steam inlet Enthalpy	2778kJ/kg	(Incropera, 2007)
Parameters		
Description	**Value**	**Source**
Delta T (Δ ˚C)	15˚C	ProTherm Systems (Pty) Ltd
Cp cooling fluid	4.19kJ/kgK	(Incropera, 2007)
Cp steam	2778kJ/kgK	(Incropera, 2007)
Condensing pressure	11.2kPa	ProTherm Systems (Pty) Ltd

4.4 Verification of the TRNSYS model

All input values and parameter data for all TYPES selected were entered into TRNSYS for modelling. This section compares the TRNSYS model outputs to the CHP dual fuel demonstrator outputs.

The output values from the TRNSYS model were compared to the specifications, measured values and calculated values of the CHP dual fuel demonstrator to determine whether these values correlated. This would verify whether the TRNSYS model could be used to select an appropriate CHP dual fuel system.

4.4.1 Engine and generator output values

Figure 4.3 shows the output values obtained from the TRNSYS model for the engine exhaust temperature, the water jacket temperature and the engine oil temperature. Figure 4.4 shows the corresponding actual values obtained from the CHP dual fuel demonstrator.

In Figure 4.3, the red line represents the exhaust temperature as simulated by the TRNSYS model. The temperature fluctuates by approximately 10˚C from the average of 470˚C.

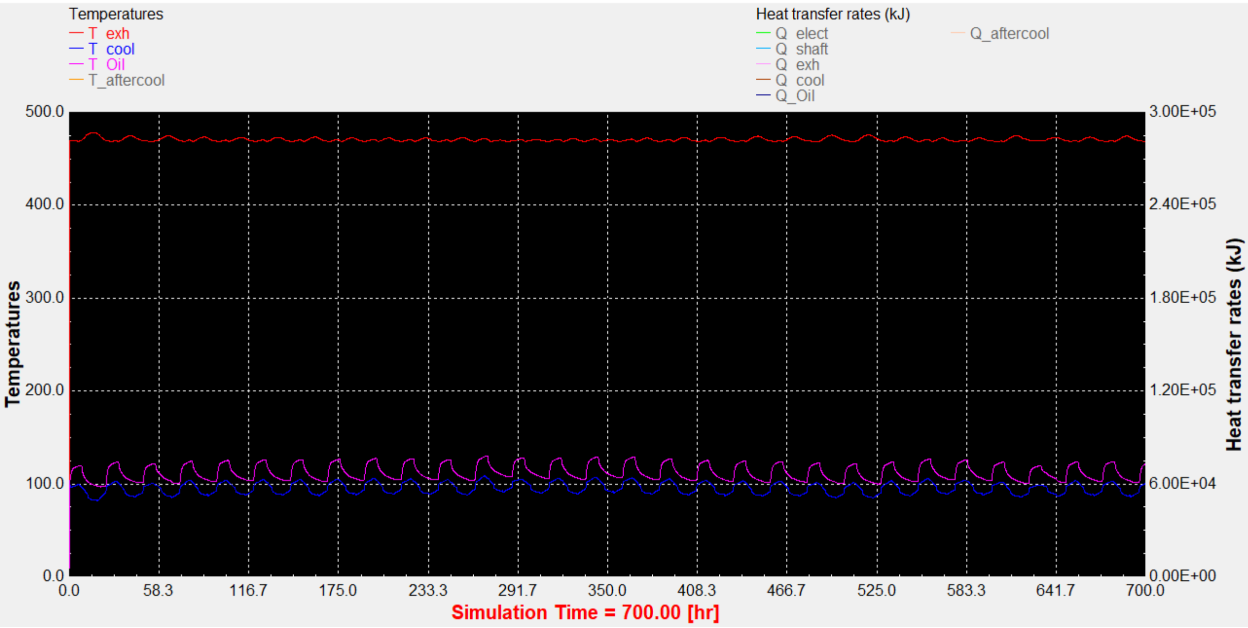


Figure 4.3: TRNSYS simulated output temperatures for the engine

Figure 4.4 indicates the measured exhaust temperature emitted by the CHP dual fuel demonstrator. The temperature, measured over time, fluctuates between 460˚C and 480˚C which correlates well with the TRNSYS output value obtained.

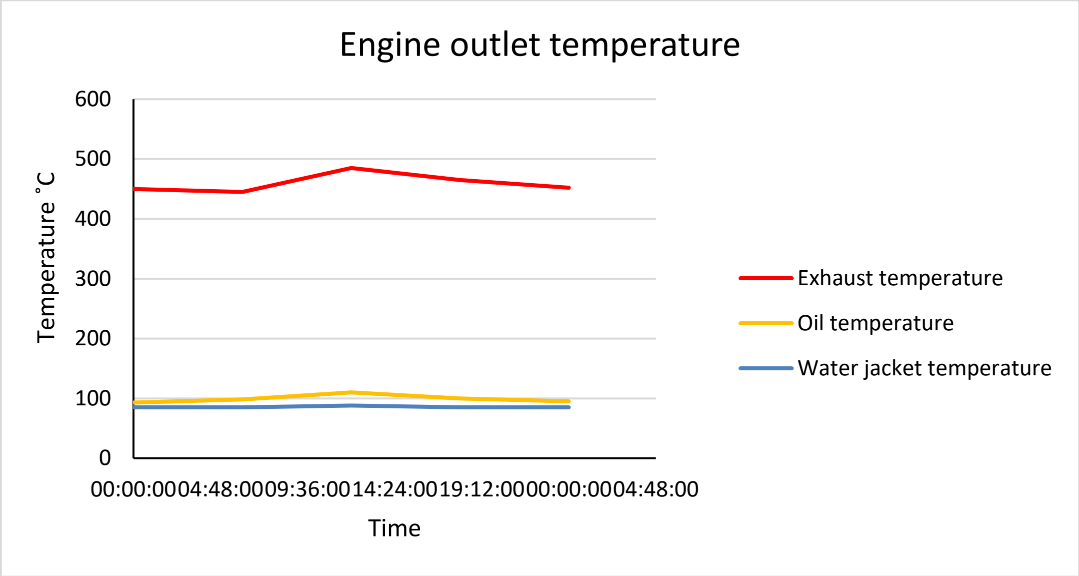


Figure 4.4: CHP dual fuel demonstrator output temperatures for the engine

The blue line in Figure 4.3 represents the water jacket temperature, obtained from the TRNSYS model, which varies between 80˚C and 100˚C. The actual engine water jacket temperature measured over time, for the CHP dual fuel demonstrator is 82˚C as shown in Figure 4.4.

The TRNSYS output values for the engine oil temperature, the purple line in Figure 4.3, varies between 100˚C and 120˚C. The engine oil temperature from the CHP dual fuel demonstrator was measured at 95˚C as shown in Figure 4.4.

The TRNSYS model values are slightly higher than the measured temperatures from the CHP dual fuel demonstrator. The lower temperatures obtained from the demonstrator could be as a result of the opening and closing of the thermostat, causing variations in flow rate through the engine.

Figure 4.5 shows the energy values obtained from the TRNSYS model. The blue line represents the engine shaft energy and the green line indicates the electrical energy. The engine shaft energy values fluctuate between 50kW and 66kW and the electrical energy fluctuates between 45kW and 61kW.

The difference between the mechanical energy and the electrical energy is due to the generator efficiency value of 0.9, which was used in the model.

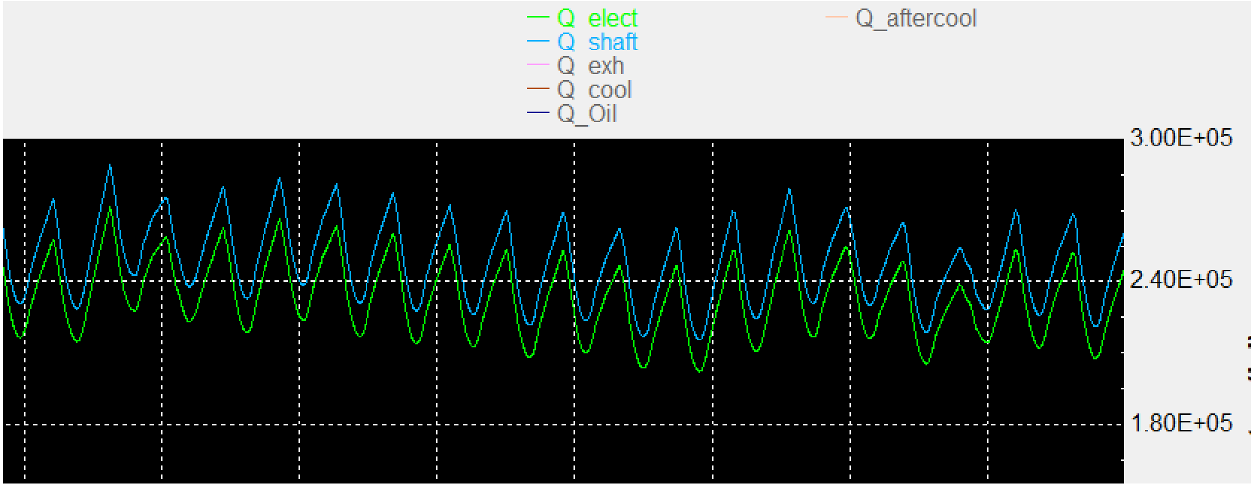


Figure 4.5: TRNSYS simulated energy output for the engine

The GENSYS 2.0 controller installed in the CHP dual fuel demonstrator, maintains a constant engine output power of 45kW and the engine revolutions at 1500rpm. This is crucial for power grid synchronisation. The generator output is 40.5kW electrical energy.

The significant differences between the TRNSYS output values and the demonstrator output values are due to the use of the 2D performance map (Table 4.1) that was used to simulate the performance of the engine selected in TRNSYS.

4.4.2 Heat exchanger output values

The outlet temperature from the water jacket heat exchanger, indicated in red in Figure 4.6 fluctuated between 80˚C and 60˚C for the TRNSYS model. The blue line represents the engine oil heat exchanger output temperatures and a fluctuation between 35˚C and 58˚C can be seen.

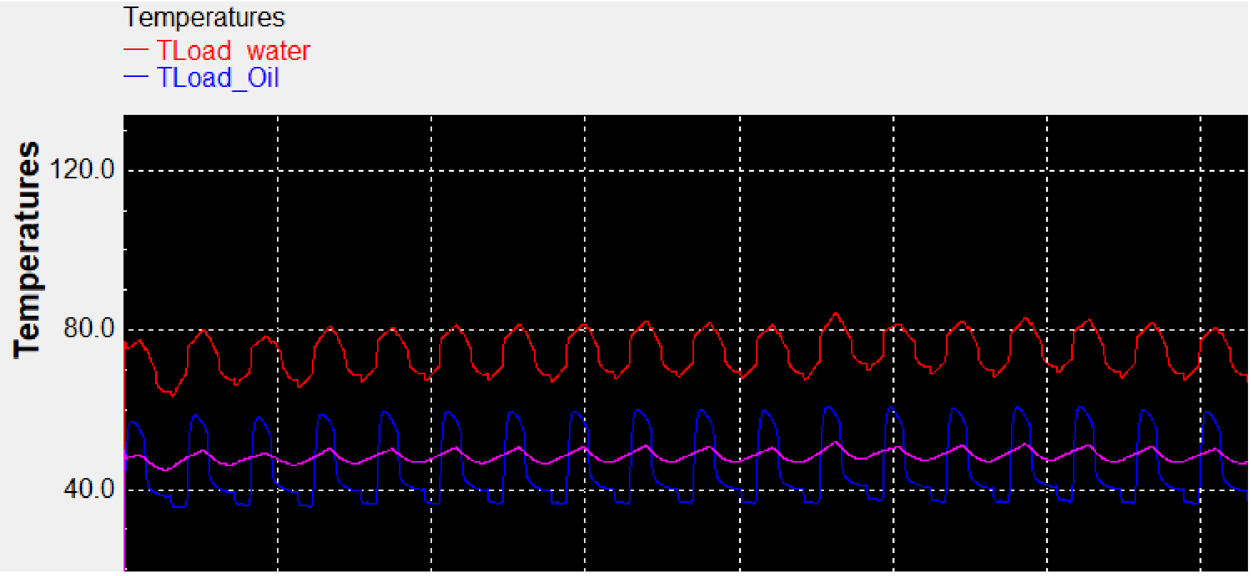


Figure 4.6: TRNSYS simulated output for the heat exchangers

As actual heat exchanger measurements could not be obtained from the CHP dual fuel demonstrator the values were calculated in Excel. Using the Excel model in Annexure 3 an outlet temperature of 70˚C, to the bio-digester was calculated for the water jacket heat exchanger. An outlet temperature of 45˚C, to the bio-digester, was calculated for the engine oil heat exchanger using the Excel model in Annexure 2. These calculated temperatures are shown in Table 4.8.

Table 4.8: Calculated heat exchanger outlet temperatures from Annexure 2 & 3

Fluid	Supply from engine temperature	Outlet temperature to the bio-digester
Engine oil	85˚C	70˚C
Water jacket water	80˚C	45˚C

The heat exchanger output values obtained from the TRNSYS model correlated well with the calculated output values for the CHP dual fuel demonstrator.

4.4.3 HRSG output values

The TRNSYS simulated exhaust gas temperature leaving the HRSG was 250˚C as indicated by the red line in Figure 4.7. The exit temperature of the exhaust gas leaving the CHP dual fuel demonstrator's HRSG, as calculated by ProTherm Systems (Pty) Ltd (ProTherm, 2018), was 230˚C.

The blue line in Figure 4.7 represents the steam outlet temperature at 224˚C as determined by the TRNSYS model. The outlet temperature of the steam produced by the demonstrator is 186˚C (ProTherm, 2018).

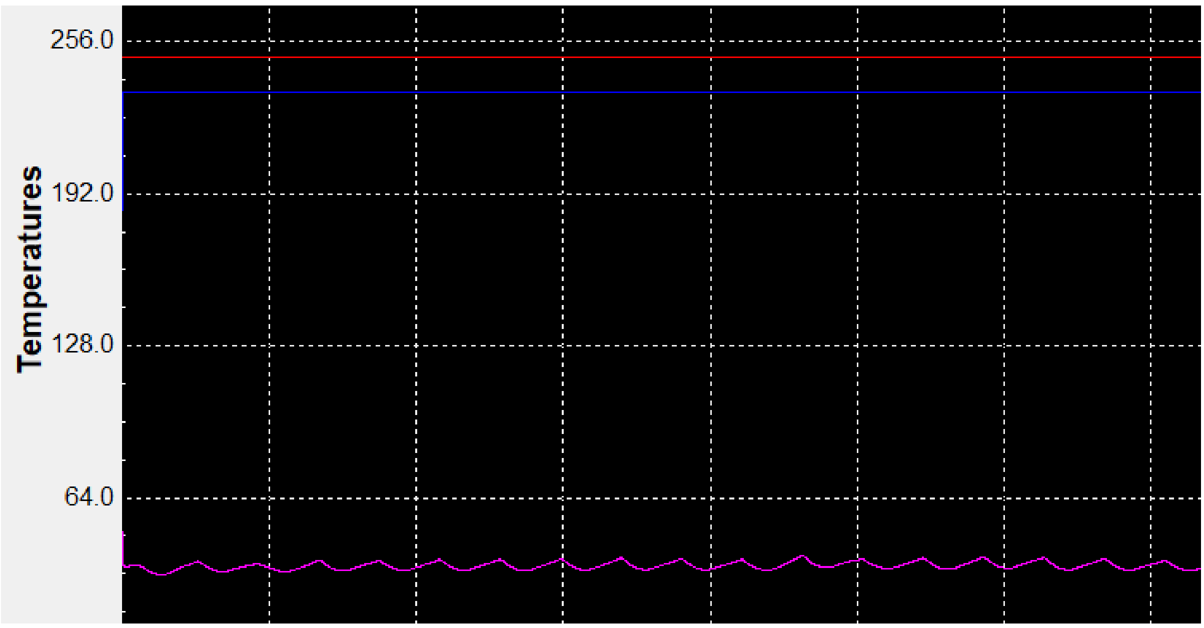


Figure 4.7: TRNSYS simulated output for the HRSG

The difference between the TRNSYS output values and the demonstrator output values is due to the use of the 2D performance map (Table 4.1) that was used to simulate the performance of the engine selected in TRNSYS.

4.4.4 Steam condenser output values

It can be seen in Figure 4.8 that the condensate temperature fluctuated between 120˚C and 150˚C in the TRNSYS model as indicated by the yellow line. The temperature of the feed water that would flow back to the bio-digester fluctuates between 42˚C and 50˚C in the TRNSYS model, as indicated by the pink line in Figure 4.8.

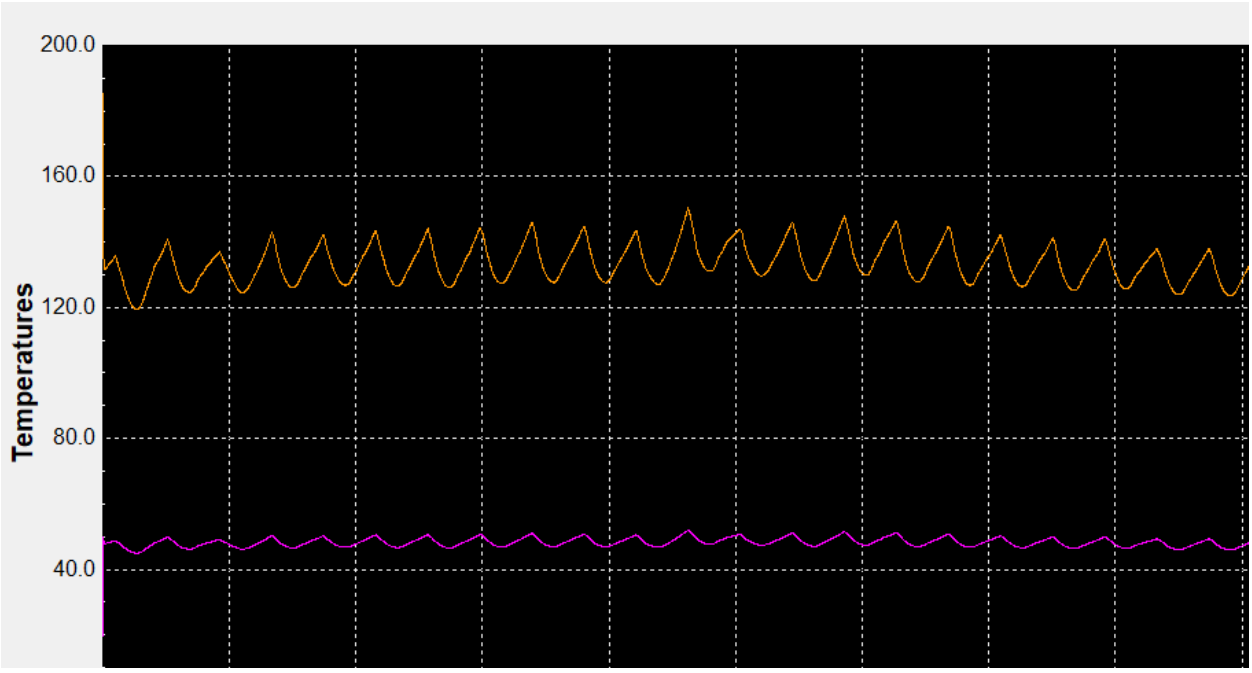


Figure 4.8: TRNSYS simulated output for the steam condenser

The calculated design temperature for the condensate by ProTherm Systems (Pty) Ltd was 185˚C (ProTherm, 2018).

The measured temperature of the feed water that flowed back to the bio-digester from the CHP dual fuel demonstrator was between 40˚C and 50˚C as shown by the purple line (Tdigest-in) in Figure 4.9.

The difference between the condensate temperature of the TRNSYS model and the CHP dual fuel demonstrator's calculated output value, was due to the slightly higher steam temperature generated by the HRSG.

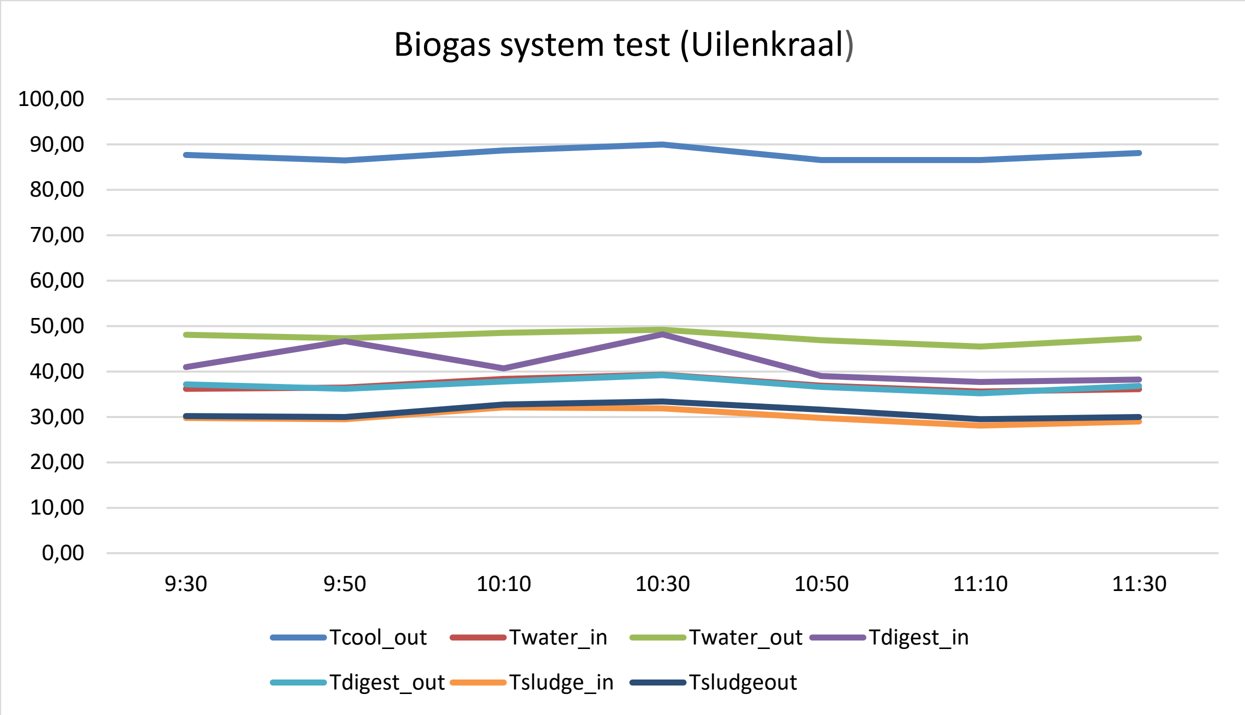


Figure 4.9: CHP dual fuel demonstrator output temperatures for the feed water entering the bio-digester

The temperature of the feed water as determined by the TRNSYS model correlated well with the actual temperature of the feed water produced by the CHP dual fuel demonstrator.

4.4.5 CO_2 emissions

The TRNSYS model can also be used to indicate the expected CO_2 emissions. Figure 4.10 shows the TRNSYS model values for these emissions. The emissions fluctuated between 14 kgCO_2/hr and 25 kgCO_2/hr.

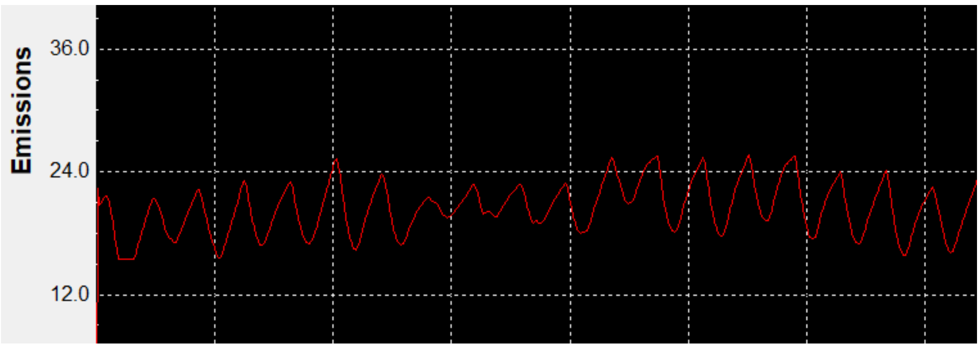


Figure 4.10: TRNSYS model CO_2 emissions

For bio gas electricity generation, as generated by the CHP dual fuel demonstrator, the calculation of CO_2 emissions was based on the 0.370 kg CO_2/kWh value established by the Hungarian Energy Structure (Szabó, et al., 2014).

To determine the CO_2 generated by the CHP dual fuel demonstrator the total amount of fuel used was measured using the data from CAE as per Annexure 1.

On average 1.4 kg/h of a diesel- biogas mix was consumed by the CHP dual fuel demonstrator whilst producing 45 kW of electricity. Thus, the CO_2 emissions for the CHP dual fuel unit, based on the values determined by the Hungarian Energy Structure (Szabó, et al., 2014) are:

$45kw\ x\ 0.37\ kg\ CO_2/kWh = 16.65\ kg\ CO_2/h$ (Szabó, et al., 2014).

The values derived from the TRNSYS model correlated well with the calculated CO_2 emissions for the CHP dual fuel demonstrator.

For biogas electricity generation, a reduction of approximately 63.3% in CO_2 emissions can be achieved when compared to traditional coal electricity generation as research has shown that under complete combustion conditions, 1kg of coal will generate 2.86kg of CO_2 gas (Hong & Slatick, 1994). In addition, 1.01kg of CO_2 is emitted for every 1kWh of electricity produced by traditional coal burning power stations (Environmental Protection Agency, 2017). This excludes any other greenhouse gases and power line losses.

4.4.8 Efficiency gains

To calculate efficiency of electricity generation the following formula was used (Leenhouts, 2018):

$$Efficiency = \frac{Usable\ energy}{Total\ fuel\ energy\ \ input} \times \frac{100}{1}\%$$

For a normal equivalent electricity generator, using dual fuel, the efficiency was calculated as follows, based on data obtained from CAE in Annexure 1:

$$Efficiency = \frac{45kW\ electrical}{80kW\ gas + 40kW\ diesel} \times \frac{100}{1}\%$$

=37%

The efficiency of the CHP dual fuel demonstrator was determined by comparing the available energy from the dual fuel to the thermal energy harvested plus the electricity generated. Using the data provided by CAE in Annexure 1, the efficiency of the CHP dual fuel demonstrator was calculated as follows:

$$Efficiency = \frac{45kW\ electrical + 40kW\ thermal}{80kW\ gas + 40kW\ diesel} \times \frac{100}{1}\%$$

=71%

An efficiency gain of 34% can, thus, be achieved through the installation of a CHP dual fuel system as opposed to the use of a standard generator.

TRNSYS can be used to model the total usable energy generated by a CHP dual fuel system and the electric energy and thermal energy output. In Figure 4.11 a total energy output value of about 95kW is indicated by the purple line. This is higher than the calculated value of 85kW usable energy generated by the CHP dual fuel demonstrator. This deviation can also be explained by the use of the 2D performance map by TRNSYS when modelling the engine.

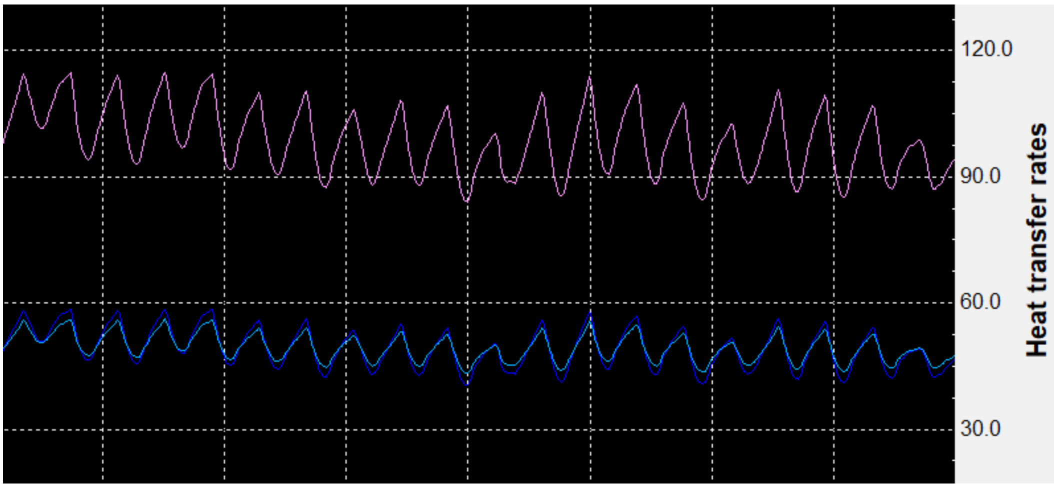


Figure 4.11: TRNSYS total usable energy output

4.4.9 Cost savings

A traditional coal burning power station has an efficiency of between 39% and 41%. The current cost of electricity generation though coal as a fuel source is between 49,46c/kWh and 86c/kWh (Eskom, 2018), (ESI Africa, 2018). In April 2018 the average cost of coal per ton was approximately R1123.00 (Index Mundi, 2018). One ton of coal generates about 2500kWh of electricity (Eskom, 2018). Thus, the cost of using coal to generate electricity is approximately 45c/kWh.

As calculated in the previous section, the efficiency of the CHP dual fuel generator was found to be 71%. The use of a CHP dual fuel system at Uilenkraal has reduced the electricity bill by around 90% (Claasen, 2015) and although the c/kWh is approximately the same as that for coal burning power stations, it should be borne in mind that the thermal energy produced through a CHP system is also utilised and less CO_2 is emitted.

Taking into consideration, the efficiency gains and the potential cost savings to be gained when using bio-fuel it can be assumed that a CHP dual fuel system will lead to cost saving over time.

4.4.10 Summary of findings

It can be seen from Table 4.9 that to some extent the TRNSYS model outputs correlated with the outputs of the CHP dual fuel demonstrator. Component TYPEs that correlated well, within a 15% deviation, are highlighted in red.

Table 4.9: Summary of findings

Component/ TYPE	**Measurement**	**TRNSYS Output**	**CHP dual fuel demonstrator output**	**% Variation**
Engine/ TYPE 907	Exhaust temperature	470˚C	470˚C	0%
	Oil temperature	110˚C	95˚C	15%
	Water jacket temperature	90˚C	82˚C	9.7%
	Shaft energy	58kW	45kW	29%
	Electrical energy	53kW	40.5kW	30.5%
Heat exchangers/ TYPE- 5	Water jacket temperature	70˚C	70˚C	0%
	Engine oil temperature	46.5˚C	45˚C	3.3%
HRSG/ TYPE- 637	Exhaust gas temperature	250˚C	230˚C	8.7%
	Steam temperature	224˚C	186˚C	20.4%
Condenser/ TYPE- 598	Condensate temperature	135˚C	185˚C	37%
	Feed water temperature	46˚C	45˚C	2%
CO_2 emissions	$kgCO_2/h$	$19.5kgCO_2/h$	$16.65kgCO_2/h$	17%
Total usable energy	Thermal energy + Electrical energy	95kW	85kW	11.7%

A possible reason for the deviation of 29% in shaft energy and 30.5% in electrical energy outputs obtained through the TRNSYS model could be as a result of the 2D performance map used by TRNSYS for the engine TYPE selected.

The 2D performance map used in the model differs from the actual engine installed in the demonstrator. This could have led to the difference in the engine output, which in turn, could affect the output temperatures modelled.

Based on the number of correlations between the outputs obtained from TRNSYS compared to the outputs of the CHP dual fuel demonstrator, it is concluded that the TRNSYS energy system simulation model could be used to identify a suitable CHP dual fuel system that will provide an alternative, permanent and constant energy supply that will lead to a reduction in CO_2 emissions, efficiency gains and cost saving.

4.5 Summary

This chapter focussed on the selection of the specific input values and parameters for each component TYPE selected for TRNSYS modelling, followed by the verification of the resultant outputs from the TRNSYS model versus measured and calculated values obtained from the CHP dual fuel demonstrator. The CO_2 emissions, efficiency gains and cost savings derived from the use of a CHP system were also indicated. In the next chapter, conclusions will be drawn and recommendations will be made, based on the results discussed in this chapter.

CHAPTER 5: CONCLUSIONS AND RECOMMENDATIONS

5.1 Introduction

In the previous chapter the outputs of the TRNSYS model are verified against the outputs of the CHP dual fuel demonstrator. In this chapter, an overview of the study is provided, final conclusions are drawn and recommendations are made. The limitations of the study and possible avenues for future research are mentioned and the chapter is concluded with a summary of the value of this research study.

5.2 Overview of the study

In Chapter 1, the background to the study was provided and the problem statement was discussed. It was evident that the use of CHP systems as a potential energy source needed to be investigated. The TRNSYS energy system modelling software was selected to verify whether TRNSYS could be used as a predictive model for the selection of the components of a CHP dual fuel system.

Research questions were posed, with emphasis on the accuracy of TRNSYS as a modelling tool for CHP systems and whether the use of a CHP dual system could lead to a reduction in CO_2 emissions, energy efficiency gains and cost saving.

The methodology chosen for this study comprised of both a literature and empirical study. The research procedure followed was described, the delimitations were discussed and the expected contributions of the research were outlined.

Chapter 2 focused on the theoretical objectives of this study. The chapter contains a literature study regarding the importance of energy management with reference to the South African context. CHP was defined, the applications, advantages and disadvantages were discussed and CHP systems were described with the focus on the crucial components of such systems. Dual fuel, including the use of bio-gas, as an alternative energy source for CHP systems was emphasised and the need to model CHP dual fuel systems was discussed.

In Chapter 3, the origins of the research project, and the purpose of the research were described. The research methodology followed was briefly outlined. The CHP dual fuel demonstrator used in this project was described and the crucial components used for modelling were defined in detail. The TESS library components that were selected for use in the TRNSYS model were also described in depth.

Chapter 4 outlined the process flow that was used for the TRNSYS model simulation. The input data requirements for each library component TYPE, selected for modelling purposes, were entered into the TRNSYS model and output values were generated. The TRNSYS output values were then compared to the measured and calculated values, obtained for the CHP dual fuel demonstrator in use at Uilenkraal farm.

The TRNSYS model produced similar outputs, within a 15% deviation, to that of the CHP dual fuel demonstrator for the following components:

- exhaust temperature;
- oil temperature;
- water jacket temperature;
- water jacket temperature;
- engine oil temperature;
- exhaust gas temperature;
- feed water temperature;
- CO_2 emissions and
- thermal energy + electrical energy.

Significant differences in output were obtained for these components:

- shaft energy;
- electrical energy;
- steam temperature and
- condensate temperature.

Based on the comparison of the results obtained, it was found the selection of the engine TYPE, used for the TRNSYS model, did not correlate well with the actual engine installed in the CHP dual fuel demonstrator. The simulated engine output differed from that of the demonstrator which could also have led to the temperature differences that were also noted in the TRNSYS model.

CO_2 emissions simulated by TRNSYS compared favourably to the calculated emissions obtained from the CHP dual fuel demonstrator. It was determined that the use of biogas as a fuel source could lead to a reduction in CO_2 emissions by as much as 63,3% in comparison to traditional coal burning electricity generation.

It was determined that an efficiency gain of 34% could be achieved when using a CHP dual fuel system as opposed to a standard dual fuel electricity generator. In addition, it was determined that the use of a CHP dual fuel system, that utilises biogas, could lead to significant electricity cost savings over time.

It was concluded that the TRNSYS energy system simulation model could be used to identify a suitable CHP dual fuel system that will provide an alternative, permanent and constant energy supply that will lead to a reduction in CO_2 emissions, efficiency gains and cost saving.

5.3 Final conclusions

In light of the findings of the literature and empirical study, the following conclusions have been drawn:

- Using TRNSYS, an energy system simulation model can be developed, to verify the outputs of an actual CHP dual fuel system.
- The use of a CHP dual fuel system contributes to more effective energy management.
- Data collected from a CHP dual fuel demonstrator correlates, to a large extent, with simulated data generated by the TRNSYS model.
- A CHP dual fuel system that will provide an alternative, permanent, constant energy supply that will be more cost effective, lead to a reduction in CO_2 emissions and reduced heat waste, can be identified using the TRNSYS energy system simulation model.
- The use of TRNSYS as an energy system simulation model for CHP dual fuel systems is verified.

5.4 Recommendations

Recommendations are based on the above conclusions:

- The TRNSYS energy system simulation model should be used to assess the viability of a CHP system, prior to manufacturing and installing the system, to assist with the selection of desirable sizes and specifications of the components of the envisaged CHP dual fuel system.
- On obtaining the actual manufacturing specifications for the components to be used in the envisaged CHP dual fuel system, this data should be entered into TRNSYS to obtain a more accurate prediction of the output values that could be expected from the actual CHP dual fuel system selected.
- The TRNSYS model should be used to determine the expected CO_2 emissions based on the CHP dual fuel component selection.
- For better verification of the TRNSYS energy system simulation model as a predictive tool, more extensive data measurement is required from the CHP dual fuel demonstrator as opposed to the use of calculated outputs.
- For more accurate results the actual 2D performance map, specific to the actual engine used in the CHP dual fuel system, should be entered into TRNSYS prior to the simulation.

- An in-depth analysis of the costs associated with CHP duel fuel energy generation systems should be done. This analysis should include the cost of bio gas generation, transportation of gas and maintenance of the system.

5.5 Limitations

This researcher regards the following as limitations of this study:

- The 2D performance map used in TRNSYS is engine specific and thus did not accurately reflect the actual performance of the engine installed in the CHP dual fuel demonstrator.
- The measured data obtained from the dual fuel demonstrator was limited due to project time constraints. This led to the use of calculated data for some components of the demonstrator.
- The CHP dual fuel demonstrator is a small-scale energy generator.

5.6 Future research

Possibilities for future research in this direction could include the following:

- Conduct a similar study using other combinations of dual fuel as the use of bio gas as a fuel source is limited in the South African environment.
- Investigate the liquefaction of bio-gas to enable access to a larger market for use as a dual fuel.
- Investigate the incorporation of cooling elements into the TRNSYS model so as to simulate predicted outputs when considering tri-generation systems.
- Refine the algorithms used in TRNSYS to improve the accuracy of the TRNSYS model outputs.
- Verify the TRNSYS energy system simulation model by conducting a similar study on a large-scale CHP dual fuel system.

5.7 Value of the research

The value of this study is described as follows:

- The researcher obtained specific insight re the use of an energy system simulation model as a tool for predicting the outputs that can be obtained for CHP dual fuel systems. As a result, this knowledge can be applied within the Technology Station at VUT to further research in this field.
- Confirmation that a CHP dual fuel system can lead to energy efficiency gains, reduced CO_2 emissions and potential cost saving.

5.8 Conclusion

The purpose of this study was to develop an energy system simulation model using TRNSYS to model a CHP dual fuel system. The literature established the need for and use of CHP dual fuel systems to better manage energy requirements. During the empirical investigation, the TRNSYS model was developed though the selection of component TYPES from the TESS library that corresponded to the components installed in a CHP dual fuel demonstrator. The measured and calculated outputs from the CHP dual fuel demonstrator were then compared to the outputs obtained from the TRNSYS model. The use of TRNSYS as a CHP dual fuel system modelling tool was verified as the majority of outputs obtained correlated well. The study concludes with the recommendation that TRNSYS be used as an application tool with the energy management field.

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ANNEXURE 1

CAE (Pty) Ltd. Dyno Meter Test Data

Diesel	Engine	Speed	1500	rpm				
Engine power	**Boost pressure**	**Post-Turbine Exhaust temperature**	**Pre-Turbine Exhaust temperature**	**Temp Coolant In**	**Temp Coolant Out**	**Coolant flow**	**Cp**	**Waste heat energy Coolant**
	kPa gauge	**degrees C**	**degrees C**	**degrees C**	**degrees C**	**kg/s**	**J/g degrees C**	**kW**
20,24	95,03	315	279	79,52	80,93	1,65	3,62	8,42
25,34	130,39	363	320	81,41	83,63	1,65	3,62	13,24
30,32	172,28	402	360	83,01	85,33	1,65	3,62	13,86
35,52	218,02	443	395	82,54	85,38	1,65	3,62	16,94
40,59	267,27	479	428	82,01	85,36	1,65	3,62	19,99
45,15	311,37	508	455	81,64	85,38	1,65	3,62	22,37
49,68	363,37	537	485	81,18	85,40	1,65	3,62	25,26

CAE (Pty) Ltd. Fuel Flow Rates

Fuel Flow		**Fuel energy consumed**	**Thermal efficiency**	**Coolant heat**
kg/h	**g/s**	**kW**	**%**	**%**
5,04	1,40	62,96	32%	13%
5,98	1,66	74,81	34%	18%
6,96	1,93	86,99	35%	16%
7,99	2,22	99,83	36%	17%
8,98	2,50	112,29	36%	18%
9,93	2,76	124,08	36%	18%
10,92	3,03	136,55	36%	19%

ANNEXURE 2

Excel model data for the engine oil heat exchanger design

Problem Statement: Define components for the hot and cold streams

Heat balance		Heat transferred	
19231440	kJ/h	5342,07	Watts

Shell (Cold) side		
Fluid Name	Distilled Water	
Total flow	kg/h	3500
Temperature, In	°C	25
Temperature, out	°C	26
Pressure in		
Fouling Resistance	m²*°C/W	0,00011
Tube (Hot) side		
Fluid Name	Engine Oil	
Total flow	kg/h	908
Temperature, In	°C	85
Temperature, out	°C	75
Pressure in		
Fouling Resistance	m²*°C/W	0,0001

	Density	Viscosity	Sp Heat Cap	Prandtl Num
Hot side (tube), fluid properties	kg/m3	Ns/m^2	kJ/kg-°C	
	841,4	1,94E-02	2118	546
	Density	Viscosity	Sp Heat Cap	Prandtl Num
Cold side (shell), fluid properties	kg/m3	Ns/m^2	kJ/kg-°C	
	960	8,55E-04	4178	5,83

Fluid Name	**Distilled Water (Shell, Cold Side**	
Total flow	kg/h	3500
Temperature, In	°C	25
Temperature, out	°C	26
Shell inside diameter	mm	65,00

Fluid Name	**Engine Oil (Tube, Hot Side)**	
Total flow	kg/h	908
Temperature, In	°C	85
Temperature, out	°C	75
Tube inside diameter	mm	5,2324
Tube area required	m²	0,65
Total tube length req	m	32,63
Number of tubes		47
Actual area	m²	0,6510
Flow rate per tube	kg/h	908

F Factor

Problem Statement: Calculate the LMTD configuration correction factor

Hot Side

Fluid Name		
Temperature, in	°C	85
Temperature, out	°C	75

Cold Side

Fluid name		
Temperature, in	°C	25
Temperature, out	°C	26
Tube passes		1
Shell passes		1

Calculations

Intermediate value	R	7,60
Intermediate value	P	0,022
Intermediate value	S	0,160
Intermediate value	W	7,6692
Intermediate value	W'	1,2046

General Case

Numerator		1,228
Denominator		1,229
General Case Answer	F	0,999

R=1 Case

Numerator		(0,240)
Denominator		(0,241)
R=1 Answer	F	0,995
Choose which one	F	0,999

Tube Pressure Drop

Inputs

Fluid flowing in tubes		
Assumed overall U	W/m²-°C	182
Safety factor for fouling		20%
Tube OD	mm	6,350
Tube wall thickness	BWG	24
Tube length	m	0,7
Tube Passes		1
Shell Passes		1

Data (from the Process Data and F Factor worksheets)

Flow rate	kg/h	908
Heat transferred	W	5 342
Temp diff correction factor		0,999
Average viscosity	mPa-s	0,019358
Average density	kg/m3	841,40
Pressure at inlet	kPa(g)	
Pressure drop allowed	kPa(g)	
Tube roughness	m	

Calculations

Tube inside diameter	mm	5,232
Flow area per tube	m²	0,0000215
Tube area available	m²/m	0,019949
Log-mean temp diff	°C	54,15
Mean temperature difference	°C	54,11
Adjusted heat transfer	W	6 410,48
Tube area required	m²	0,65
Total tube length req	m	33
Number of tubes		47
Tubes per pass		47
Actual area	m²	0,65
Flow rate per tube	kg/h	908,0000
Velocity in tube	m/s	0,939
Reynolds Number		0,06801
Friction Factor		0,8288
Tube mass flux density		4 739,53
Equivalent Diameter	mm	6,283
Pressure drop	kPa(g)	4,321

Tube Heat Transfer Co-efficient

Problem Statement: Calculate the tube side heat transfer coefficient

Inputs

Assume heat transfer coefficient	W/m²-°C	100
Assumed overall U	W/m²-°C	
Outside surface area	m²	0,7
Tube outside diameter	mm	6,350
Tube inside diameter	mm	5,232
	m	0,005232
Tube length (one path)	m	32,6330
Bulk viscosity		0,019358
Bulk heat capacity	kJ/kg-°C	2118
Bulk thermal conductivity	W/m-°C	0,0138
Reynolds Number		0,0680

Calculations

Inside surface area	m²	0,54

Laminar flow calculation

Inside heat transfer coefficient	W/m²-°C	10

Turbulent flow calculation

Inside heat transfer coefficient	W/m²-°C	0

Inside heat transfer coefficient	W/m²-°C	10

Problem Statement: Calculate the shell side geometrical parameters

Inputs

Number of shells		1
Baffle thickness	mm	5
Tube length	m	0,7
Shell length assumed	m	1,7
Shell inside diameter	mm	65,00
Outer tube limit (diameter)	mm	
Baffle cut	fraction	0,25
Baffle diameter	mm	62,40
Tube pitch layout		90
Tube pitch ratio		1,25

Data (from Tubes Pressure Drop worksheet)

Number of tubes in the exchanger		47
Outside diameter of tubes	mm	6,35
Tube length	m	0,7
Tube passes		1

Calculations

Baffle spacing	mm	16,25
Tube pitch	mm	7,94
Longitudinal Tube Pitch	mm	7,94
Number of baffles		24,00

Problem Statement: Calculate the shell side film coefficient using the Bell-Delaware method

Data

Flow rate	kg/h	3 500
	kg/s	0,97
Assumed overall U	W/m²-°C	182,0
Outside surface area	m²	84,5
Tube outside diameter	mm	6,350
	m	0,00635
Shell Diameter	mm	65,00000
Tube inside diameter	mm	5,232
Equivalent Diameter	mm	6,283
	m	0,00628292
Prandtl Number		5,83
Thermal Conductivity	W/m-°C	0,613

Calculations

Tube bundle clearance	mm	1,588
Cross flow area		1,47
		0,00147
Mass flux density	kg/m2*h	662,721893
Reynolds Number		4869,97781
Outside heat transfer coefficient	W/m²-°C	97,566
		24,244
		1,789
		1523,640

Problem Statement: Calculate the shell side pressure drop

Inputs	Fluid flowing in shell

Data

Flow rate	kg/h	3 500,000
	kg/s	0,97
Assumed overall U	W/m²-°C	182,0
Outside surface area	m²	0,7
Tube outside diameter	mm	6,350
	m	0,00635
Number of tubes in the exchanger	N	47
Shell inside diameter	mm	65,00
	m	0,07
Baffle cut fraction		0,25
Baffle spacing	mm	16,25
Pitch layout		90
Pitch Ratio		1,25
Tube Pitch	mm	7,94
Tube Pitch, normal to flow	mm	7,93750
Tube Pitch, parallel to flow	mm	7,94
Hydraluic Diameter	mm	1,12

Calculations

friction factor	f1	0,0064
	f2	0,0004
	a	0,0059
	b	0,7500
	c	0,0056
f-ideal factor		0,116

Pressure drop		331 959,64
		12,06321333
	kPa(g)	27,52

Overall U

Inputs

Material of construction, tubes	Copper

Data

Assumed U	W/m²-°C	182
Fouling resistance, tubes		0,00010
Fouling resistance, shell		0,00011
Outside diameter, tubes	mm	6,35
Inside diameter, tubes	mm	5,23
Thermal conductivity, tubes	W/m-°C	381
Heat transferred	W	5 342
Mean temperature difference	°C	54,11

Calculations

Overall U, calculated, clean	W/m²-°C	7,81
Total fouling resistance	m²*°C/W	0,00023136
Overall U, calculated, clean	W/m²-°C	7,80

Overall U, calculated, required	W/m²-°C	117,96
Over Surface		-93%
Over Design		-93%

ANNEXURE 3

Excel model data for the water jacket heat exchanger design

Information Spread

GIVEN DATA

Hot Side (Engine)

		Units
Th_in=	358,15	K
Th_out=	348,15	K
m.flow_hot=	0,6	kg/s

Th	Units	cp_hot	Units	µ_hot	Units	K_hot	Units	ρ_hot	Units	Pr_hot
353,15	K	4197,52	KJ/kg*K	0,000351	N*s/m^2	0,66989	W/m*K	971,8	kg/m^3	2,1955

Cold Side (Tank)

		Units
Tc_in=	298,15	K
Tc_out=	343,15	K
m.flow_cold=	0,133884	kg/s

Tc	Units	cp_cold	Units	µ_cold	Units	K_cold	Units	ρ_cold	Units	Pr_cold
320,65	K	4180,26	KJ/kg*K	0,000571	N*s/m^2	0,64065	W/m*K	989,125	kg/m^3	3,7245

Q=	25 185,12	W

R=	0,22222222	
P=	0,75	
Ft=	0,95	
LMTD=	29,0704241	K
Tm=	27,6169029	K

Assumptions

90	Square Arrangement
30	Triangle Arrangement
30	**Triangle Arrangement**

CL is the Tube Layout Constant

CL=	**0,87**

1	90deg and 45deg
0,87	30deg and 60deg

For standard outside diameters of steel tubes, refer to Table A3

do=	0,016	m
di=	0,0136	m

Pt is the Tube Pitch

Pt=	0,02	m

CTP is the Tube Count Calculation Constant

CTP=	0,93	one-tube pass
CTP=	0,9	two-tube pass
CTP=	0,85	three-tube pass

Tube passes **1**

CTP=	0,93

PR is the Tube Pitch Ratio

PR=	1,25

Do=	0,1524	m
Di=	0,137	m

Uestimate=	**1000**	**W/m^2*K**

Shell Equivalent Diameter	**0,011566**	**m**

Tube Side Fouling Factor	6000	W/m^2*K
Shell Side Fouling Factor	5000	W/m^2*K

Area, length and number of tubes

Area=	0,911946	m^2

Length=	0,461087	m

Number of Tubes	39,36736
	40

Shell and bundle geometry

Number of Tubes at Centerline	6,85
	6

Baffle Spacing	0,0685	m

Clearance Between Adjacent Tubes	0,004	m

Tube Sheet Thickness	0,0137	m

All Summation of All Baffle Spacing	0,433687	m

Number of Baffles	5,3312
	5

B/Ds	0,5

Segmental Baffle Cut	0,25	*Read Value From Table (Refer to Segmental Baffle Cut Sheet)*

Baffle Cut Height	0,03425	m

Tube Bundle Diameter	0,12	m

Diameter of Circle Through The Centres of the Tubes Located Within the Outermost Tubes	0,104	m

Bypass Channel Between Tube Bundle and Shell Inside Diameter	0,017	m

Inside Shell to Baffle Clearance (Lsb)	3,100548	mm

Kern method

Tube Side Heat Transfer Coefficient Calculation

velocity through the tubes=	0,333808	m/s

Tube Side Reynolds Number	12564,12	Turbulent Flow

Laminar Flow
Transitional Flow
Turbulent Flow

Tube Side Friction Factor	0,00739

Tube Side Nusselt Number	63,61707

Tube Side Heat Transfer Coefficient	3133,562	W/m^2*K

1,732051	Square root of 3
3,141593	pi

Shell Side Heat Transfer Coefficient Calculation

Bundle Cross Flow Area	0,001877	m^2

Shell Side Cross Flow Velocity	71,33244	kg/m^2*s

Shell Side Reynolds Number	1445,88	Laminar Flow

Shell Side Heat Transfer Coefficient	1691,034	W/m^2*K

Overall Heat Transfer Coefficient Calculation

Overall Heat Transfer Coefficient	688,7402	W/m^2*K

Tube Side Pressure Drop

ΔP_t	270,8286	N/m^2

Shell Side Pressure Drop

fs	0,446404

ΔP_s	81,60061	N/m^2

Bell Delaware method

Shell Side Pressure Drop

ΔP_bi	3,172328139
ΔP_c	2,00139E-66
ΔP_e	33,70918952
ṁ_w	74,84670013
ΔP_w	3,59275E-68
ΔPs	**36,88151766**

Kern method iteration

U_estimate	Q	T_m	Heat Transfer Area	Length of Tubes	Number of Tubes		Velocity Through the Tubes	Tube Side Reynolds Number	Friction Factor	Nusselt Number
1000	25 185,12	27,6169	0,911945851	0,461087231	39,34741	40	0,333807845	12564,11889	0,00738954	63,61706623
688,7402412	25 185,12	27,6169	1,324078073	0,66946463	39,34741	40	0,333807845	12564,11889	0,00738954	63,61706623
688,7402412	25 185,12	27,6169	1,324078073	0,66946463	39,34741	40	0,333807845	12564,11889	0,00738954	63,61706623

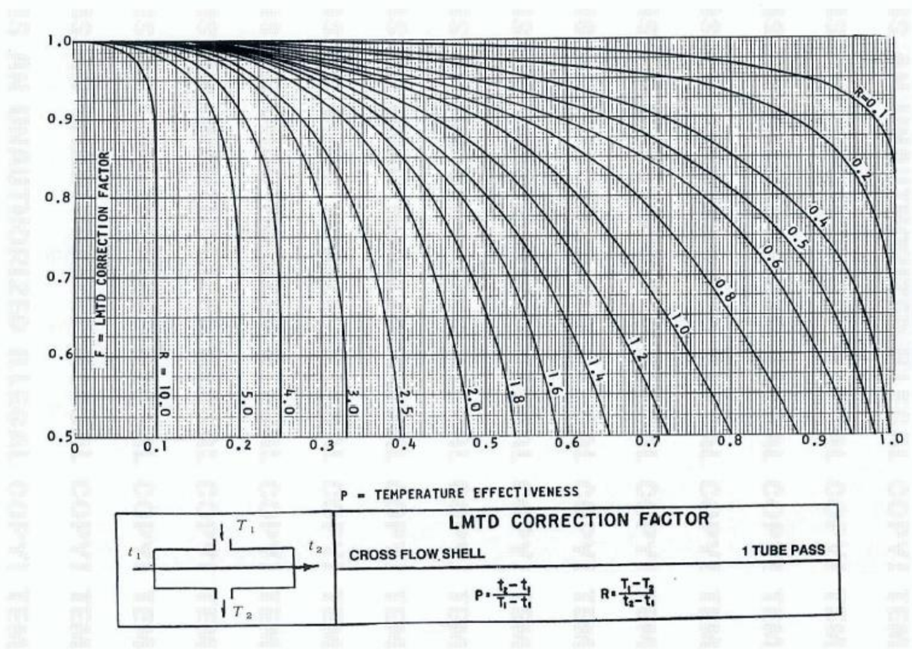
Tube Side Heat Transfer Coefficient	Bundle Cross Flow Area	Shell Side Mass Velocity	Shell Side Reynolds Number	Shell Side Heat Transfer Coefficient	Overall Heat Transfer Coefficient	ΔP_t	f_s	ΔP_s
3133,561507	0,0018769	71,33244036	1445,880398	1691,033609	688,7402412	270,8286	0,446404	81,60061
3133,561507	0,0018769	71,33244036	1445,880398	1691,033609	688,7402412	295,349	0,446404	81,60061
3133,561507	0,0018769	71,33244036	1445,880398	1691,033609	688,7402412	295,349	0,446404	81,60061

Bell Delaware Iteration

U_estimate	Q	T_m	Heat Transfer Area	Length of Tubes	Number of Tubes		Velocity Through the Tubes	Tube Side Reynolds Number	Friction Factor	Nusselt Number	Tube Side Heat Transfer Coefficient
1000	25 185,12	27,6169	0,911945851	0,461087231	39,34741	40	0,333807845	12564,11889	0,00738954	63,61706623	3133,561507
796,9058266	25 185,12	27,6169	1,144358368	0,578596887	39,34741	40	0,333807845	12564,11889	0,00738954	63,61706623	3133,561507
796,9058266	25 185,12	27,6169	1,144358368	0,578596887	39,34741	40	0,333807845	12564,11889	0,00738954	63,61706623	3133,561507

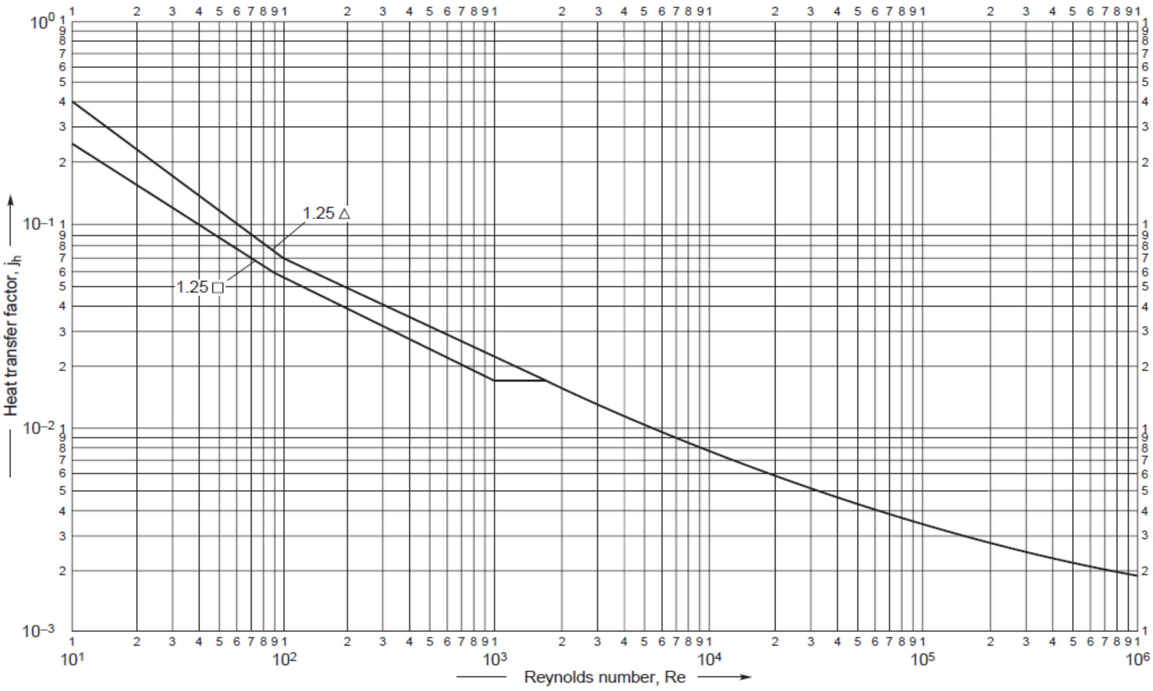
Cross Flow Area at Centerline	Shell Side Cross Flow Mass Velocity	Shell Side Reynolds Number	Ideal Cross Flow Coefficient	J_c	J_l	J_b	J_s	J_r	Tube Side Heat Transfer Coefficient	Overall Heat Transfer Coefficient
0,002809766	47,64947575	1336,052454	15755,56388	0,830447	0,393613	0,571492	1,043929	0,825463	2536,258854	796,9058266
0,002809766	47,64947575	1336,052454	15755,56388	0,830447	0,393613	0,571492	1,043929	0,825463	2536,258854	796,9058266
0,002809766	47,64947575	1336,052454	15755,56388	0,830447	0,393613	0,571492	1,043929	0,825463	2536,258854	796,9058266

Correction factor



R=	0,222222
P=	0,75
Ft=	**0,95**

Heat transfer factor



Re=	1445,88	
Arrangement	*30*	*Triangle Arrangement*

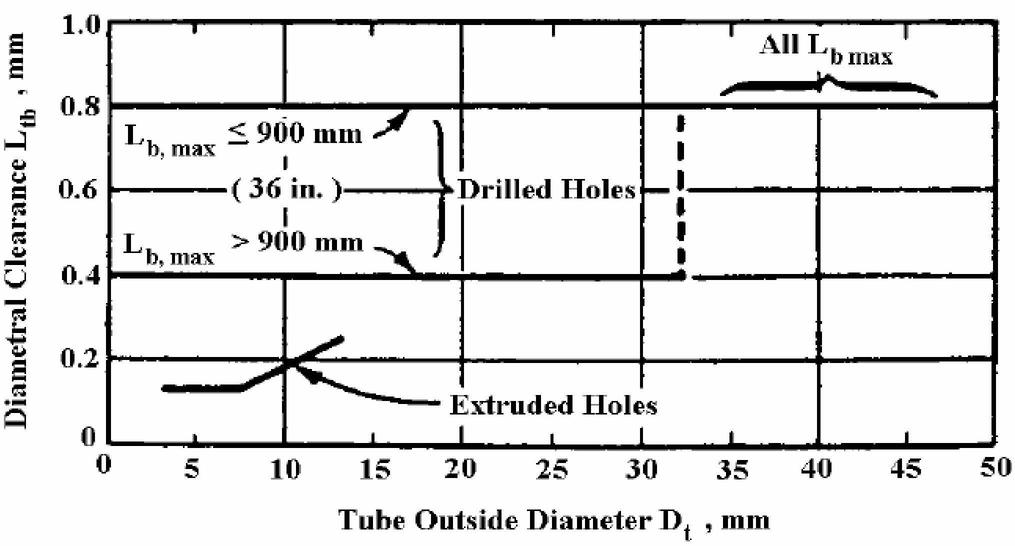
Heat Transfer Factor, Jh=	**0,19**

Correction coefficients

Layout Angle	Reynolds Number	a_1	a_2	a_3	a_4	b_1	b_2	b_3	b_4
30°	10^5–10^4	0.321	–0.388	1.450	0.519	0.372	–0.123	7.00	0.500
	10^4–10^3	0.321	–0.388			0.486	–0.152		
	10^3–10^2	0.593	–0.477			4.570	–0.476		
	10^2–10	1.360	–0.657			45.100	–0.973		
	<10	1.400	–0.667			48.000	–1.000		
45°	10^5–10^4	0.370	–0.396	1.930	0.500	0.303	–0.126	6.59	0.520
	10^4–10^3	0.370	–0.396			0.333	–0.136		
	10^3–10^2	0.730	–0.500			3.500	–0.476		
	10^2–10	0.498	–0.656			26.200	–0.913		
	<10	1.550	–0.667			32.00	–1.000		
90°	10^5–10^4	0.370	–0.395	1.187	0.370	0.391	–0.148	6.30	0.378
	10^4–10^3	0.107	–0.266			0.0815	+0.022		
	10^3–10^2	0.408	–0.460			6.0900	–0.602		
	10^2–10	0.900	–0.631			32.1000	–0.963		
	<10	0.970	–0.667			35.0000	–1.000		

Re_s	1336,052	30deg
a1	0,321	
a2	-0,388	
a3	1,45	
a4	0,519	
b1	0,486	
b2	-0,152	
b3	7	
b4	0,5	

Diameter clearance



Ltb	0,4

Material properties

Table A3: Standard Dimensions for Steel Tubes					
Do (mm)	Wall Thickness (mm)				
16	1,2	1,6	2	—	—
20	—	1,6	2	2,6	—
25	—	1,6	2	2,6	3,2
30	—	1,6	2	2,6	3,2
38	—	—	2	2,6	3,2
50	—	—	2	2,6	3,2

Triangle Pitch					
No, of passes	1	2	4	6	8
K1	0,319	0,249	0,175	0,0743	0,0365
n1	2,142	2,207	2,285	2,499	2,675

Squarer Pitch					
No, of passes	1	2	4	6	8
K1	0,215	0,156	0,158	0,0402	0,0331
n1	2,207	2,291	2,263	2,617	2,643

Baffle Spacing Range
0,2
0,3
0,4
0,5
0,6
0,7
0,8
0,9
1

Shell Equivalent Diameter (square Arrangement)	0,015847	m

Shell Equivalent Diameter (Triangle Arrangement)	0,011566	m

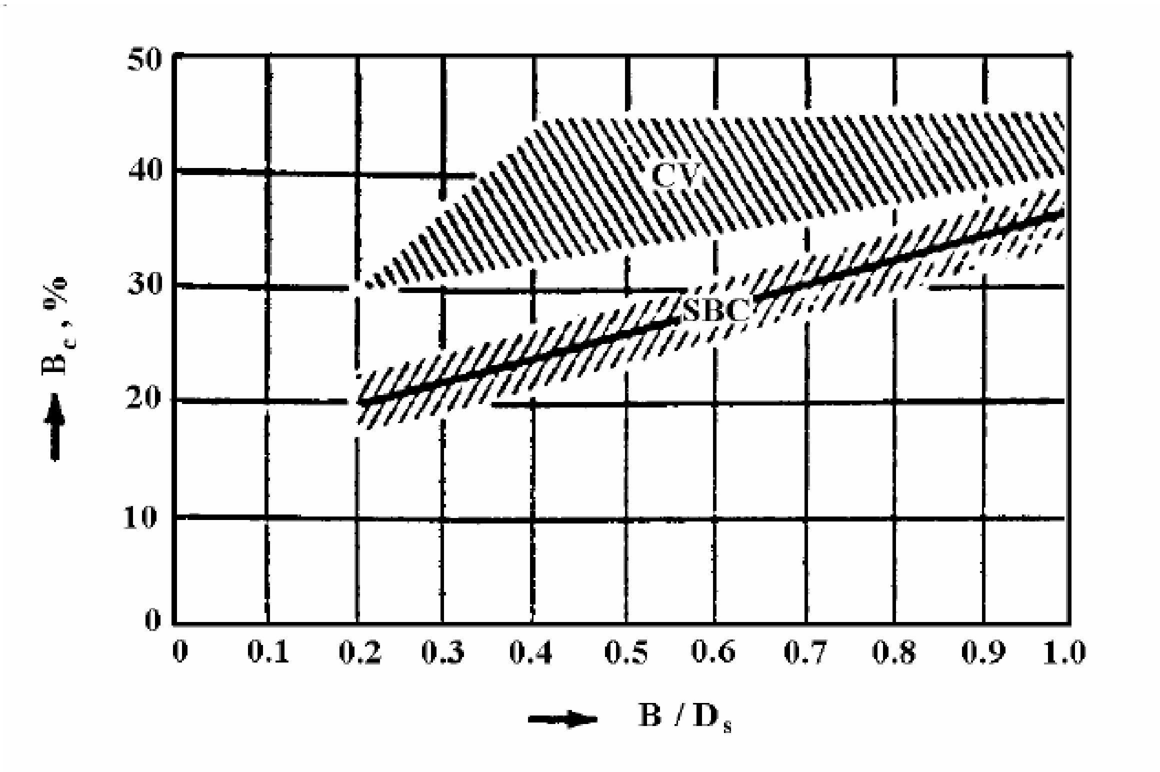
30 deg	0,01732	m
90 deg	0,02	m
45 deg	0,01414	m

Saturated water properties

A	Pressure	Column1	Column2	Column3	Column4	Column5	Column6	Column7	Column8	Column9	Column10	Column11	Column12	Column13
273,15	0,00611	1	206,3	2502	4,217	1,854	1750	8,02	569	18,2	12,99	0,815	75,5	-68,05
275	0,00697	1	181,7	2497	4,211	1,855	1652	8,09	574	18,3	12,22	0,817	75,3	-32,74
280	0,0099	1	130,4	2485	4,198	1,858	1422	8,29	582	18,6	10,26	0,825	74,8	46,04
285	0,01387	1	99,4	2473	4,189	1,861	1225	8,49	590	18,9	8,81	0,833	74,3	114,1 285
290	0,01917	1,001	69,7	2461	4,184	1,864	1080	8,69	598	19,3	7,56	0,841	73,7	174
295	0,02617	1,002	51,94	2449	4,181	1,868	959	8,89	606	19,5	6,62	0,849	72,7	227,5
300	0,03531	1,003	39,13	2438	4,179	1,872	855	9,09	613	19,6	5,83	0,857	71,7	276,1
305	0,04712	1,005	29,74	2426	4,178	1,877	769	9,29	620	20,1	5,2	0,865	70,9	320,6
310	0,06221	1,007	22,93	2414	4,178	1,882	695	9,49	628	20,4	4,62	0,873	70	361,9
315	0,08132	1,009	17,82	2402	4,179	1,888	631	9,69	634	20,7	4,16	0,883	69,2	400,4
320	0,1053	1,011	13,98	2390	4,18	1,895	577	9,89	640	21	3,77	0,894	68,3	436,7
325	0,1351	1,013	11,06	2378	4,182	1,903	528	10,09	645	21,3	3,42	0,901	67,5	471,2
330	0,1719	1,016	8,82	2366	4,184	1,911	489	10,29	650	21,7	3,15	0,908	66,6	504
335	0,2167	1,018	7,09	2354	4,186	1,92	453	10,49	656	22	2,88	0,916	65,8	535,5
340	0,2713	1,021	5,74	2342	4,188	1,93	420	10,69	660	22,3	2,66	0,925	64,9	566
345	0,3372	1,024	4,683	2329	4,191	1,941	389	10,89	668	22,6	2,45	0,933	64,1	595,4
350	0,4163	1,027	3,846	2317	4,195	1,954	365	11,09	668	23	2,29	0,942	63,2	624,2
355	0,51	1,03	3,18	2304	4,199	1,968	343	11,29	671	23,3	2,14	0,951	62,3	652,3
360	0,6209	1,034	2,645	2291	4,203	1,983	324	11,49	674	23,7	2,02	0,96	61,4	697,9
365	0,7514	1,038	2,212	2278	4,209	1,999	306	11,69	677	24,1	1,91	0,969	60,5	707,1
370	0,904	1,041	1,861	2265	4,214	2,017	289	11,89	679	24,5	1,8	0,978	59,5	728,7
373,15	1,0133	1,044	1,679	2257	4,217	2,029	279	12,02	680	24,8	1,76	0,984	58,9	750,1
375	1,0815	1,045	1,574	2252	4,22	2,036	274	12,09	681	24,9	1,7	0,987	58,6	761
380	1,2869	1,049	1,337	2239	4,226	2,057	260	12,29	683	25,4	1,61	0,999	57,6	788
385	1,5233	1,053	1,142	2225	4,232	2,08	248	12,49	685	25,8	1,53	1,004	56,6	814
390	1,794	1,058	0,98	2212	4,239	2,104	237	12,69	686	26,3	1,47	1,013	55,6	841
400	2,455	1,067	0,731	2183	4,256	2,158	217	13,05	688	27,2	1,34	1,033	53,6	896
410	3,302	1,077	0,553	2153	4,278	2,221	200	13,42	688	28,2	1,24	1,054	51,5	952

420	4,37	1,088	0,425	2123	4,302	2,291	185	13,79	688	29,8	1,16	1,075	49,4	1 010
430	5,699	1,099	0,331	2091	4,331	2,369	173	14,14	685	30,4	1,09	1,1	47,2	—
440	7,333	1,11	0,261	2059	4,36	2,46	162	14,5	682	31,7	1,04	1,12	45,1	—
450	9,319	1,123	0,208	2024	4,4	2,56	152	14,85	678	33,1	0,99	1,14	42,9	—
460	11,71	1,137	0,167	1989	4,44	2,68	143	15,19	673	34,6	0,95	1,17	40,7	—
470	14,55	1,152	0,136	1951	4,48	2,79	136	15,54	667	36,3	0,92	1,2	38,5	—
480	17,9	1,167	0,111	1912	4,53	2,94	129	15,88	660	38,1	0,89	1,23	36,2	—
490	21,83	1,184	0,0922	1870	4,59	3,1	124	16,23	651	40,1	0,87	1,25	33,9	—
500	26,4	1,203	0,0766	1825	4,66	3,27	118	16,59	642	42,3	0,86	1,28	31,6	—
510	31,66	1,222	0,0631	1779	4,74	3,47	113	16,95	631	44,7	0,85	1,31	29,3	—
520	37,7	1,244	0,0525	1730	4,84	3,7	108	17,33	621	47,5	0,84	1,35	26,9	—
530	44,58	1,268	0,0445	1679	4,95	3,96	104	17,72	608	50,6	0,85	1,39	24,5	—
540	52,38	1,294	0,0375	1622	5,08	4,27	101	18,1	594	54	0,86	1,43	22,1	—
550	61,19	1,323	0,0317	1564	5,24	4,64	97	18,6	580	58,3	0,87	1,47	19,7	—
560	71,08	1,355	0,0269	1499	5,43	5,09	94	19,1	563	63,7	0,9	1,52	17,3	—
570	82,16	1,392	0,0228	1429	5,68	5,67	91	19,7	548	76,7	0,94	1,59	15	—
580	94,51	1,433	0,0193	1353	6	6,4	88	20,4	528	76,7	0,99	1,68	12,8	—
590	108,3	1,482	0,0163	1274	6,41	7,35	84	21,5	513	84,1	1,05	1,84	10,5	—
600	123,5	1,541	0,0137	1176	7	8,75	81	22,7	497	92,9	1,14	2,15	8,4	—
610	137,3	1,612	0,0115	1068	7,85	11,1	77	24,1 4	67	103	1,3	2,6	6,3	—
620	159,1	1,705	0,0094	941	9,35	15,4	72	25,9	444	114	1,52	3,46	4,5	—
625	169,1	1,778	0,0085	858	10,6	18,3	70	27	430	121	1,65	4,2	3,5	—
630	179,7	1,856	0,0075	781	12,6	22,1	67	28	412	130	2	4,8	2,6	—
635	190,9	1,935	0,0066	683	16,4	27,6	64	30	392	141	2,7	6	1,5	—
640	202,7	2,075	0,0057	560	26	42	59	32	367	155	4,2	9,6	0,8	—
645	215,2	2,351	0,0045	361	90	—	54	37	331	178	12	26	0,1	—

Segmented baffle cut



B/Ds=	0,5
Bc(%)	**25**

Integration sheet

Iteration for specific heat

353,15	17	
x1	350	
x2	355	
y1	4,195	
y2	4,199	
cp_hot	**4,19752**	**KJ/kg*K**

320,65	11	
x1	320	
x2	325	
y1	4,18	
y2	4,182	
cp_cold	**4,18026**	**KJ/kg*K**

Iteration for viscosity

353,15	17	
x1	350	
x2	355	
y1	365	
y2	343	
μ_hot	**351,14**	**N*s/m^2**

320,65	11	
x1	320	
x2	325	
y1	577	
y2	528	
μ_cold	**570,63**	**N*s/m^2**

Iteration for thermal conductivity

353,15	17	
x1	350	
x2	355	
y1	668	
y2	671	
k_hot	**669,89**	**W/m*K**

320,65	11	
x1	320	
x2	325	
y1	640	
y2	645	
k_cold	**640,65**	**W/m*K**

Iteration for Prandtl number

353,15	17
x1	350
x2	355
y1	2,29
y2	2,14
Pr_hot	**2,1955**

320,65	11
x1	320
x2	325
y1	3,77
y2	3,42
Pr_cold	**3,7245**

Iteration for density

353,15	10	
x1	353,15	
x2	363,15	
y1	971,8	
y2	965,3	
ρ_hot	**971,8**	**kg/m^3**

320,65	6	
x1	313,15	
x2	323,15	
y1	992,2	
y2	988,1	
ρ_cold	**989,125**	**kg/m^3**