University of the Witwatersrand, School of Architecture and Planning

Energy-efficiency improvement study: a case study of waste heat recovery in selected manufacturing industries in Johannesburg

By

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A research report submitted to the Faculty of Engineering and Built Environment, University of the Witwatersrand, Johannesburg, in partial fulfilment of the requirements for the degree of Master of Urban Studies in the field of Sustainable and Energy Efficient Cities.

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Declaration

I hereby declare that this research report is my own unaided work. It is being submitted in partial fulfilment for the Degree of Master of Urban Studies in the field of Sustainable and Energy Efficient Cities at the University of the Witwatersrand, Johannesburg.

I declare that this research report has not been previously submitted for any degree or examination to any other University.

Signature ………………………………

Date 09/10/2020

ABSTRACT

Waste energy from manufacturing industries is released as heat, steam or exhaust gases. These released energy forms contribute to the CO_2 emissions of cities where these industries are situated. European countries at large have benefited from previous studies on the estimation of the waste heat recovery potential in industrial processes. Considerable progress into the reduction of energy use, cost and CO_2 emission has been achieved in this region based on these findings. However, research into estimating waste heat recovery and re-use on a production-scale is not fully explored in South Africa due to several factors which include a lack of systemic approach, the cost of waste heat recovery framework, and inaccessible or inconsistent data sets. For this purpose, this study uses a bottom-up approach to assess the waste heat potential to be used for onsite work in three case study manufacturing industries in Johannesburg.

Factory-level data consisting of CO_2 emissions and energy consumption in selected case study manufacturing sites are used in this study to estimate the potential for waste heat recovery. Consideration was given to each manufacturing subsector-specific parameters, and the study finds that low to medium grade waste heat streams is contained in exhaust gases, air and vapour emitted from steam boiler systems, air compressors, heating, and drying processing units; which typically consume a high amount of energy and are generic processing units widely used in manufacturing industries.

About 125,922.44 GJ (34, 978.3kWh) of waste heat with a work potential of between 18.93 to 29.4% representing about one-fifth to a third (20 - 30 %) of the total estimated waste heat streams for all three selected manufacturing case studies was estimated in this research. Given that this waste heat stream is associated with carbon emissions from fossil fuel combustion during manufacturing activities; the study also finds that the recovery of waste heat promises about 7 - 24 % potential savings in energy consumption and about 60 % reduction in CO_2 emissions per year. In light of the finding from the study, it is logical to state that waste heat recovery has the potential for reducing energy demand and cost, as well as a significant reduction in carbon emission from manufacturing industries.

Keywords: waste heat; waste heat recovery; CO_2 emission; energy reduction; manufacturing industries.

DEDICATION

I dedicate this research report to my loving family; my parents, Hakim, Iniola, and Abbey, this is for you as well. You all made the journey worthwhile for me.

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LIST OF ABBREVIATIONS, ACRONYMS AND UNITS OF MEASUREMENTS

CO_2: Carbon dioxide

Cp: Carnot potential

C_T: Total emissions of the site

DECC: Department for Energy and Climate Change

DoE: Department of Energy

F_C: Combustion emission fraction

GHG: Greenhouse gas

GJ: Giga joules (10^9 Joules)

HSRC: Human Science Research Council

H_T: high temperature

IEA: International Energy Agency

IEO: International Energy Outlook

IPCC: Intergovernmental Panel on Climate Change

KJ: Kilo Joules (10^3 Joules)

K_T: Overall emission factor for the subsector

L_F: Load factor

L_T: low temperature

$\dot{m}$: M*ass* flow in Kg/s

M_T: medium temperature

MJ: Mega joules (10^6 Joules)

η_C: Efficiency conversion from fuel to heat

OECD: Organization for Economic Cooperation and Development

PHASA: Public Health Association of South Africa

PJ: Peta Joules (10^{15} Joules)

R_F: Recovery fraction

SMME: Small and Medium-sized Manufacturing Enterprises

TJ: Terra Joules (10^{12} Joules)

WH_T: Waste heat potential

CHAPTER ONE: INTRODUCTION AND MOTIVATION FOR THE STUDY

1.0. Overview

The average global temperature is predicted to reach a "crucial threshold of 1.5 $^{\circ}$C above pre-industrial levels as early as 2030" (Roberto et al., 2019:2), with associated severe consequences such as intense desertification, reduced production of food, sea-level rise and drastic climatic change (IPCC, 2018). In this context, predictions by the International Energy Agency (IEA, 2014a) and World Energy Outlook (2014) of a 37% increase in the world's energy supply by 2040 has resulted in global concerns around issues of climate change and energy security.

Regarding both energy demand and greenhouse gas emission, the manufacturing sector remains the world's largest energy end-use (Zhou et al., 2016). This sector consumes over 30% of the world's total energy which represents approximately a third of energy consumption and about 36% of global carbon dioxide emissions (IEA, 2014b). Direct carbon dioxide emissions from heating processes during manufacturing operations currently represent about 25% of the total global energy-related carbon dioxide emissions; an estimate observed to be increasing faster than total carbon dioxide emissions at an average annual rate of 3.4% between 2000 and 2014 (Roberto et al., 2019). Approximately 70% of carbon dioxide emissions from manufacturing processes are mainly attributed to the iron and steel, non-metallic minerals, chemicals and petrochemicals operating processes (IEA, 2007). Other Small and Medium-sized Manufacturing Enterprises (SMMEs) and industries, which dominate the sector contribute significantly to the world's total carbon emissions. According to the World bank 2020 report, the IEA Statistics of 2014 revealed that manufacturing industries and construction in South Africa account for 12.6 % of the country's total carbon emission.

Manufacturing processes involve taking raw materials as inputs into a variety of processing steps incorporated into machinery and transform them into finished products and wastes. The manufacturing sector falls under the industrial sector, which is mainly classified into three industry types, namely: energy-intensive manufacturing, non-energy-intensive manufacturing, and the non-manufacturing (see Table 1.1). The energy mix, intensity and consumption in each of these industrial sectors differ for various regions and countries, based on their level of economic activity and technological advancement. Energy is widely consumed in the manufacturing sector for processing, steam generation, in processing units such as heating, drying, evaporation and cooling, lighting, space heating and air conditioning (IEO, 2016).

Table 1.1: Global industrial sector showing the main classifications and the representative subsectors (adapted from U.S. EIA, 2016). The food, pulp and paper and plastic (classified as basic chemicals) are classified as energy-intensive manufacturing subsectors (adapted from IEO, 2016).

Industrial grouping	**Representative industries**
Energy-intensive manufacturing	
Food:	Food, beverage and tobacco product manufacturing
Pulp and paper:	Paper manufacturing, printing and related support activities
Basic chemicals:	Inorganic chemicals, organic chemicals, (e.g., ethylene propylene) resins and agricultural chemicals; which includes chemical feedstocks
Refining	Petroleum refineries and coal products manufacturing, including coal and natural gas used as feedstocks
Iron and steel	Iron and steel manufacturing, including coke ovens
Nonferrous metals	Primarily aluminium and other non-ferrous metals i.e., copper, zinc and tin.
Non-metallic minerals	Primarily cement and other non-metallic minerals, i.e., glass, lime, gypsum and clay products
Non-energy intensive manufacturing	
Other chemicals	Pharmaceutical (medicinal and botanical), plants and coatings, adhesives, detergents and other miscellaneous chemical products, including chemical feedstocks
Other industries	All other industrial manufacturing, including metal-based durables (fabricated metal products, machinery, computer and electronics products, transportation equipment and electrical equipment)
Non-manufacturing	
Agricultural products	Agricultural, forestry and fishing
Mining	Coal mining, oil and natural gas extraction
Construction	Construction of buildings (residential and commercial), heavy and civil engineering construction industrial construction, and speciality trade construction.

Also, according to the U.S. EIA report(2016), the global energy consumption for the industrial sector energy consumption is projected to increase by an average of 1.2% per year, from 222 quadrillion British thermal units (Btu) equivalent to 234 billion Giga joules (GJ) in 2012 to 309 quadrillion Btu equivalent to 326 billion GJ in 2040. an additional growth of 1.5 % is predicted for countries outside of the Organization for Economic Cooperation and Development (OECD), as compared to 0.5% per year in OECD countries. The non-OECD countries include countries in South America, the Middle the East and Asia, Africa and Eastern Europe and Scandinavian countries. According to the EIA (2016), the energy-intensive manufacturing industries namely: the food, pulp and paper, basic chemicals, refining, iron and steel, non-ferrous metals (i.e. aluminium) and non-metallic minerals (i.e. cement industry) account for about half of all energy use in the industrial sector. Likewise, these same main energy-intensive industries globally and in South Africa release the largest quantities of CO_2 emissions due to the massive scale fuel combustion and energy consumption that occurs during their manufacturing processes (U.S. EIA, 2016; (2015 National GHG inventory: DEA, 2014; 2019).

Presently in South Africa, there is an increase in demand for electricity and pressure on the power utility companies to increase their capacity to meet the demand of power load. Likewise, energy consumption and cost are increasing alarmingly. In addition, the escalating energy cost and the need to reduce energy demand is further reason to pursue improved energy efficiency in the manufacturing sectors of South Africa (Fawkes, 2005; Nersa, 2005). This study focuses on selected Small to Medium-sized Manufacturing SMMEs based on their total energy consumption a (combination of fossil fuel, electricity and thermal energy), and energy or heat loss during their manufacturing processes. According to the South African Department of Energy (DoE) 2016 and 2019 energy sector reports, the industrial sector currently accounts for 52% of energy demand in the country (Figure 1.3). This demand in the manufacturing subsector of the industrial sector which is mostly dominated by industrial SMMEs is due to a large amount of energy used in the processing units for heating, drying, separation, high and low-temperature processes, all of which typically accounts for 72% of total energy consumption in manufacturing industries, of which 31% of this is dominated by low-temperature processes in the energy-intensive manufacturing subsectors (U.K. DECC, 2014).

Currently, energy has become an expensive and scarce resource in South Africa, and the energy consumed by the manufacturing sector has contributed significantly to the county’s current energy crisis and continual rise in energy prices (Pollet et al., 2015). Given that energy resources are limited, and the demand for manufactured products continues to escalate, meeting the energy demand of manufacturing industries and mitigating its environmental and economic impact remains a challenge. Figure 1.1 shows the percent energy demand for each economic sector in South Africa.

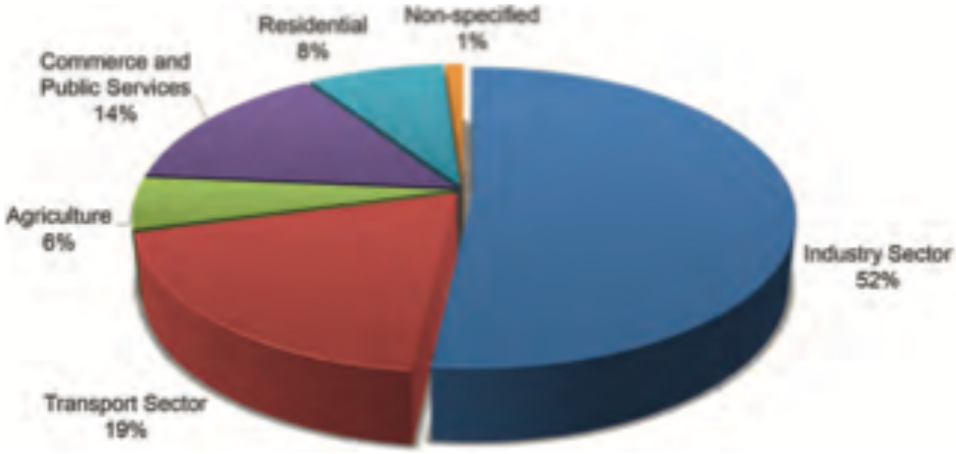

Figure 1.1: The South African energy demand by sector. (Source: DoE energy balance, 2016 in the South African energy sector report, 2019:23).

1.1. The main manufacturing industries in South Africa

According to 2019 GDP data released by Statistics South Africa**,** the top four manufacturing industries based on contribution to the GDP (see Figure 1.2) are the food, beverage and tobacco at 25.93%; followed by the petroleum products, chemicals, rubber and plastic at 21.48%; the metal products; and lastly is the wood, paper, publishing at print at 11.11%. However, the metal products are often manufactured in large-sized industries, so it is not considered as an industrial SMME; which is the main focus of this study.

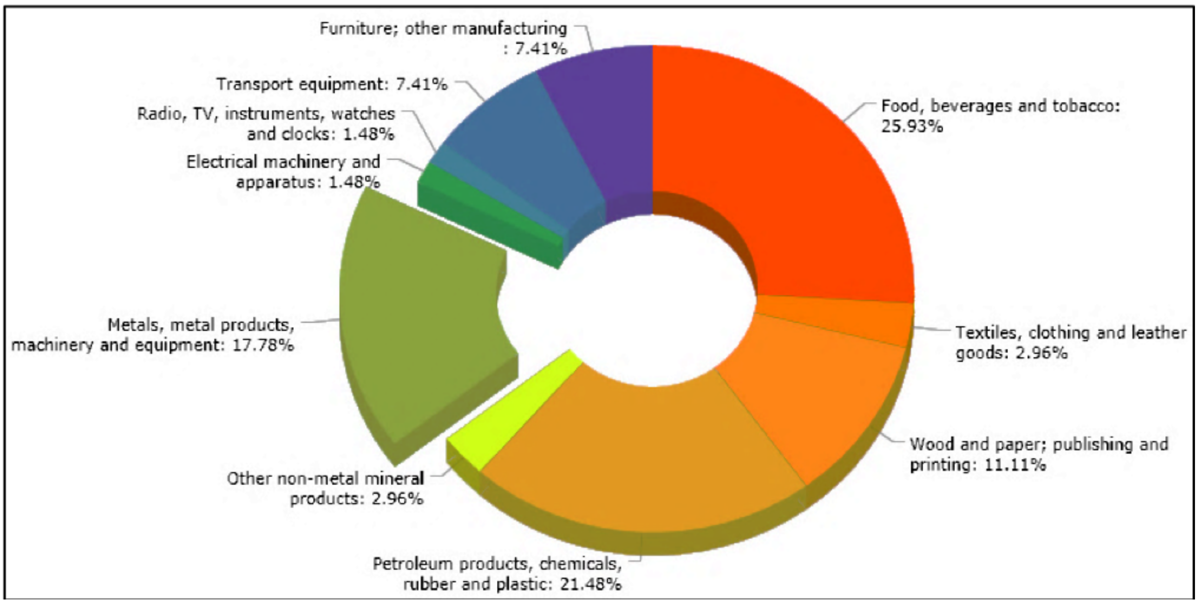

Figure 1.2: The main manufacturing subsector in South Africa (source: Statistics South Africa, 2020).

The growth rate for the year 2018- 2019 (seasonally adjusted) in the volume of production in the food and beverages sector shows a comparison of the overall growth in production volumes in the food production subsectors to total production in all other manufacturing sectors (see Figure 1.3). The milk and dairy production subsector showed by far, the highest year on year growth at 9.96% production volume in 2019, much higher than it was in January 2018. This was closely followed by the beverage manufacturing subsector at 5.58%. Whereas the meat, fish and fruits showed a decrease in production volume of -0.86% in January 2019 when compared to January 2018.

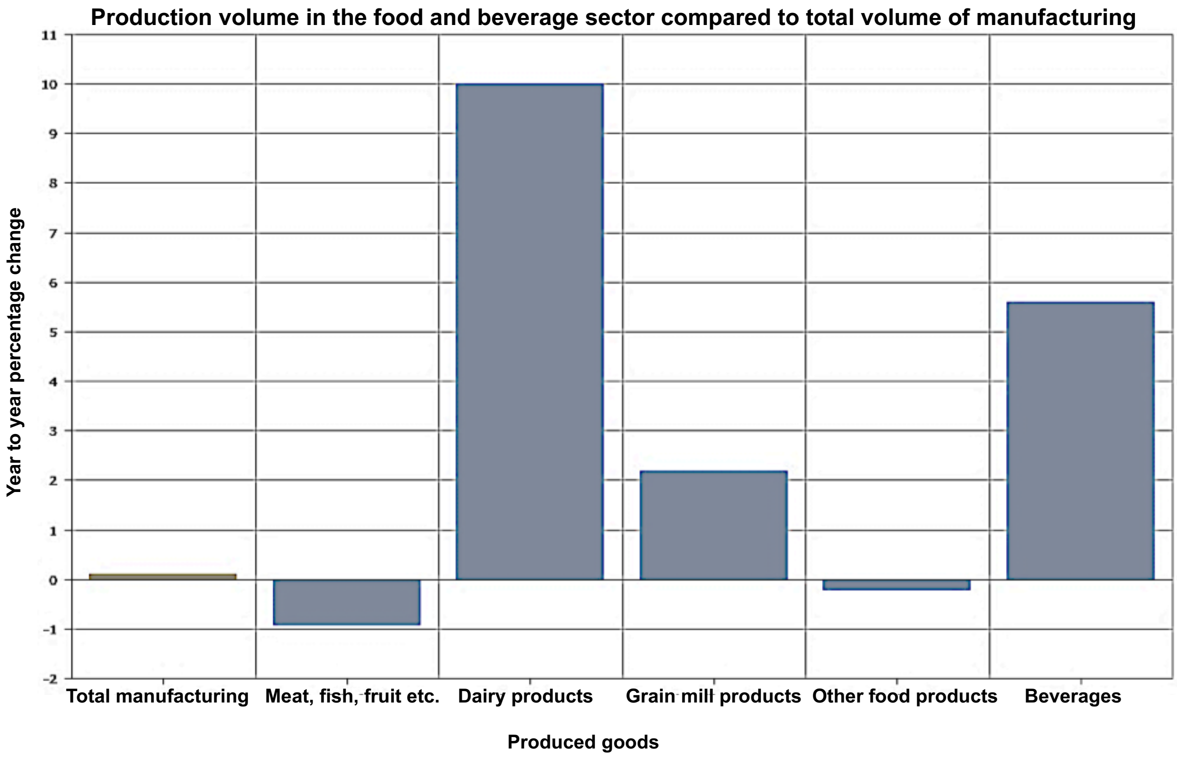

Figure 1.3: Comparison of the overall growth in production volumes in the food production subsectors to total production in all other manufacturing sectors (source: Statistics, South Africa, 2020).

1.2. Context of energy consumption in South African manufacturing sector

According to the South African energy sector report 2019 by the department of energy (DoE), for the 2016 energy balance shows the total energy consumed by the food and tobacco sector as 7,842 TJ with gas accounting for 51%, followed by electricity at 35%, and petroleum products at 14% (see Figure 1.4). The main energy source for the pulp and paper was 52% of electricity and 48% of gas (see Figure 1.5), and total energy consumption of 9,343 TJ is consumed by this manufacturing subsector; which excludes this subsector's own generated energy from black liquor and biomass. The basic chemical and petrochemical manufacturing industry consume 128,154 TJ of coal and 52,079 TJ of gas, which makes this subsector the second largest consumer of coal and gas after the iron and steel industry. The consumption of electricity by this manufacturing subsector accounts for 9.5% of the total energy consumed in the sector (see Figure 1.6).

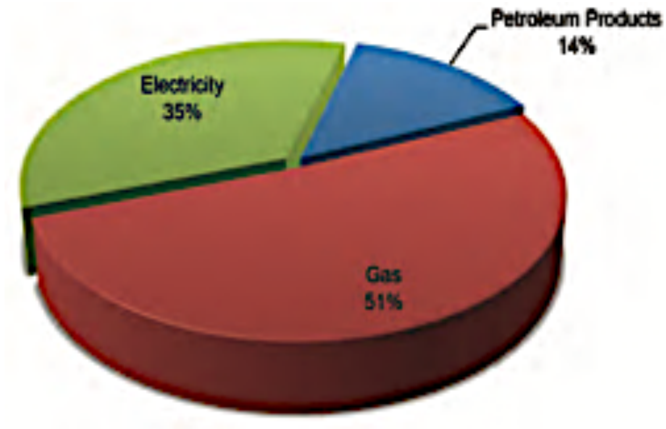

Figure 1.4: The energy demand of the food and tobacco manufacturing subsector for 2016 (Source: DoE energy balance, 2016, in the South African energy sector report, 2019:30).

Figure 1.5: The energy demand of the pulp and paper manufacturing subsector for 2016 (Source: DoE energy balance, 2016, in the South African energy sector report, 2019:31).

Figure 1.6: The energy demand of the basic chemical manufacturing subsector for 2016; note: the plastic and rubber manufacturing subsector is classified under chemical subsector (Source: DoE energy balance, 2016 in the South African energy sector report, 2019:27).

1.2.1. Context of waste heat and carbon emission in South African manufacturing sector

Furthermore, South African manufacturing industries release 34% of heat-related CO_2 emissions, due to the combustion of fossil fuels for energy during their manufacturing activities (Matekenya and Mehlwana, 2006). Heating processes and increase in manufacturing activities remains one of the main causes for large energy consumption in South Africa (Inglesi-Lotz and Blignault, 2011; Olanrewaju, 2018; Kwakwa and Adusah-Poku, 2019); with the most intensive processes identified to be conducted within the iron and steel non-ferrous metal, cement, ceramics, glassmaking, chemicals, refinery, paper and pulp; food and drinks manufacturing industries (DoE, 2009).

Furthermore, about 31% of operating units within these heat and energy-intensive manufacturing subsectors use energy for low-temperature processes and 22% is used for high-temperature processes (DECC, 2014). Since manufacturing activities are directly related to increased electricity consumption, energy intensity and carbon emissions, it becomes important to pursue improvements in energy efficiency in manufacturing industries and reduction in the subsector's energy consumption. This requires implementing measures that could promote energy efficiency, investigating avenues for waste heat recovery and reuse to reduce energy demand.

Given these DoE energy reports on the energy demand and carbon emissions by energy-intensive manufacturing subsectors, there is a need to implement energy efficiency and explore any potential opportunities for reducing energy consumption and waste heat recovery avenues from their processing units South Africa, waste heat recovery systems have not been put in place in the energy-intensive manufacturing sector, particularly the recapturing of flue gas which is a common waste-heat recovery technique, unlike in other developing countries, such as China, where the technology is in widespread use (Burger, 2018).

Few studies on the harnessing of waste heat in South Africa has been restricted to the potential thermodynamic analysis and investigations of waste heat recovery using Rankine cycle on exhausts of the engines of vehicles (Katamba, 2016) waste heat recovery from domestic and agricultural wastewater for production of bioethanol, bio-mass, combustion and biogas generation, and microbial fuel cells (Stafford et al., 2013).

In a recent attempt to reduce emissions from the manufacturing sector (and other sectors too), the Carbon Tax Act of South Africa came into effect from June 1st, 2019, with a first and second phase of implementation that compels minimal to major fines in carbon tax respectively, and according to section 12L of the Income Tax Act, a deduction of 95c/kWh for companies that are compliant. Thus, waste heat recovery is a powerful tool that may assist manufacturing facilities to meet their carbon emissions targets and bottom line as well as directly result in a reduction in climate change impact on the environment.

In this context, although the recovery of industrial waste heat is being used to a relatively large extent internationally (Brueckner et al., 2014; 2015; Broberg, 2015; Miró et al., 2015; 2016; 2018; Panayiotou et al., 2017), there is still some potential for its adoption and wide use in South Africa. The study seeks to increase awareness of the recovery of excess waste heat as a potential energy resource that could contribute to sustainable energy for the city of Johannesburg.

1.3. Background of the study

Gauteng Province contributes 40% to South Africa's manufacturing industry, making it the largest contributor (see Figure 1.7). The City of Johannesburg is the provincial capital of Gauteng (the wealthiest province) and characterised as the largest, most economically vibrant city, and a major contributor to the economy of both Gauteng Province and South Africa. The City’s key economic sectors are finance and business services, community services, manufacturing and trade. These sectors show a rapid economic growth rate than both the national and provincial levels (HSRC, 2015). The City of Johannesburg metropolitan municipality characterizes Johannesburg as a leading financial centre in the world, and South Africa’s economic and financial hub, which produces 16% of nation’s GDP and accounts for 40% of economic activity in Gauteng Province. The economic activities of Johannesburg were formerly centred on mining activities, but this is gradually declining due to depleting reserves of resources and service and fast being replaced by small to medium-sized manufacturing industries. In this regard, this research was conducted in Johannesburg.

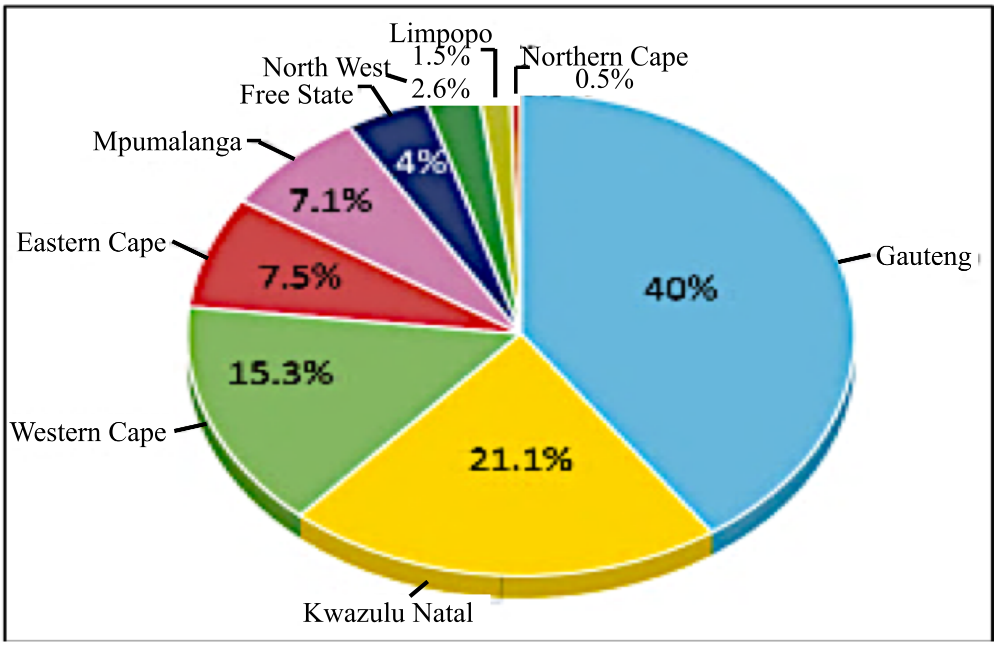

Figure 1.7: Provincial contribution to total manufacturing in South Africa for 2016 (source: Statistics South Africa).

1.4. Study rationale

The current energy crisis and rising energy prices that South Africa is facing as well as environmental degradation is associated with lack of energy security and carbon emissions. These issues motivate the need to improve energy efficiency in manufacturing industries. In this context, the motivation for investigation of the feasibility of waste heat recovery and how harnessing this heat could make a significant impact on manufacturing plant efficiency, particularly in Johannesburg are as follows:

- ***Possibility of improving energy efficiency in manufacturing industries***

High energy consumption poses a threat to the energy security of a nation, and it is especially crucial for manufacturing industries involved in large scale operations powered by industrial heating equipment to become more energy efficient in their production.

- ***To possibly reduce energy consumption***

The steam boiler remains the main energy consumer in manufacturing industries. Thus, it is important to reduce the fuel consumption used by steam boilers to produce steam or heat. The recovery of waste heat during operations, cold help to reduce operating/energy cost, carbon emissions and conserve resources. this study explores the possibilities of reduction in energy consumption.

- ***To possibly reduce operating costs***

Recovering a significant amount of waste heat released during processing and reusing it onsite as a source of energy in the same or other processes could help reduce energy-related costs and energy demand by the manufacturing site.

- ***To possibly decrease waste heat and emissions***

By harnessing waste heat, a significant amount of waste heat and associated hazardous emissions generated during operating processes can be reduced. On one hand, this measure is extremely important for mitigating environmental degradation, and on the other hand, promotes more efficient operations and reduces demand for additional heat source altogether.

In light of these facts, the study could contribute to the improvement of energy efficiency in SMMEs in Johannesburg, which form 97% of businesses and 35 5 of the Gross Domestic Product (GDP) in the country's economic growth (Dagut and Bernstein, 2008; Liedtke, 2019; Nieman and Nieuwenhuizen, 2009), as well as to achieve sustainable energy for the city and the SMMEs themselves.

1.5. Problem statement

Approximately 63% of the world's primary energy consumption is lost during combustion and heat transfer processes in manufacturing industries, which in turn is identified as waste heat (Cullen and Allwood, 2010). Despite continuous global recognition of the importance of improving energy efficiency in the manufacturing sectors, South African manufacturing plants are currently undergoing high energy usage resulting in high incurred cost and unrecovered waste heat at the detriment of the environment. The industrialized cities such as Johannesburg currently face air pollution (see Figure 1.9) due to coal-burning for electricity generation, combustion of fossil fuel and, to a large extent the release of waste heat as exhaust gases by manufacturing industries (Sustainable Energy Africa, 2009). The Public Health Association of South

Africa (PHASA) asserts that burning of fossil fuel energy is currently a major health hazard for South Africans and urges the South African government to tackle climate change through the reduction of air pollution and industrial waste heat. These situations and continuous reliance on fossil fuel reserves result in the depletion of natural reserves, environmental degradation due to excessive CO_2 emissions and threats to energy security in South Africa (ibid). This makes it important to explore ways to improve energy efficiency and seek alternative energy sources on a large scale through waste heat recovery in manufacturing industries.

Figure 1.8: Localized air pollution in South African cities caused by the burning of fossil fuel. A) massive air pollution from South African Petroleum refinery (SAPREF) plant, south Durban and B) Excessive air pollution from factory emissions (source: south Duran Community Environmental Alliance (SDCEA).

1.6. Study aims

For the purpose of contributing towards the goal of achieving sustainable energy for the City of Johannesburg, the study mainly focuses on the selected manufacturing industries within the Johannesburg area, Gauteng Province of South Africa. The main aims of this study are as follows:

- To investigate the main waste heat streams during manufacturing processes and the opportunities for recovery.
- To quantify the waste heat stream and the potential for onsite use as an energy source.
- To explore suitable waste heat recovery techniques and their applicability.

1.9. Research question

To meet the above-mentioned objectives, this study attempts to answer the following research question:
What possibilities exist for waste heat recovery in manufacturing industries in Johannesburg, and how can it contribute to the mitigation of GHG emission and related climate change due to ongoing global warming?

There is a further exploration for possible answers to the sub-questions such as:

- What potential exists for waste energy recovery in selected manufacturing industries in Johannesburg?
- What are the key points of energy loss and waste heat channels in manufacturing processes?
- What technically viable and practical ways are applicable for harnessing the identified waste heat?
- In what ways can waste heat recovery contribute towards the reduction of GHG emission for manufacturing industries?

1.10. Conceptual approach

The conceptual framework diagram seeks to establish the link between the recovery of waste heat from manufacturing processes and the possibility of mitigation of CO_2 emission (see Figure 1.10). Given the complex nature of manufacturing plants and the available dataset for investigating waste heat potential and recovery within these operating facilities, it is important to define a process for assessing the waste heat sources and eventually recommending compatible recovery techniques. As substantiated in chapter 4 and 5, manufacturing processes involving heating, cooling, evaporation and drying release waste heat coupled with CO_2 as exhaust gas at varying temperatures to the atmosphere. Besides being a potentially useful energy source, waste heat creates a “heat island effect” which raises the temperature of urban areas slightly higher than that of the rural area. This phenomenon causes the warmer cities to have higher energy demand for cooling and creates a vicious circle.

The quality and quantity of the released waste heat are driven by the temperature at which it is given off and the estimate of the waste heat stream respectively (Brueckner et al., 2014; 2015; Broberg, 2015; Miró et al., 2015; 2016; 2018; Panayiotou et al., 2017). In most cases, the waste heat source is of a low-temperature grade that requires an upgrade to a higher temperature for it to be usable at the sink. Therefore, to reduce energy consumption during manufacturing processes and mitigate CO_2 emission, it is important to investigate the waste heat sources and potential sinks. In addition, quantification of the waste heat potential, exergy and quality in terms of the temperature grade is required before an effective selection and recommendation of the most suitable recovery technique is conducted.

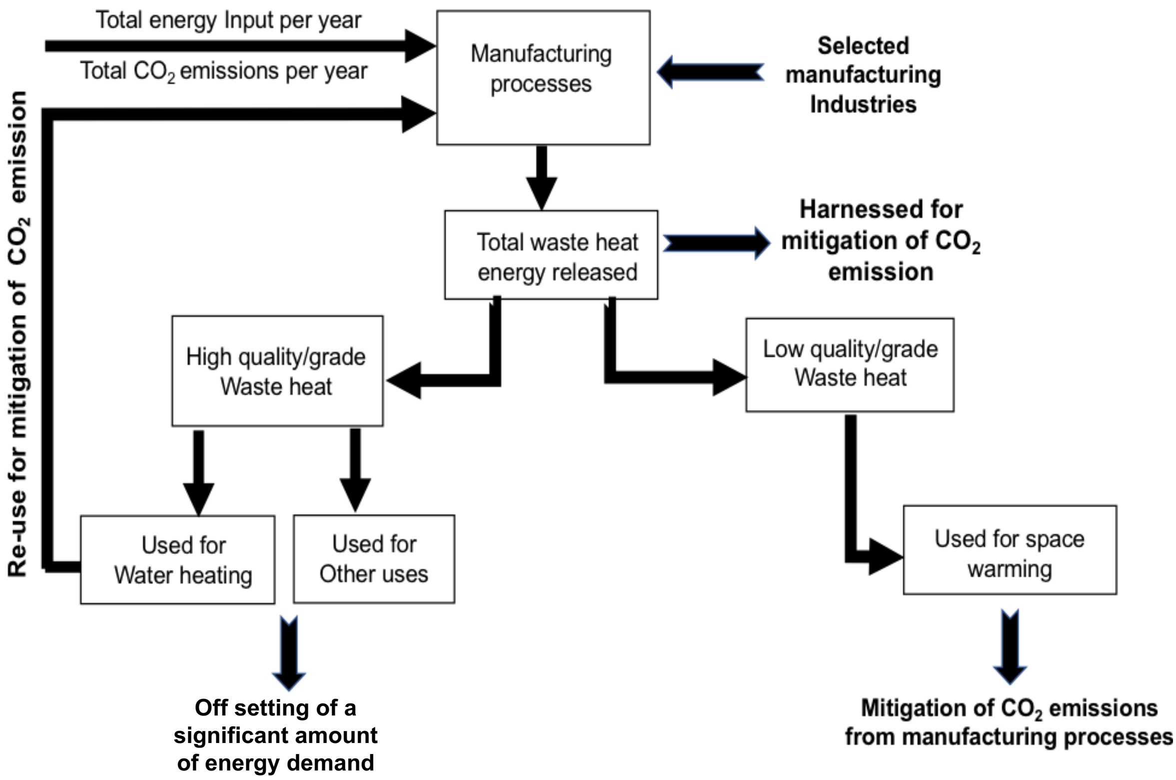

Figure 1.9: Conceptual framework of waste heat recovery in this study.

1.11. Working hypothesis

The study selected manufacturing industries because waste heat is believed to be released from most of their processes at temperatures that are potentially re-usable for onsite use. This assumption is based on the large consumption of energy, installation of a boiler system, drying and heating system which serve as the major energy-intensive manufacturing units

It is anticipated in this study that waste heat released during manufacturing processes has the potential to be reused for work. Particular focus is on the exhaust gases and streams that are emitted during manufacturing processes with consideration of opportunities for waste heat recovery as a means of energy source.

In addition, the hypothesis for this study is that the recovery of this waste heat will provide an attractive opportunity for a less costly and low carbon energy resource. Moreover, by reducing energy demand and related costs and associated environmental impact. This study also hypothesises that the competitiveness of the manufacturing sector could be improved. Although this study is restricted to manufacturing industries in Johannesburg, it hopes to serve as a platform for feasible studies in other manufacturing plants across South Africa to promote sustainable urban energy use and reduce carbon emissions scale-up contribution towards climate change mitigation.

1.12. Definition of key concepts

This section presents a brief overview of the key concepts applied in this study as follows:

Energy efficiency: Energy efficiency involves using less energy input to achieve the same work (Patterson, 1996). Bosseboeuf et al. (1997) define energy efficiency as using the same or less energy to yield more output. The Intergovernmental Panel on Climate Change (IPCC, 2015) reports that energy efficiency measures across all economic sectors prove to be an effective and immediate environmentally friendly intervention for achieving a significant reduction in energy consumption, costs and carbon emissions. The potential of using recovered waste heat from manufacturing plants are considered in this study, and the contributions of the findings to reduced energy consumption and carbon emission towards climate change mitigation are explored.

Energy systems: Energy system are units in the manufacturing plant that are primarily designed to supply energy to end-users. Manufacturing energy systems include process heating, combustion, compressed air, combined heat and power, motors, heat pumps and fans. These units account for approximately 80% of total energy consumption in the manufacturing plant. An average of 30% to 40% of that energy is lost during production activities (U.S. DoE, 2004; Schobert, 2013). Waste heat could reduce and recover this lost energy, and in turn lower their productions costs as well as energy demand. This entire measure facilitates the mitigation of the threat of global warming by reducing the GHG emission by these manufacturing plants.

Waste heat recovery*:* The recovery of waste heat involves capturing and reusing the heat lost or released as waste during industrial manufacturing processes (Panayiotou et al., 2017). This process is possible since during the manufacturing processes, as much as 50% of consumed energy is ultimately lost as waste heat from the energy stream system in the form of hot air and vapour through exhaust pipes, as well as through the conduction, convection, and radiation of heat from hot surfaces of equipment and heated product streams (Miró et al., 2016). The scope of this study focusses on the hot air and vapour released from exhaust pipes since these constitute the bulk of waste heat in manufacturing activities (*ibid).*

Exergy and anergy: Based on thermodynamic analysis, energy is described as the sum of exergy and anergy: energy = exergy + anergy;

Where exergy of the system is the maximum potential energy available for potential technical work during a manufacturing process, whereas anergy is the destroyed exergy during manufacturing process. The useful energy content which is exergy is quantified for the case study manufacturing plants in the study.

***Carnot's potential* (η_C):** Carnot's potential is the estimation of the exergy content of waste heat. Thus, application of the Carnot factor (η_C) to the quantity of waste heat and their corresponding temperatures ($Thigh$) gives the respective potential technical work also known as and further indicated in this study as Carnot's potential (η_{max} or η_C).

Where $\eta_{max} = \eta_C = 1 - \frac{T\ low}{T\ high}$

Load factor ($L_{F,\ i}$): *Load factor* is defined as the ratio of the actual electrical *load consumed* in kW over a given period to the maximum demand or peak *load* occurring in that period. The load factor values used in this study are derived from the Eskom tariff schedule of standard prices SC0207 (mega flex general tariff - 2018/19 page 24).

Mass flow rate (ṁ): *Mass flow* rate is the *mass* of a medium or substance in kilogram that passes per unit of time in seconds. The SI unit is kilogram per second (kg/s). The mass flow rates for each waste heat source and sink streams in this study are used to quantify the waste heat stream in this study's case study.

Specific heat capacity (Cp): The specific heat capacity of a substance is the amount of heat energy required to raise the temperature of 1 gram of the substance by 1°C. Specific heat thus describes the relationship between the applied heat energy and the temperature change. The specific heat capacity of steam, exhaust gas and flue gas from the case study manufacturing plants in this study are considered in this study.

Technical work: Technical work is classified as any processing activity carried out in the manufacturing plant such as heating, washing, mixing etc. the available waste heat is quantified in this study and the feasibility of using it for any onsite potential technical work is evaluated.

Waste heat potential (WH_T): Waste heat potential is the total technical waste heat recovery potential of a waste heat stream. This represents the energy content (exergy) in the waste heat stream that has the potential to be used for work. This concept which forms the core of this study quantifies the waste heat released from three case study manufacturing plants in Johannesburg.

1.13. Study delimitation

The delimitations of this research are highlighted as follows:

- This research is limited to selected small to medium-sized manufacturing industries, hence our findings are outside of the processes conducted in larger sized industries.
- The dataset is subject to a disclosure made by the individual manufacturing industries and may be subject to some elements of verification. However, the primary energy source and total energy expenditure are reported at the company level while the energy consumption values are evaluated for individual process units involving the use of steam boilers, dryers, refrigerators etc. The CO_2

emission used in the study is attributed to direct (within the plant) emission during manufacturing operations.

- Given that the study is focussed on the waste heat from exhaust air and gases, investigation of waste heat from ventilation and lighting were neglected, as they only provide a small quantity of waste heat in the case study manufacturing plants.
- In addition, due to time and technical constraints, the researcher did not focus on an exhaustive compilation of the waste heat recovery techniques but rather focused on the immediate onsite need and use of recovered waste heat.
- Lastly, the sub-findings of CO_2 emission reduction is presented, however, given that the main focus of the study was to investigate the potential for waste heat recovery, a brief overview of scaling-up or modelling of the CO_2 emission reduction is presented.

1.14. Structure of the research report

This study consists of six chapters followed by the reference list and the appendices at the end of the research report.

Chapter One is the introductory chapter that presents an overview of the background on the manufacturing industries in South Africa and the context of energy consumption in this sector. This chapter also highlighted the study rationale, problem statement, study aims, working hypothesis, the definition of key concepts and any delimitation to this study.

Chapter Two presents a literature review of the existing studies and key theories on the scope of the study. These include an appraisal of the main theoretical context, different methodological approaches for the identification and quantification of waste heat potentials and recovery techniques. The choice of previous research reviewed in this chapter was guided first by the research sub-questions, and secondly, by the theoretical context of waste heat recovery with regards to the processing units in selected manufacturing industries in Johannesburg. Some of the key literature reviewed includes McKenna (2009) that classified waste heat based on their temperature range; McKenna and Norman (2010) and Miró et al. (2018) used an existing bottom-up approach based on the carbon dioxide emission of case study industrial sites to quantifying the waste heat from manufacturing industries; Panayiotou et al. (2017) outlines the opportunities for waste heat recovery in the European Union by quantifying the energy consumption, and identifying the associated waste heat stream and temperature levels.

Chapter Three presents the research method used in this study and focused on the steps taken within a mixed-method study approach. The nature of the primary and secondary data collected includes semi-structured interviews, site visit and energy assessment dataset respectively. Also presented in this chapter are the various tools used for data collection; the approach used for data analyses and the findings derived from the study; as well as the ethical considerations observed.

Chapter Four and five are the substantive chapters of the study, given that they provide answers to the research sub-questions guided by the approach adopted in the manufacturing industries in the European Union by Panayiotou et al. (2017) and Miró et al. (2018). Chapter four provides answers to the first sub-question by quantifying and presenting findings on the potential waste heat available from individual processing units in the selected manufacturing industries in Johannesburg. Lastly, this chapter concludes with a synthesis of waste heat recovery potential with available waste heat recovery techniques.

Chapter Five, on the other hand, substantiates on the second sub-questions focusing on estimating waste heat based on carbon dioxide emission. This chapter further substantiates on the extent to which waste heat recovery in manufacturing industries can contribute to the mitigation of CO_2 emission.

Chapter Six presents a consolidation of the key findings presented in the preceding chapter Four and Five, followed by sections covering the discussion, conclusion and recommendation for future research. This final chapter integrates the research findings and answers to the four sub-questions presented in the substantive chapters. Recommendations for further studies concerning investigating the technical and economic feasibility for assessment of the waste heat source and potential sink in industries are proposed.

Lastly, a detailed reference list and appendices of additional datasets that were not incorporated in the main chapters of the research report are presented.

CHAPTER TWO: LITERATURE REVIEW

2.0. Introduction

South Africa's dependence on coal as its major source (up to 95%) of electricity (Euston-Brown and Cilliers, 2015) coupled with rising concerns about the associated environmental degradation, as well as South Africa's rank as the 12th largest carbon emitter in the world (UNEP, 2011), has stimulated interests in energy efficiency initiatives, particularly in the manufacturing and industrial sectors where energy consumption and carbon emissions remain high (DoE, 2016). Also, based on the increasing energy demand and costs in South Africa, and the need to mitigate climate change due to CO_2 emissions, it has become crucial that waste heat from manufacturing industries are systematically explored and investigated. This study is centred on the theoretical framework of energy efficiency for sustainable cities, with particular focus on improving industrial energy efficiency through the recovery of waste heat for the reduction of energy consumption and mitigation of CO_2 emissions from manufacturing industries.

This literature appraisal first reviews studies on the energy-intensive manufacturing processes and its associated energy consumption and CO_2 emissions. The review then focusses on the various studies conducted on measuring, quantifying and harnessing waste heat within the manufacturing sector. The literature review in this field is divided into two main aspects, namely: (1) the manufacturing processing units and (2) the waste heat potential.

2.1. Overview of energy systems in manufacturing industries

Across the world, small to medium-sized manufacturing enterprises (SMME) and industries are fast-growing and projected to grow even further as 'countries continue to reorient their economies towards services' (IEA, 2015:15). Given the nature of the scale of production in manufacturing industries collectively, it is expected that the sector would be energy-intensive (IEA, 2015). The rise in global energy demand coupled with industrial and population growth remains relentless, as it is predicted to rise by 50% by 2030 (IEA, 2013; Yang, 2016).

According to the IEA, over 13% of the world's total energy demand is consumed by industrial SMMEs. Furthermore, the International Energy Outlook 2019 confirms the manufacturing subsector which is dominated by industrial SMMEs as the largest consumer of energy, particularly in Africa and South Asia that shows a significant rise in energy consumption. The IEA further predicts an average annual growth rate of 1.4% and 2.6% for Africa and South Asia's total industrial energy consumption for electricity demand respectively (see Figure 2.1). Mean, while the sub-Saharan Africa region is projected to experiences an average annual economic growth rate of 3.6%. However, despite having 14.1% of the world's population, industries in Africa consumed only 4.2% of the world's total industrial energy use in 2007 (IEA, 2010).

Concerning the link between changes in energy consumption and economic growth in African countries, Eggoh et al. (2013) draw a connection that energy consumption decreases with decreasing economic growth and vice versa. Implications of this study are that it is important to consider economic growth in the projection of changes in global energy consumption.

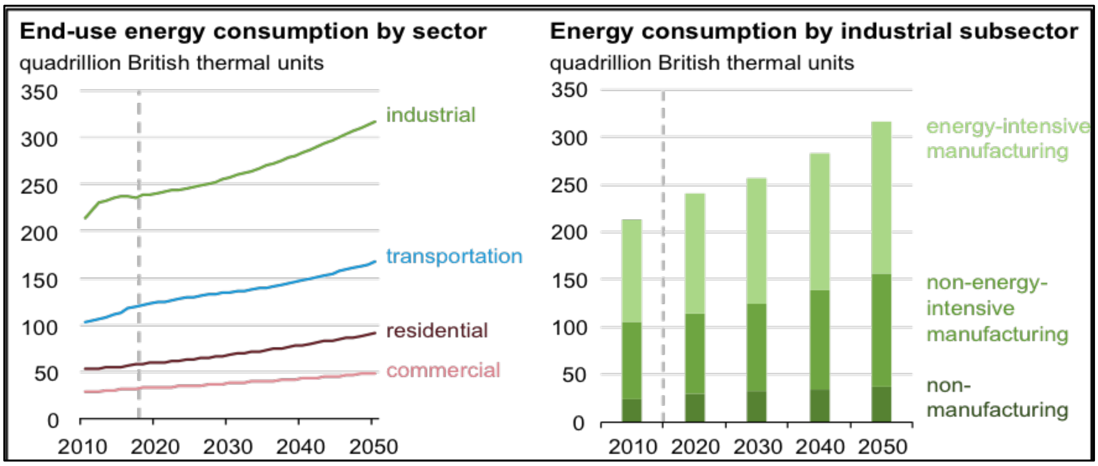

Figure 2.1: (a) End-use energy consumption by sector and (b) Energy consumption by the manufacturing subsector (adapted from International Energy Outlook, 2019:29-37).

Based on the 2016 energy balance by the South African DoE, the industrial sector (which includes manufacturing processes) remains the largest single energy consumer and accounts for 52% of the country's total energy consumption (see Figure 1.1). Suggestions of ways to reduce energy consumption in the South African manufacturing sector include

a study by Blignaut and De Wet (2001) which proposes that focus should be on implementing technological changes in the energy systems and improved energy efficiency in the operating unit of facilities, rather than imposing “increased electricity prices, nor imposed taxes, subsidies or legislation”.
Söderström (1996) classifies energy systems in manufacturing industries into smaller energy-using portions based on their purposes in the processing unit, which could be production-related (e.g. casting, welding, forming, mixing and painting), or production-supporting processes (e.g. heating, lighting, cooling, conveyor systems, pumping) (*ibid*). Rosenqvist et al. (2012) supports the grouping of energy systems into processing unit and affirms that it provides a visual illustration of the production-related and supported process and eases the task of determining areas where energy efficiency measures could be implemented.

To further unpack the energy systems of manufacturing industries, Law et al. (2013) classified processing units into two, namely: generic operating units which consists of air compressors and steam boilers; and sector-specific operating units which conducts specialized processes such as cooking in the oven or furnace, pasteurization, drying, evaporation, distillation, cooling or refrigeration, washing and sterilisation (see Figure 2.2.). These processes mainly use fossil fuel to produce steam for end-use in low-temperature process heating (such as cooking food in the oven and frying); cooling or refrigerating; combined heat (thermal energy and electricity) for use in electric motors, compressors, heat pumps and fans (Reay and Morrell, 2007; Law et al., 2013). Given that the demand for manufactured products is unlikely to diminish in South Africa, and that above-listed systems which account for a large portion of the total energy use in the manufacturing sector are dominated by low-temperature processes (see Figure 2.2), a significant amount of low-temperature waste heat is envisaged for harnessing.

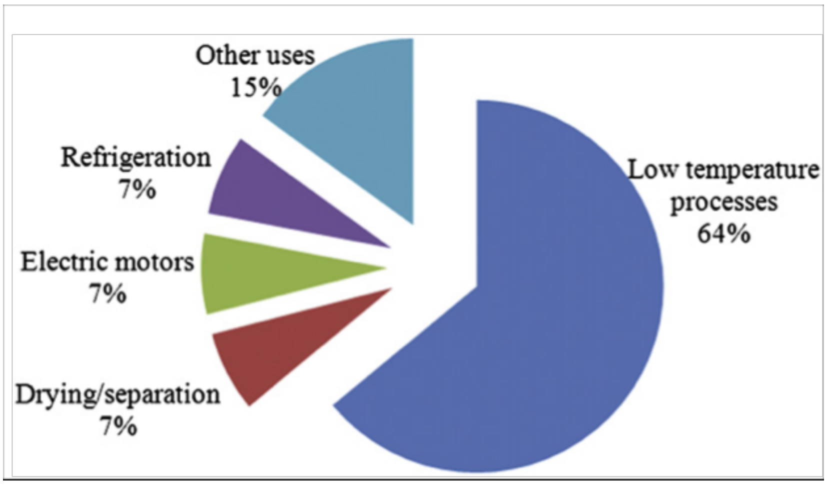

Figure 2.2: Breakdown of energy systems/use in the manufacturing sector. Note: other uses include energy for lighting, space heating, and instrumentation purposes (adapted from Law et al., 2013:189).

2.2. Overview of energy loss from manufacturing processes

Pehnt et al., 2011 defines waste heat as a stream from the operation process of equipment that results in energy losses, either through the surfaces of the equipment or through exhausts released to the atmosphere; both of which are potential sources for waste heat recovery. According to Cullen and Allwood (2010), an average of 30 - 40% of the total input energy is lost during manufacturing processes (Schobert, 2013), where the inevitable energy loss adds up to the embodied energy necessary for the manufacturing processes and product lifecycle, resulting in increased production costs and a reduced profit margin for manufacturing industries (U.S. DoE, 2004).

Despite the complex nature of manufacturing processes, the energy-intensive manufacturing industries (such as chemicals, pulp and paper, petroleum refining, agro-processing, food and drink processing) have a homogenous processing unit such as heating, refrigerating, drying, and evaporation operations (NAM, 2005) that releases substantial waste heat as bulk energy losses during manufacturing processes (see Figure 2.3).

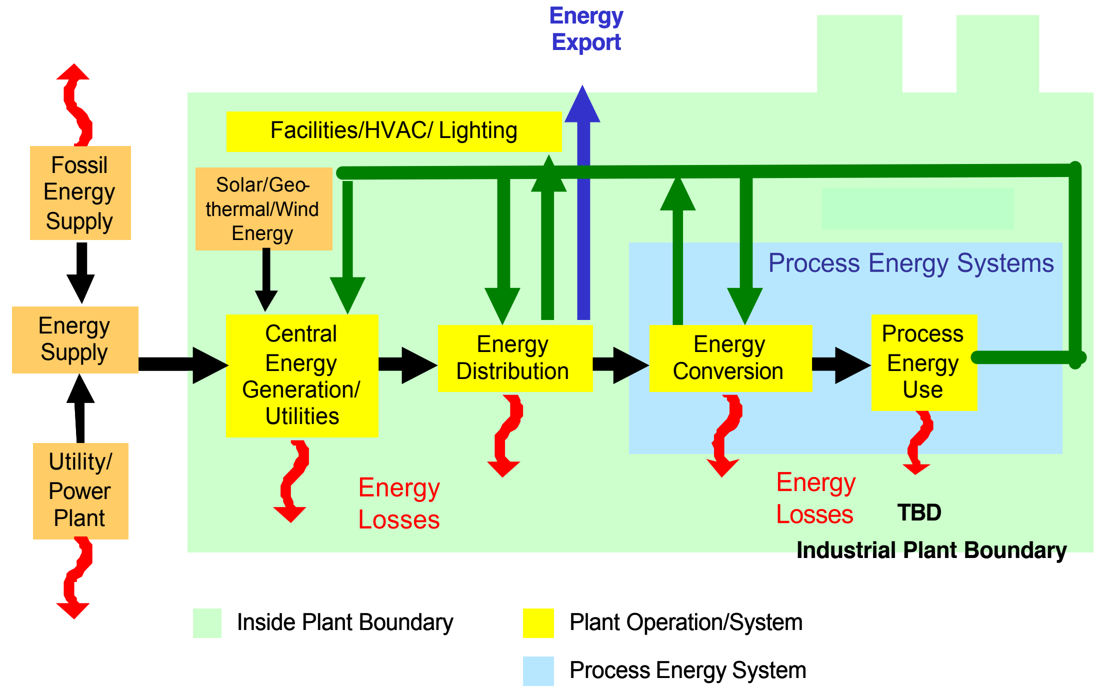

Figure 2.3: Schematic illustration of an energy footprint identifying avenues of energy loss (red wiggly arrows) both inside and outside the manufacturing site (adapted from U.S. DoE, 2004:4).

According to the South African National Cleaner Production Centre (NCPC-SA), some of the energy losses (Table 2.1) are unavoidable, but the majority of incidents of energy loss presents opportunities for harnessing (reduction and re-use of waste heat). This review of the energy loss at the manufacturing process level reveals a research gap with regards to identifying and quantifying waste heat potential in manufacturing industries in South Africa.

Table 2.1: Percent energy loss for manufacturing equipment. Energy losses were determined by applying equipment loss factors to the energy used in selected functional categories: the five major energy systems.

Energy System	Energy Loss Percent*
Steam systems	Boilers – 20% Steam pipes – 20% Heat exchangers – 15%
Power generation	Heat + power – 24 % (4500 KWh) Power supply – 45% (6200 KWh)
Energy distribution	Electricity and fossil fuel distribution pipes – 3%
Energy conversion	Process heaters – 15% Cooling system – 10% Onsite transport systems – 50% Electrolyte cells – 15%
Motor system	Pumps – 40% Fans – 40% Compressed air – 80% Refrigeration – 5% Materials processing – 90%

Footnote: *The loss factors listed were obtained from the energy assessment of equipment conducted and reported by the National Cleaner Production Centre (NCPC-SA).

2.3. Energy efficiency in manufacturing industries

Szargut (1994) affirms that energy efficiency measures in manufacturing industries are strongly affected by three main factors, namely: 1) the vulnerability context; 2) the policies and regulatory standards in place and 3) how the industrial system is structured. The 'vulnerability context' highlights the main factors influencing high energy consumption in the manufacturing industry sector, and involves seven main factors (*ibid:74-76*):

- The thermodynamic imperfection of production processes resulting in losses of energy quality expressed as energy losses and higher consumption of primary energy

- Inadequate use of waste energy by simply allowing it to be discharged to the environment.
- Lack of efficient production operations and manufacturing facilities.
- Excessive use of raw materials during the production process resulting in immediate and indirect energy use.
- Inadequate use of recycled materials as a renewable source of material and energy.
- Incorrect industrial structure leading to excessive production of energy-consuming goods.

Nevertheless, improvement in achieving energy-efficient manufacturing can be attained by considering the total energy inputs of manufacturing industries in relation to their output energy. In this context, according to Rosenqvist et al. (2012), initial efforts of manufacturing industries towards becoming energy efficient begins with an energy audit of the energy input and output, involving measuring or quantifying energy use within the operating plant, followed by recommendations on the measures for improving energy efficiency.

The major approaches adopted to achieve energy efficiency in manufacturing industries has been centred on the reduction of energy consumption and the use of alternative or renewable energy sources. However, Turner (1999) refutes the adoption of alternative or renewable energy source and claims that the development and investment cost in renewable energy technologies has been somewhat slow. Implementation of the second option involving a reduction in energy consumption in manufacturing industries could be pursued through several measures, namely:

1. Through the reduction of manufacturing activities (Sorrell, 2015);
2. Through the implementation of energy management strategies such as the use of energy-efficient equipment (Seow and Rahimifard, 2011); and
3. Lastly, through the harnessing of waste heat (Vallack et al., 2011).

Whilst the first two strategies could be regarded as proactive measures that allow manufacturing industries to earmark short and long-term achievable goals (Yang, 2016), the last strategy can be considered as a reactive approach to the unavoidable loss of heat that occurs during manufacturing processes. In addition, the reduction of manufacturing activities is counterproductive as it directly impacts profitability which is the main goal of the business enterprise. Whereas improvement in energy efficiency through the implementation of energy management has a had limited impact (Thollander et al., 2007), due to its requirement of a long waiting interval (Sandberg and Söderström, 2003), and extra efforts and high incurred cost (Doty and Turner, 2012).

Given that the first two methods have been widely explored and deemed to yield limited success, research into waste heat recovery is currently being more recognised as a strategy towards improving industrial energy efficiency (Antizar-Ladislao et al., 2010). Since the release of waste heat during manufacturing processes through several channels into the atmosphere, it becomes crucial to investigate the temperatures of this waste heat and its potential to be reused through recovery techniques as an alternative energy or heat source (IEA, 2014a). In this context, waste heat recovery involves capturing released heat and either using it directly, or upgrading it to a more useful temperature, and/or converting it to onsite energy use.

2.4. Overview of waste heat recovery

Waste heat is defined as the unused heat lost to the environment by a piece of equipment or any process that uses energy. According to Law et al., 2013, the recovery of waste heat can be regarded as a green, carbon-free source of energy essentially generated from a waste product, hence the replacement of fossil fuels use with harnessed waste heat could yield a significant reduction in greenhouse gas emissions and energy cost.

Brückner et al. (2015) affirm waste energy recovery in manufacturing industries as a more economically viable energy efficiency measure for energy-use and cost reduction in processing systems than the installation of renewable energy technologies and other mechanisms, based on the accessibility and availability of the waste heat. In support, Yang (2016) confirms that waste heat recovery requires low-level technology and involves relatively short payback times, making the approach more preferable for most industries.

Concerning harnessing of waste heat, Suryavanshi, and Pitale (2017) emphasizes the need to determine key parameters such as the waste heat stream quantity, temperature, and composition before a waste energy stream can be estimated or its usefulness quantified.

Further elaboration by Feidt et al. (2020) reveals that adoption of conventional techniques in waste heat recovery depends on important characteristics of the waste heat stream, such as the temperature, the composition and the available heat transfer area.

2.5. Approaches for estimating waste heat potentials in manufacturing industries

According to McKenna and Norman (2010); Hammond and Norman (2014); and Miró et al. (2018), the theoretical background for the approaches used for estimating waste heat potential and their areas of applicability to this study is divided into three folds, namely:

1. The identification of energy loss during manufacturing process conducted via an energy flow analysis to show where most energy losses occur in manufacturing processes.
2. The classification of waste heat temperature

I. Analysis of the waste heat and Carnot's potential during in-plant operation under thermodynamic conditions; and
II. The analysis of the potential for recovery of waste heat based on exhaust gases and carbon emission

These analyses are to a large extent quantitative without including any experimental considerations. Qualitative studies have mostly focused on technologies for harvesting this waste heat, which can be costly with long payback time. Simeone et al. (2016) present a decision support tool which computes and matches waste heat source(s) and sink(s), by considering the exergy balance and temporal availability. This study also evaluates the economic and environmental benefits of currently available heat exchanger technologies and proposes a streamlined and optimised heat recovery strategy that promises significant improvement in plant energy efficiency as well as a reduced payback time for heat recovery initiatives.

2.5.1. Quantitative analysis of energy losses

Analysis of energy loss from manufacturing processes involves identifying the waste heat source and quantifying the waste heat contained in the stream by calculating the energy content of the waste heat stream using the equation described below:

$Q = \dot{m} \times \rho \times CP \times \Delta T$ equation (1)

The quantity of the waste heat stream Q (W) is calculated as a function of the waste heat stream; the mass flow rate ($\dot{m}$ in kg/h); the density (ρ) of the flue gas (kg/m^3), Cp is the specific heat of the substance (J/Kg.ºC) and the heat source to sink temperatures expressed as ΔT (Hussam et al., 2018). This calculated quantity of waste heat is defined by the temperature (T_{in} - T_{out}) of the waste heat in association with the applicability of recovery technologies.

2.5.2. Classification of waste heat temperature

According to U.S. (DoE, 2008), waste heat recovery technique depends on the temperature grade, medium, chemical composition of the waste exhaust stream, as well as the nature of the sink (the end-use for the recovered waste heat). Although low-temperature heat is considered as having less thermal and economic value compared to high-temperature, it is often pervasively available in abundant quantities (*ibid*). To further emphasize the usefulness of low-temperature waste heat stream, comparison of the total work potential of waste heat from different sources by the U.S. Department of Energy showed that the large magnitude of low-temperature waste heat stream is usable and hence should not be left unrecovered (see table 2.2).

However, to classify waste heat streams based on temperature grade, McKenna (2009) and McKenna and Norman (2010) developed a classification scheme which involves measuring the waste heat from the source and qualifying it based on temperature grades highlighted as follows:

- Low Temperatures (LT): < 100^{o}C
- Medium Temperatures (MT): 100–299^{o}C
- High Temperatures (HT): ≥ 300^{o}C

The above-listed classification of waste heat based on temperature grades proposed by McKenna (2009) and McKenna and Norman (2010), appears more realistic than that of the US DoE (2008), and is thus adopted in this study.

Table 2.2: Classification of waste heat temperature grade and sources and associated recovery opportunities

Temp. grade (°C)	Typical source	Temperature (°C)	Advantages	Disadvantages	Typical recovery techniques
High >650	Refining furnaces Melting furnaces Fume incinerators Coke ovens	820 – 1650 1300 - 1540 650 - 1430 650 - 1000	Available high-quality energy for a wide range of uses with differing temp. requirements	Increased thermal stresses and corrosion on heat exchanger due to high temp. waste heat. Highly efficient for power generation	For preheating combustion air For steam generation For preheating furnace load For the transfer to low-medium temperature processes
Medium 230 – 650	Steam boiler exhausts Gas turbine exhaust Heat treating furnace Drying/baking ovens Cement kilns	230 - 480 70 - 540 430 - 650 230 - 590 450 – 620	High compatible with heat exchanger material Very practical for heat generation	Suitable for transfer to low-temperature processes	For preheating combustion air For preheating furnace load For power/steam generation For preheating feedwater Suitable for power generation via organic Rankine cycle
Low < 230	Air compressors Process steam condensate Furnace doors Air conditioning & refrigerating condensers Drying/baking/curing ovens Hot processed liquids and solids	30 - 50 50 - 90 30 - 50 30 - 40 90 – 230 30 - 230	Large quantities of waste heat stream contained in numerous exhausts	Limited end uses Low efficiency for power generation Mostly contains acidic condensates that corrode heat exchanger materials	For space heating For preheating domestic water Temperature upgrade via a heat pump Due to large waste heat stream, useful for power generation via organic Rankine cycle

Footnote: Comparison of waste heat temperature grades is based on available heat exchange technologies suitable to applicable temperature ranges, waste heat sources and sink (adapted from U.S. DoE, 2008:8).

2.5.3. Analysis of waste heat and Carnot's Potential during in-plant operation

Analysis of the waste heat and Carnot's Potential involves quantifying the work potential of the waste heat stream. This analysis is based on Carnot efficiency, which is the measurement of maximum energy recoverable from the waste heat stream. Quantification of the work potential allows for effective comparison of waste heat sources with different exhaust temperatures. This method is based on the theory of Thermodynamic analysis, which describes energy as (Jaynes, 1988):

energy = exergy + anergy; equation (2)

Where the exergy of a system is the maximum energy available for useful technical work during a process that aids a system into equilibrium; and anergy is the destroyed exergy.

The exergy content of waste heat can be calculated by Carnot's theorem, which specifies that a heat engine's maximum efficiency is dependent on its hot and cold heat reservoirs (Panayiotou et al., 2017). Thus, application of the Carnot factor (η_C) to the quantity of waste heat and their corresponding temperatures ($Thigh$) gives the respective technical work potential also known as and further indicated as Carnot's potential (η_{max} or η_C).

where $\eta_{max} = \eta_C = 1 - \frac{T\ low}{T\ high}$ equation (3)

The next step includes calculation of the waste heat potential and Carnot's potential as the percentage of the reported total energy consumption of the manufacturing site and waste heat stream temperature range respectively. According to Panayiotou et al., 2017, the purpose of this step is to use the Carnot's Potential to determine whether the calculated waste heat is reusable for technical work, as it is assumed that Carnot's Potential increases with a temperature range.

2.5.4. Analysis of waste heat potential based on carbon dioxide emission

The analysis of waste heat potential based on the carbon dioxide emission of a case manufacturing site is an existing bottom-up approach that involves quantifying the site's carbon dioxide emission per kilogram of production without considering other greenhouse gas emissions such as methane, nitrogen oxides, sulphur dioxide or dust.

Typically, there are two types of emissions in manufacturing processes, namely: emission relating to chemical reactions and emission due to fuel combustion (Miró et al., 2018). For instance, in manufacturing, the emission of CO_2 is not only due to combustion but also as a result of decomposition of non-metallic mineral products at high temperature (*ibid*). Hence, to obtain accuracy in this analysis, certain parameters such as the load factor and combustion emission fraction specific to the manufacturing subsector are considered.
This approach was used by McKenna and Norman (2010); Hammond and Norman (2014); and Miró et al. (2018) to quantify waste heat and make a recommendation of options for onsite and offsite use. The technical waste heat potential (WH_T) at a case manufacturing plants is calculated using equation 4 (*ibid:5*):

$$WH_T = \frac{RF\ ..F.Ci}{KCi\ .} \qquad \text{Equation (4)}$$

Where:

WH_T is the total technical waste heat recovery potential (PJ);

R_F is the heat's recovery fraction;

C_T is the total carbon dioxide emissions of the manufacturing plant (tCO_2);

$F_{C,i}$ is the subsector's combustion emission fraction i;

$\eta_{C,i}$ is the subsector's efficiency conversion from fuel to heat determined by measuring how well an appliance turns fuel into useful heat

K_{Ci} is the subsector's overall emissions factor n (t CO_2 equivalent /kWh) and

$L_{F,i}$ is the subsector's load or power factor i; which is the ratio of the actual load power in kW to the apparent load power in kVA drawn by an electrical load.

With regards to the above-listed subsector-specific parameters required in equation 4, the heat recovery fractions (R_F) ranges are based on the assumption that some amount of waste heat in any exhaust stream remains unrecoverable, however, it is typical for about half of the heat in an exhaust stream to be technically recoverable (Miró et al., 2018). The surface temperature of the equipment is outside of the scope of this study and disregarded in the calculations given that it is not inclusive in the waste heat stream released from the exhaust pipes of manufacturing plants.

The fuel to heat (η_C) efficiency conversion is indicative of the assumption that not all of the primary energy used by the subsector is converted to heat. Lastly, the load factor (L_F) signifies the annual working time expressed as the average capacity utilized.

Also, the sum of the manufacturing subsector's "emissions (C_T), the combustion emission fraction (F_C) and the overall emission factor (K_{Tn})" is equal to the total fuel consumption for a case manufacturing site (Miró et al. 2018), expressed below as:

Total fuel = $C_T + F_{C,I} + K_{T,n}$ equation 5

Equations 1 – 5 stated above are applied to the factory-level parameters and datasets obtained in this study.

2.6. Appraisal of studies on waste heat recovery potentials

Previous regional and national studies on quantifying industrial waste heat that buttresses on the waste heat end users, suggestions of suitable technologies to achieve reduced CO_2 emission include the following studies:

Bonilla et al. (1997) and Lopez et al. (1998) estimated approximately 51 GJ of industrial waste heat in Basque County in Spain. The proposed recovery technologies in the study included the installation of heat pumps and heat exchangers for temperature upgrade; and organic Rankine cycles for cogeneration of energy. Although the study findings were calculated based on published data from the regional energy department rather than from factory level data, the findings showed significant potential for waste heat recovery.

Dupont and Sapora (2009) investigated and reported the application of heat pumps for the recovery of waste heat from air-compressors, cleaning systems and chillers in manufacturing industries in France. The study showed great potential as the heat obtained was of higher temperature grade and useful for heat supply and for other end uses.

Sollesnes and Helgerud (2009) investigated waste heat potential using a questionnaire-based approach on 72 industries spanning from the wood, pulp and paper industry; metal and chemical industries in Norway. The research findings showed that despite being diverse in production of their finished goods, these manufacturing industries have similar or the same processing units with significant potential for waste heat recovery.

McKenna et al. (2010) conducted a country scale bottom-up approach of waste heat potential based on an industrial level. The study first classified waste heat from a single manufacturing site in the United Kingdom into temperature ranges, and secondly, estimated the average waste heat recovery potentials for the period of 2000-2003 in industrial sites based on their CO_2 emission recorded in the European Union Emissions Trading System (EU ETS). This study considered specific subsector parameters (such as the combustion emission fraction and the load factor) and the quantified total waste heat potential of 65-144 PJ.

An assessment of industrial waste heat recovery potential in Sweden was conducted by Broberg et al. (2012) using a bottom-up approach based on sending questionnaires to 85 energy-intensive industries in the country. The results from the study indicated a total waste heat potential of 75.6 PJ/a and represent an extrapolated value to represent the whole country. Subsequently, Hammond and Norman (2014) built on this study by using the thermodynamic quality (Carnot-factor) for the estimating waste heat potential and recommending recovery options for on-site use and upgrade of the recovered heat to a higher temperature; heat conversion for cold utility systems and power generation; and heat transfer for off-site use.

An investigation of a wide array of approaches for estimating waste heat potential by Brueckner et al. (2014) showed that based on available data, a waste heat potential ranging between 5 to 30%, which is often equivalent to the total energy demand of the industrial sector of a region. At a regional scale, a review of industrial waste heat recovery potentials in Europe in relation to industrial energy consumption specific to individual countries was conducted by Miró et al. (2015). However, the authors of this study declared that a substantial amount of the published data was unreliable and that well explained industrial waste heat assessments were absent in the study.

A review, comparison and systematic grouping of the waste heat recovery techniques used in over 30 European countries selected from previous literature were conducted by Brueckner et al. (2015) to present a regional-based estimation of industrial waste heat. However, similar to the previous study by Miró et al. (2015), the authors of this study also noted that many countries lacked country-specific data and the majority of previous studies simply applied the key Figures from other countries. Thus, this inherent problem of limited or non-existing data has restricted most previous studies on the estimation of waste heat and its potential for recovery at the state or regional scale.

Given the inaccessible data on waste streams characteristics from energy-intensive non-metal manufacturing sites in South Africa, there has been limited availability of accurate analysis. Using two manufacturing sites in Sweden and Germany, Miró et al. (2016) investigated the validity of estimating waste heat potential based on transferring assessment data developed for a specific region to another region. The suitability of the approach and study findings was assessed by comparing results to previous studies in the same region. The difference in the industrial waste heat potential obtained in the study was evened out over a stretch for the periods of 2001, 2009, 2010 and 2013, and the final results showed a fairly close range of values due to observed similar manufacturing processes with comparable efficiencies.

The technological feasibility of waste heat recovery from low-temperature waste heat streams for use in offsite heat supply has been implemented in numerous districts heating systems in European countries. Cooper et al. (2016) present off-site use of waste heat based on the findings of a significant amount of waste heat stream. The suggested end-use of waste heat include district heating networks in Great Britain. Ziemele et al. (2018) explored the economic feasibility of developing a district heating project from recovered waste heat. This study proves that the transmission distance between the manufacturing plant to the district heating system as a critical parameter in the venture which if favourable can yield a monthly transfer of about 67.5 MWh of heat to the heat supply network which covers 4–12 % of the system load during cold seasons and a monthly reduction of 5 to 10% of CO_2 emissions from the heating system. Albeit, the use of recovered waste heat requires the development of a new heating main supply and it is crucial to consider the heat losses in transmission. Also, the application of recovered waste heat for district heating is most suitable for regions with a cluster of manufacturing plants.

Brueckner et al. (2017) used a bottom-up approach on production companies in Germany to obtain an estimated 127 PJ/a of industrial waste heat. Similarly, Panayiotou et al. (2017) estimated waste heat and Carnot potentials of waste heat streams from major European industries. Miró et al. (2018) estimated the waste heat stream and used the CO_2 emissions of more than 400 industrial sites as well as country- and sector-specific parameters to estimate the waste heat work (Carnot's) potential. An average potential of 0.33 PJ/a per year was obtained in this study and approximately 134 PJ/a of potential was obtained for the whole sector. Based on the magnitude of the findings of the study, further assessment of the effective matching of the waste heat sources and potential sinks was recommended for maximum waste heat recovery.

Based on the previous studies, the estimation of the waste heat recovery potential in case study industrial sites has been conducted in many European countries and considerable progress into the reduction of energy consumption, cost and CO_2 emission from manufacturing processes have been achieved in this region based on these findings. Studies by Dupont and Sapora (2009) on the waste heat from industrial heat pumps; waste heat recovery from manufacturing activities from a pulp and paper factory by Sollesnes and Helgerud (2009), and estimation of 65-144 PJ based on CO_2 emissions by McKenna et al. (2010), shows that the concept of industrial waste heat recovery is worthwhile.

However, studies on waste heat recovery in South Africa remain unexplored systematically. The closest research was conducted by Stafford et al. (2013) that quantified the energy potential from wastewater from several manufacturing industries in South Africa (such as the distillery and breweries, the textile, paper and pulp and petrochemical industries) and also from domestic blackwater, animal husbandry wastewaters and agri-waste. The study estimates that the energy recovery potential from all the wastewater stream amounts to about 7% of the current national power supply.

Although the scarcity of research on the estimation of the potential for waste heat recovery on a production-scale and lack of systematic approach and framework for scale-up adaption in South Africa could be attributed to inaccessible datasets, it has created a significant gap in the literature that needs to be addressed. This scarcity may be due to undocumented and uncoordinated reports on waste heat, however, the insight and better understanding of the approaches used in previous studies, stimulate adoption of the same approach in this study to estimate waste heat and assess its potential to be used for technical work in case of manufacturing industries in Johannesburg.

In addition, manufacturing processes can result in environmental issues and associated carbon emissions as a result of material consumption (Lun et al., 2016). Thus, it is important to appraise previous studies that involved mapping of energy use in manufacturing industries and associated carbon foot emissions. Several studies have investigated the environmental impacts of the manufacturing of wood and forest products.

Eshun et al., 2010 conducted an inventory analysis of carbon emission of the timber industry in Ghana; Wilson (2010 [a]; 2010[b]) investigated the life-cycle inventory of particle and fibre boards and considered energy and carbon emissions; and Heath et al. (2010) investigated the greenhouse gas and carbon profile of the value chain in forest products industry in the U.S.

Most recently, Meinrenken et al. (2020) report a database of the carbon footprints of about 866 products using data reported for public disclosure by 145 companies, 30 industries and 28 countries. Firstly, this study presents a breakdown of the variability in embodied carbon emissions across the products' value chains; and secondly, this study investigates how any achievement of emission reductions within the industries may vary with the level of the product carbon footprint. This study proposes that a sector-level understanding of emissions, without a detailed understanding of the individual product carbon footprints, is inadequate to achieve emission reductions or reliably quantify carbon emissions.

The study by Meinrenken et al. (2020) showed 40% carbon intensity exists during production operations in the food and beverage subsector, 15% during transportation of materials and products and 0% carbon intensity during the end of life stage of the products (see Figure 2.4). This appraisal of manufacturing energy use and carbon footprints helps to better understand the procedure for investigating energy distribution in energy-intensive manufacturing plants and the accompanying energy losses. The inclusion of footprints in these studies provide a benchmark for prioritizing analysis of opportunities for improving energy efficiency and evaluating the associated benefits.

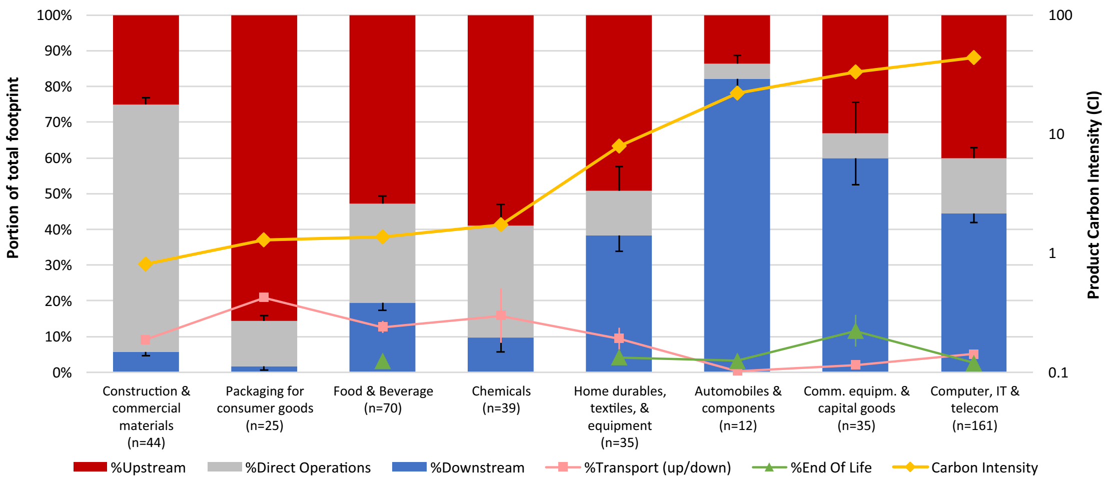

Figure 2.4. Breakdown of carbon emissions along a product's value chain across sectors. Average carbon intensity (CI) increases from left to the right and the percentage of end of life percent could not be quantified for chemicals, packaging products and construction materials industry (adapted from Meinrenken et al., 2020:5).

2.7. Conclusions

The appraisal of previous research shows that investigation of the potential for waste heat recovery is a commendable approach to improving overall energy efficiency by capturing and reusing waste heat contained in exhaust gases or air which is unavoidable during manufacturing processes. Furthermore, the literature review reveals that investigation of the waste heat source and estimation of waste heat recovery potential play a major role in the selection of available recovery techniques that will yield optimum efficiency. Likewise, certain important parameters such as the waste heat mass flow and the source temperature categorizes of low, medium and high-temperature grades determine the overall waste heat quality and effective matching of the source to sink.

Lastly, the appraisal of the studies that evaluated the carbon footprint throughout the life cycle assessment of various industries particularly during manufacturing operations, highlights the need for cleaner energy and increasing positive impact on global carbon mitigation. In light of this, investigation of waste heat recovery potential could serve as a platform to achieve reduced energy consumption in manufacturing equipment such as boilers, furnaces, dryers etc., reduced GHG emissions and overall potential savings costs for manufacturing industries in Johannesburg.

CHAPTER THREE: RESEARCH METHOD

3.0. Introduction

This chapter presents the research method adopted in the study and focuses on the mixed-method approach used in the data collection and analysis process. The main dataset used for the research was on the total energy consumption and carbon emission, as well as the temperature readings of the waste heat stream from selected case manufacturing industries in Johannesburg. The chapter comprises of five main parts namely: research design; data collection; a tabulated summary of the data required to provide answers to each sub-question; the ethical considerations undertaken before commencing with the data collection; and finally, the limitations faced during the research.

3.1. Case description

The case studies selected were three manufacturing industries in Johannesburg (see Figure 3.2) and are henceforth referred to as case study A, B and C as follows:

A. A milk and dairy products plant in the northern part of Johannesburg;
B. A rubber and tyre manufacturing industry in Village Deep;
C. A pulp and paper manufacturing industry in Wadeville.

The milk and dairy products case study shows the highest overall growth in production volumes in the food processing subsector (see Figure 1.3). In addition, the selected case studies A, B and C are characterised as energy-intensive subsectors (DoE, 2009), which conduct heating, drying and steam treatment processes (such as heating, drying, pasteurization, evaporation and spray drying). These selected case study manufacturing subsectors represent the most common SMMEs in Johannesburg and utilize a generic manufacturing process that releases low to medium temperature waste heat to the environment. Based on this, the study hypothesized that there would be vast amounts of heat generated in the processing units, with associated release of excess heat. This, therefore, presents opportunities for the investigation of the portion of the excessive heat which could be harnessed.

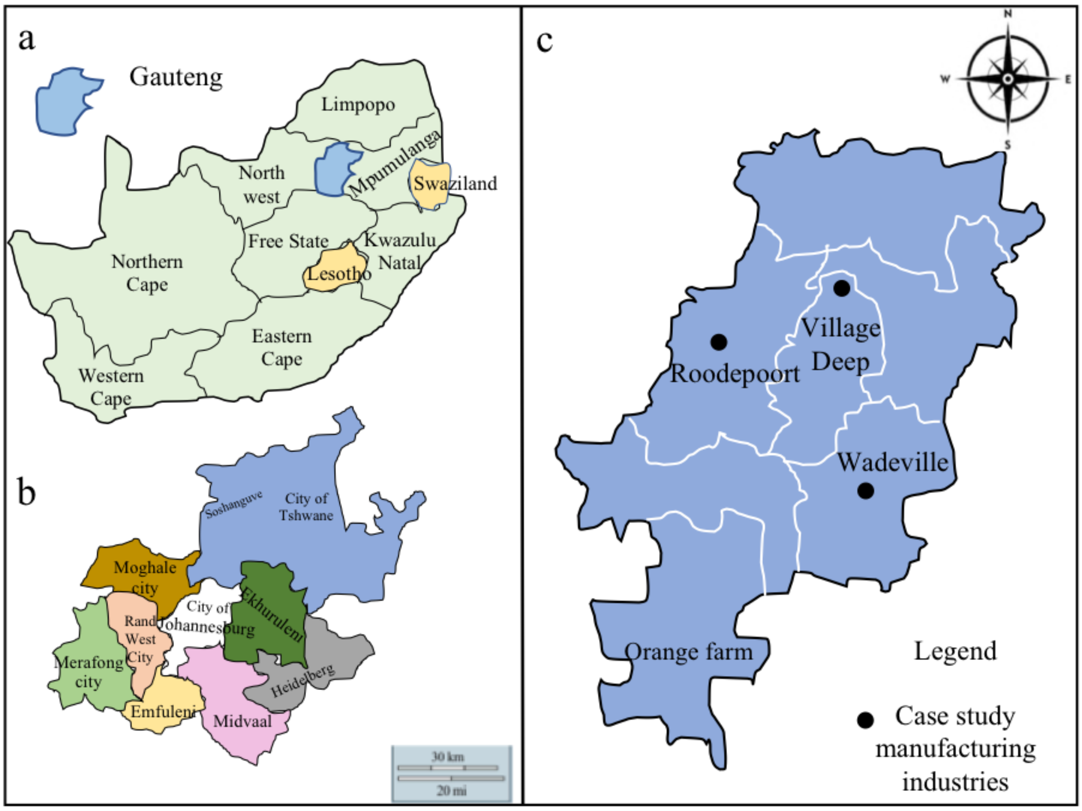

Figure 3.1: a) Map of Gauteng Province in South Africa; b) map of the City of Johannesburg; c) the location of selected case study manufacturing industries in Johannesburg.

3.2. Research design and overall method

The study adopted a mixed-method research approach. This allows for the analysis of numerical (Sheard, 2018), and interpreting qualitative data to deepen understanding with regards to the gap in the literature (see Figure 3.2). An important aspect of "quantitative research design is the process of quantifying (or measuring) phenomena" (Jones, 2000:152), and also using the approach to report relationships and associations among the studied variables. The applicability of these aspects of the quantitative research method to this study assisted in narrowing down a broad research field for ease of conducting research. This included quantifying the waste heat stream, measuring the temperature grades to quantify the waste heat and investigating variables such the waste heat and carbon dioxide emitted into the environment due to energy loss and combustion of fossil fuel during processing activities.

This study also adopted a multiple case study approach on selected manufacturing industries in Johannesburg, to explore similarities and differences between the cases. The case study approach is defined as an in-depth investigation of individual entities that allows for intense analyses of an issue (Stake, 1995; Lucas et al., 2018). In this context, the motivation for selected manufacturing case studies in this study was that they fall under the energy-intensive subsector and represent the main small to medium-sized manufacturers in Gauteng and contributed about 30% to the manufacturing sector's output in the province (GGDA, 2018).

In addition, milk and dairy production subsector is considered one of the most energy-intensive subsector in the food processing sector (Briam et al., 2015). This selected manufacturing subsectors use approximately 25% of total energy per year consumed by process industries and contributes approximately 40% to CO_2 emissions. Therefore, waste heat recovery in this case manufacturing subsector could help reduce their energy consumption and emissions, which could turn mitigate the associated environmental degradation caused by their manufacturing processes.

Due to the limitations discussed in section 3.5, direct observations were carried only out on only case study A, and no site visits were conducted for the other two cases B and C i.e. rubber and paper/pulp manufacturing industries respectively. Instead, secondary data provided by the South African National Cleaner Production Centre (NCPC-SA) were used to supplement for the lack of primary data for case studies B and C. These secondary data included the measurements of variables such as temperature grades, total carbon emissions and energy consumption collected during in-plant energy assessment (IPEA) by the energy specialist from the NCPC-SA.

Given the complex nature of manufacturing plants and the available dataset for investigating waste heat potential and recovery within these operating facilities, it is important to define a process for assessing the waste heat sources and eventually recommending compatible recovery techniques. In this context, to achieve the aims of this research, a structured methodology that will enable ease of conducting waste heat assessments and offer opportunities for making informed decisions about the suitable recovery techniques is presented below. This structured methodology which is in three phases is presented in Figure 3.2 and summarized as:

1. Waste heat mapping to identify the various waste heat sources and potential sinks in the manufacturing plant, as well as the parameters and datasets.
2. Quantitative assessment of the waste heat potential, exergy and quality in terms of the temperature grade.
3. Comparison, selection and recommendation of most suitable recovery technique.

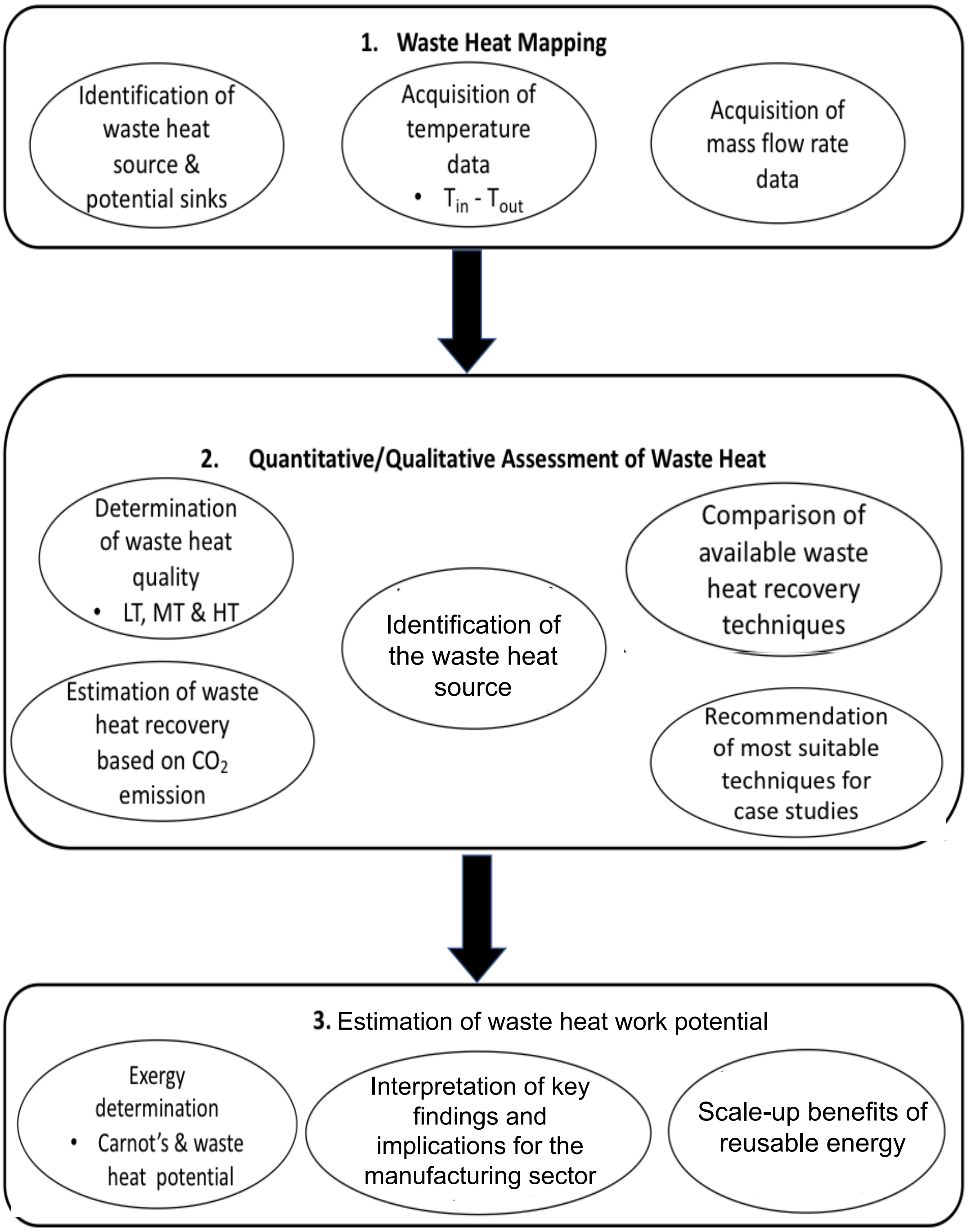

Figure 3.2: Research design /method for waste heat recovery investigation in this study.

3.3. Data Collection

Careful thought and justification were given when collecting the primary and secondary data for this study, as the focus was mainly on the manufacturing industries within sub-sectors that show the largest energy consumption and carbon dioxide emissions per year.

The data collection tools used included a review of the energy assessment report i.e., the South African GHG inventory by DEA (2014); the South African DoE (2019) energy sector reports; the South African carbon emission factors by Spalding Fletcher (2011); semi-structured interviews; and direct observation during a site visit. Secondary data were collected from the NCPC-SA in the form of In-Plant Energy Assessment (IPEA) report conducted on manufacturing industries. The primary data were collected through the direct observation and by participating in measurement during manufacturing processes of one of the case study operations and also through a semi-structured interview with the energy specialist who conducted the IPEA of the manufacturing plants. This is an open interview that allowed new ideas to be implemented while conducting the interview based on the response of the respondent. To adhere to ethical reasons, the participants remained anonymous throughout the study, rather codes were used to denote their identity such as Mrs M. from the NCPC and Mr A from the site visit (see Table 3.1).

Table 3.1 The respondents and the list of questions posed.

Respondent	Code	Designation	Questions probed
1	Mrs M.	Energy specialist	• What is the purpose of the In-plant energy assessment (IPEA) that are carried out at the manufacturing plants? • Is it possible to obtain the IPEA reports for manufacturing plants in Johannesburg? • Is it possible to attend one of these IPEA exercises? • Are there any ongoing waste heat recovery in any of these factories?
2	Mr A	Operations Manager	• What are the main processing units in the factories?

			• Are there any reasons why waste heat recovery is not conducted in the factory?

3.4. Primary Data

The primary data were mainly collected from three main sources

- Direct observation - Direct observation was conducted by the researcher during a site visit to the dairy and milk manufacturing plant to visualize and experience the operation activities first-hand. The main tool used was an observation guide which aided the researcher on what key areas to observe and participate in activities such as recording of input and output energy, the energy usage of individual equipment, duration of operations, specific heat capacity, main processing units, equipment types etc.
- Semi-structured interviews - The semi-structured interviews and communications approach were used to acquire necessary in-depth information relevant for this study that has not been previously observed, published or accessed. The researcher conducted semi-structured interviews with respondents such as the project manager of the NCPC-SA and the independent energy specialist contracted by the NCPC-SA before data collection commenced. The semi-structured interviews with the respondents allowed the researcher to gather comprehensive information from the expertise that allowed the researcher to have an in-depth understanding of the inputs and outputs, as well as the measurement, is taken during IPEA of the manufacturing processes (see table 3.1).
- Discussions about specific manufacturing activities, energy usage and sources of waste heat.

3.5. Secondary Data

According to Creswell (2014), the collection of data from documents (such as governments gazettes, technical reports and academic journals) allows for ease and accessibility to information at the required time. The secondary data were collected from South African National Cleaner Production Centre (NCPC-SA) and it consists of energy assessment reports on the measured key parameters such as energy consumption, carbon dioxide emission, energy use in individual operation units during processing activities in manufacturing industries in Johannesburg. Other secondary data used for the study include government energy reports, academic journals as well as technical reports. Some of the key reports reviewed were the Department of energy sector reports, the Greenhouse Gas (GHG) national inventory report, South Africa and Eskom's report on the calculated load factor for different sectors of the economy to derive findings on heat recovery fractions (R_F) ranges based on the assumption that some amount of waste heat in any exhaust stream remains unrecoverable; the subsector's emission fractions, the subsectors overall emission factor and load factors for different manufacturing sub-sectors, as well as methods for quantifying waste heat and estimating the potential for reusing it for onsite work.

3.6. Data analysis

The data analyses involved analysing some aspect of quantitative (measured subsector specific parameters and quantified variables) as well as qualitative (formal and semi-structured interviews) together by incorporating them into the following equations:

- The equation for qualifying the data on temperature grade of the waste heat stream expressed as $\Delta T = (T_{in} - T_{out})$
- The equation for quantifying the energy content of the identified waste heat stream (Qw) as a function of the waste heat stream mass flow rate (ṁ in kg/yr), the density (ρ) of the waste heat source (kg/m^3), the specific heat of the substances Cp (in J/Kg.ºC) and the waste heat stream temperature change expressed as ΔT:

  $$Qw = \dot{m} \times \rho \times C_P \times \Delta T$$

The equation for estimating the waste heat work (Carnot's) potential (WH_T) expressed as:

$$WH_T = \frac{RF .CT.FCi.\eta Ci}{KCi.\ Li}$$

Where R_F is the heat recovery fraction for any manufacturing subsector;

C_T is the reported carbon emission (Kilotons/year) for each case study;

F_{Ci} is the combustion emission fraction for each case study;

η_{Ci} is the calculated Carnot factor for each temperature range in each subsector;

K_T is the overall emission factors in each case study;

L_i is the load factor for each case study.

3.7. Summary of data used to answer the research questions and sub-questions

This sub-section highlights the data used for each sub-question; the various tools used to obtain these data as well as the data analyses processes followed (see table 3.2). This layout helps to outline the various data analysis processes undertaken to obtain the research findings and the eventual resolution to the main research question of the study.

Table 3.2: Summary of data used to answer the research sub-questions

Research sub-questions and overall research question	**Data needed**	**Data collection tools/procedures**	**Data analysis and procedures**
Sub-question 1: What potential exists for waste energy recovery in selected manufacturing industries in Johannesburg?	Secondary data consisting of the following parameters: *The mass flow rate (ṁ in kg/h), *The density (ρ) of the flue gas (kg/m^3), *The C_p is the specific heat of the substance (J/Kg.°C), and *The waste heat source to sink temperatures expresses as ΔT (T_{in} - T_{out}) Primary data consisting of: *The production activities and processes at one of the case study manufacturing site.	Government documents and statistics. Data collection was from electronic and print materials of academic journals (Brueckner et al., 2014; 2017; Panayiotou et al., 2017; Miró et al., 2018); semi-structured interviews with energy specialists, direct observations during the site visit and photography during the site visit.	Review data and comparison of tables Data were presented as tables, charts and graphs on the total energy consumption, and the calculated quality of waste heat defined by temperature grades for each selected case manufacturing industry. The sub-findings are calculated using equations to quantify the waste heat stream and estimate the waste heat potential. The Data Analysis and sub-finding are further substantiated in Chapter 4.
Sub-question 2: What are the key points of energy loss and waste heat channels in manufacturing process cycle of the dairy, rubber, pulp and paper manufacturing plants?	Secondary data required: *Key equipment and processing units *R_F – The heat recovery fraction *C_T - the total carbon dioxide emissions of the manufacturing plant (tCO_2 equivalent).	Factory-level data: Energy assessment reports, annual carbon emission, energy consumption dataset for the year 2017 to 2018 collected from the NCPC-SA; electronic and print materials of academic journals,	Data were presented as tables and graphs. The sub-findings are derived using the specific parameters and total carbon dioxide emission from manufacturing operations (from 2017 - 2018) to calculate the waste heat and Carnot potential (amount of energy useful for

	*$F_{C,i}$ - the manufacturing subsector's combustion emission fraction. *$\eta_{C,i}$ - the subsector's efficiency conversion from fuel to heat determined by measuring how well an appliance turns fuel into useful heat. *$K_{T,n}$ - the subsector's overall emissions factor n (t CO_2 equivalent /kWh). *$L_{F,i}$ is the subsector's load or power factor.	technical reports from Eskom, DoE and textbooks.	technical work) based on CO_2 emissions. The Data Analysis and sub-finding are further substantiated in Chapter 5.
Sub-question 3: What technically viable and practical ways are applicable for harnessing the identified waste heat?	Secondary data involving the review of available technologies for harnessing waste heat.	Selection of techniques that are applicable for onsite or possibly offsite use of the recovered waste heat.	Matching of the identified waste heat streams and sources in Chapter 4 to possible sinks
Sub question 4: In what ways can waste heat recovery contribute towards the reduction of GHG emission for manufacturing industries?	Secondary data consisting of: *Total energy consumption in MWh per year. *Total CO_2 emission per year. *Total energy costs in Rands per year,	Factory level dataset collects provided by the NCPC-SA.	The Data were presented as tables. The sub-findings presented include the potential savings on energy use and cost based on the % energy saved from waste heat recovery. The Data Analysis and sub-finding are further substantiated in Chapter 5.
Overall research question: The sub-findings from the 3 research sub-questions were consolidated to derive the main findings of the study as presented in Chapter 6 and to provide answers to the main research question which is the investigation of the extent to which waste heat recovery in manufacturing industries can contribute towards a reduction in energy consumption and GHG emissions towards climate change mitigation.			

3.8. Ethical considerations

Blumberg et al. (2005) propose that research and dissemination of research findings should be conducted in a manner acceptable for academic purposes. This makes it important to conduct any research from the onset based on established ethical principles and considerations (Jones, 2000). Given that this study utilized empirical secondary data and open-ended interview questions to respondents at the NCPC-SA. Care was taken to ensure the proper ethical clearance before commencing with the data collection process.

All necessary consent and authorisation sought from the director of the NCPC-SA, the project manager in charge of the IPEA as well as from the University of Witwatersrand before the site visit and data collection. A non-disclosure agreement stating the need to protect the identity of the case study manufacturing industries, as well as the use of the empirical data for research purposes only was entered by the researcher and the NCPC-SA before the release of the secondary data. Further conditions include ensuring non-transfer of data and its eventual deletion upon completing the study, and the booking of the appointment to attend the IPEA during the site visit.

Copies of the ethics clearance certificate released by the University of Witwatersrand and the distributed interview questions are attached as Appendices 2 and 3 at the end of the research report. Further adherence to the ethics considerations includes non-disclosure of the names of all the respondents and case study manufacturing industries due to the non-disclosure agreement and right to privacy or to remain anonymous throughout the research period.

3.9. Limitations to the study

There was a limitation of access to manufacturing sites, hence energy assessment data were collected from the South African National Cleaner Production Centre (NCPCP-SA). These datasets include declared waste heat per industrial energy consumption; the carbon dioxide emissions of the manufacturing plants and total energy expenditures incurred. The research was restricted from visiting the manufacturing sites of two of the selected case studies i.e., the rubber and the pulp and paper manufacturing plants. Also, the researcher experienced a delay of two months in accessing the dataset on the energy consumption and carbon emission from the manufacturing industries, until the full non-disclosure and future deletion of data agreement were reached by the researcher and the manufacturing industries.

However, as the researcher could not visit these two manufacturing sites, this issue was mitigated by utilizing secondary data from print media, journal articles and some credible and technical information from the energy specialist and NCPC-SA on the rubber and paper manufacturing plants and related case studies. Careful consideration was made to ensure that the data were consistent by supplementing the primary data with secondary data.

Furthermore, given that detailed data on waste heat recovery techniques in South Africa are limited and not fully explored, the researcher, conducted this research by comparing the collected data with similar case studies from European countries and incorporating the data into existing methods to complement the data collected during the site visit as well as information obtained from the energy specialists.

CHAPTER FOUR: WASTE HEAT RECOVERY POTENTIALS IN SELECTED MANUFACTURING CASE STUDY IN JOHANNESBURG

4.0. Introduction

This chapter initially presents the secondary and primary data and analyses of both descriptive and numerical dataset to provide sub-findings for sub-question 1 on the potential for waste energy recovery in selected manufacturing industries in Johannesburg. The data include a description of the major processes in the selected manufacturing subsectors followed by a quantitative assessment of waste heat and their temperature ranges.

Primary data were acquired through discussions with the respondent (Mrs M.) an energy specialist at the NCPC and direct observation during the site visit to the case study milk and dairy products manufacturing plant. This dataset was supplemented with secondary data accessed from the NCPC-SA, academic journals/manuscripts and technical reports on the specific heat capacity in J/Kg ºC and density in Kg/m for the various manufactured products. By supplementing primary data with secondary data, it became possible to derive some important data that could not be acquired during a site visit or discussions with the specialists.

The secondary dataset was released by the Mrs M. from the NCPC-SA. During the process of collecting the secondary data, a discussion with the above-mentioned respondent claims that the released data includes only raw data set of energy consumption, carbon emission, name and addresses of the manufacturing plants. Also, the data has not been analysed or used for any prior study. The claims by the respondent are as follows:

> *"The NCPC data only contains energy balance from measurements based on data released by the factories. This dataset represented selected plants in Johannesburg and the clients insist strictly on a non-disclosure agreement".*

Initial data analyses called waste heat mapping first involved quantifying waste heat released from the identified sources in GJ per year using the following parameters:

- The identified waste heat stream media for sources and sink.
- The temperatures (ºC) at inlet and outlet points in the equipment for hot mediums /streams (waste heat source) and cold streams (potential sinks).
- The mass flow rate (m^3/year) for the waste heat source and sink streams.
- Quantified carbon dioxide emissions from individual processing units.

Secondly, this waste heat stream was qualified in terms of temperature grade (McKenna, 2009; McKenna and Norman, 2010), namely:

- Low Temperatures (LT): $< 100^{o}$C;
- Medium Temperatures (MT): 100 – 299^{o}C; and
- High Temperatures (HT): $\geq 300^{o}$C.

4.1. In-plant Energy Assessment (IPEA)

The in-plant energy assessment (IPEA) was conducted by the NCPC-SA during operation. This involved measuring the energy consumption of individual equipment and making recommendations of equipment upgrades and energy efficiency measures for identified key areas of energy loss for potential improvement. In discussion with the respondent 1 about the purpose of the IPEA, the respondent claims that:

> *"The in-plant energy assessment of manufacturing plants helps to understand how energy is consumed and sector-level emissions annually. This exercise also pinpoints key areas of energy loss that the factories may be unaware of. Also, the IPEA is typically followed by recommendations on how to reduce energy consumption and increase energy efficiency and thus reduce carbon emission" [Mrs. M].*

This claim by the respondent confirms that the dataset needed to achieve the aims of this study relies on a combination of primary and secondary datasets.

Inquiries into the nature of the energy assessment, the respondent further claims that:

> *"The IPEA involves assessment and energy audit of the energy management system and manufacturing process e.g. steam boilers, dryers, compressed air system, motors etc. are reviewed and evaluated by energy experts via a walkthrough or long-duration observation during operations" [Mrs. M].*

To further gain in-depth knowledge as well as collect factory level primary data, the researcher asked the respondent if it possible to obtain the IPEA reports for manufacturing plants in Johannesburg, and also attend one of these IPEA exercises. In response, the respondent declared:

> *"The energy assessment data can be arranged; however, it is crucial to adhere to confidentially and the data can only be used for academic purpose. Also, we just concluded a site visit, but we can arrange to include you in the next one" [Mrs M]*

Based on the statement made by the respondent, the researcher was granted permission to make a site visit with the energy specialist form NCPC-SA and was able to have a semi-structured interview with respondent 2 during the site visit to case study factory A. Questions about the main processing units in the manufacturing plants, and inquiries about current implementation of waste heat recovery in the plan were posed to the respondent. The responses are as follows:

> *"The main processing system and equipment in the factory include the heating unit which consists of the steam boilers; the spray drying unit and the compressed air system. Also, with regards to waste heat recovery, we have not considered this measure in our operation because we are mostly focussed on optimizing the performance of the equipment for potential energy savings and achieving optimization of performance goals and plant yield" [Mr. A].*

Based on this revelation by respondent A who is the operations manager at factory A, it is evident that the recovery of waste heat is disregarded and considered to be of no potential value, given that it is usually expelled into the environment in large amounts that are typical of low-temperature grades between 30 to 50°C (Law et al., 2013).

4.2. Appraisal of the production processes and energy use in case study factory A

The case study commercial milk and dairy production plant referred to in this report as Factory A, is located in the northern part of Johannesburg and receives approximately 200, 000 litres of liquid raw milk from farms per day for processing and yields a total annual production of approximately 392,860 tonnes of milk and dairy products. Factory A produces the following products: fresh milk (full cream, low fat and skimmed); cheese; yoghurt; and powder milk.

It was revealed during the site visit that heat treatment and separation of milk begins with thermally treating raw milk from the farm to eliminate resistant pathogens and bacteria by heating to about 60 – 70ºC, followed by separation of the raw milk into cream and skimmed milk through a centrifugal separator. This was followed by subsequent cooling and evaporation processes to produce yoghurt and cheese. The last process involved spray drying process to produce milk powder. A schematic illustration of these main production processes as well as their respective avenues of waste heat as exhaust air is presented in Figure 4.1.

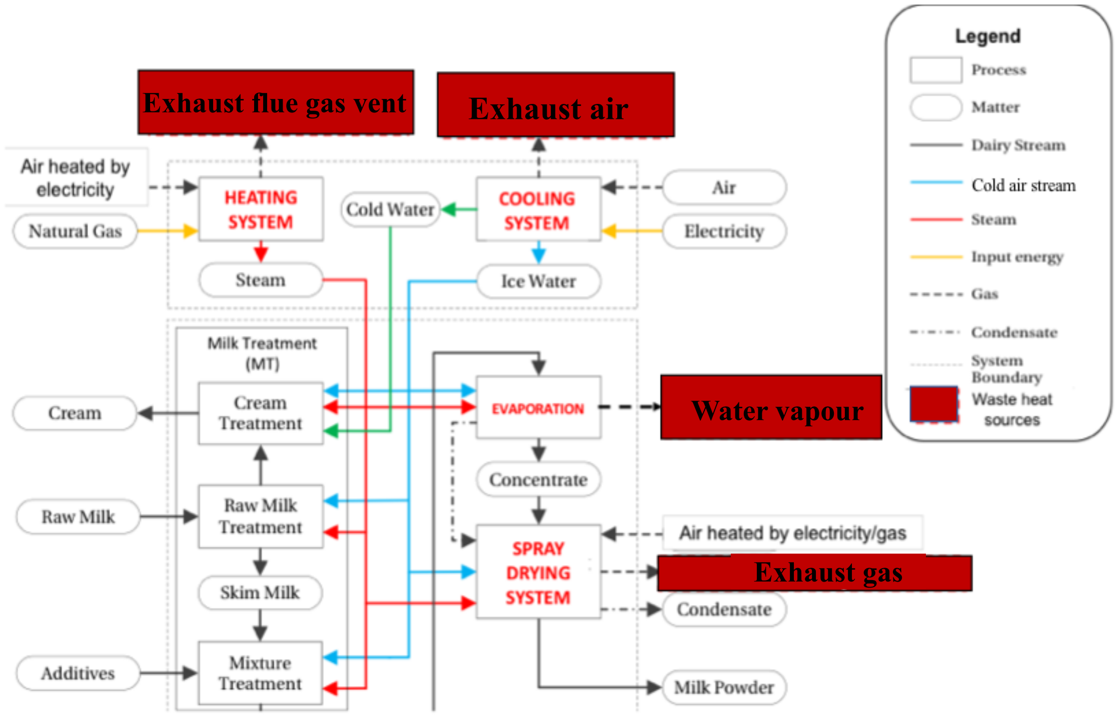

Figure 4.1: Schematic diagram of the main processing line and waste heat sources identified in case study A plant.

4.2.1. Energy source and consumption

Case study factory A uses natural gas and electricity as the main sources of energy for heating, cooling (refrigeration), evaporation and spray drying purposes. Natural gas is used to produce steam which is passed through a network to the evaporating and spray drying units (see Figure 4.2). The energy profile for case study factory A was collected from primary and secondary data. The secondary data revealed that the total energy consumed in the main processing units is 80,468 MWh per annum, and the semi-structured interviews with respondent 1 revealed that only 70% (56,327.6 MWh/year) is used in production, while the rest 30% is lost (see table 4.1).

With regards to energy loss, questions surrounding the issue was raised in the semi-structured interviews with the respondent 1, and the respondent claimed that:

> *"Despite energy loss, the issue of production goals and profit margin is prioritized over saving the cost of energy" [Mrs M}.*

This revelation by respondent 2 could be the possible causes of the ongoing high energy consumption, incurred cost and demand from this particular case study which was highlighted in the secondary data. A breakdown of the energy use in each processing units in the secondary data are as follows:

- About 20, 200 MWh of electricity and natural gas was used per year to supply electrically heated hot air and steam generation for pasteurization (heat treatment) processes;
- About 7, 830 MWh of electricity was used per year for refrigeration of 1000 litres of fresh (raw) milk from the farm;
- Approximately 14,300MWh of electrical energy and natural gas was used in the evaporation unit for yoghurt and cheese production; and
- About 38, 138 MWh of electrical energy and natural gas was used in the spray drying process for powder milk production.

Overall, although a significant amount of total energy consumption is observed in the heating process with the use of electricity for heating supplied air and natural gas for steam generation; the spray drying unit is recorded as consuming the largest amount of energy (see Table 4.1).

Figure 4.2: The case study of a manufacturing factory investigated in this study. Note: a) front view of the manufacturing plant; b) the evaporation processing unit; c) the steam boilers used mainly in the heating/pasteurization unit; d) the steam network to other processing units.

Table 4.1: The total energy use and CO_2 emission from each major processing units in the case study factory A (secondary data: NCPC-SA).

Subsector	Processing units	CO_2 emission (Ktons CO_2 equivalent)	Process Energy use (MWh/year)	Total energy use (MWh/year)
Milk and dairy products	Boiler system	206	16,455	20,200 (electricity, natural gas)
	Cooling	171	6,953.8	7,830 (electricity)
	Evaporation	136	13,518.54	14,300 (electricity, natural gas)
	Spray dryer	106	19,400.26	38,138 (electricity, natural gas)
Total annual production: 392,857.15 litres 70 % energy used 30 % energy lost	Total	619	56,327.6	80, 468

Footnote: The energy use is per-process unit and total energy consumption presented is for the total annual production at the plant.

The energy-intensive processes in case study A are also observed as indirectly generating significant amounts of CO_2 emissions through onsite combustion of fossil fuels and the use of natural gas in its processing units. The total CO_2 emission reported for this subsector is approximately 619-kilotons of CO_2 equivalent, and the heating system consisting of steam boilers showed the largest source of CO_2 emission, followed by the cold system unit, the spray drying unit and lastly, the evaporation.

4.2.2. Mapping of waste heat recovery opportunities

To effectively map the waste heat from this case study, particular focus is placed on the heating unit, evaporation and spray drying units given that these units are identified as consuming the largest amount of energy (see table 4.1). A breakdown of the key points of energy use and potential energy loss as exhaust air or gas is presented below and as a simplified process line diagram in Figure 4.3.

Heating process

The initial process starts with the annual use of approximately 20, 200 MWh of electricity and natural gas to generate steam for the entire heating process, which begins with using centrifugal separators to separate the cream, skimmed milk and yoghurt concentrate obtained in the heating process into standardized fat and solid content. This involves pasteurization of the skimmed milk and cream at 75^{o}C and 85^{o}C, respectively, followed by subsequent cooling down to 5^{o}C, first by a regenerative heat exchanger and secondly in the cold utility. Additives (such as sugars, vegetable fats, vitamins and minerals) are added to the skimmed milk to further enrich and standardize it. The identified waste heat source in the heating processing is exhaust flue gas vented at 200 ^{o}C from the exhaust pipes of the several steam boilers in the unit.

Evaporation process

The evaporation unit begins with a homogenisation process to disintegrate fat globules in the milk and cream mixture before passing it through a heat exchanger to produce cream at a lower temperature, and further heating of the mixture to 85 ºC in the heat exchanger that uses externally supplied thermal energy from steam (produced from natural gas) to produce milk concentrate. This skim milk is further passed on to the mechanical vapour recompression (MVR), which is a heat exchanger used to upgrade the temperature grade of a vapour stream to a higher temperature by using a compressor. This process helps to remove water vapour from the milk concentrate through a vacuum heat exchanger to produce dry matter content of about 48% - 60% concentrate. The identified waste heat source in the evaporation processing is exhaust vapour/air at 100 ^{o}C from the (mechanical vapour recompression MVR) heat exchanger).

Spray drying process

At 75°C, the dry concentrate is passed onto the spray drying unit to remove the remaining water content and produce milk powder. During the spray drying process, air at 20ºC is passed into the heat exchangers in the unit to upgrade the temperature to 210°C which is the required air to carry out the spray drying process. To achieve this, first, the air is heated with condensate from the evaporators, followed by heating with supplied thermal energy from the steam boiler. The liquid milk slurry (concentrate) is heated to about 70-75°C in the spray dryer that is operated by the action of a heat exchanger and hot air supplied by an air compressor. The spray dryer works to break down the liquid molecules in the milk slurry to droplets in a moving gaseous drying medium. The last phase in this operation involved passing the concentrate onto a fluidized bed dryer supported by a cyclone separator both of which use cold air stream supplied by an electrically operated air compressor. The identified waste heat source from the spray drying unit is exhaust gas at 40-60 ºC released from a filtering system. A schematic illustration of all the main processing units with their respective waste heat sources is presented in Figure 4.3.

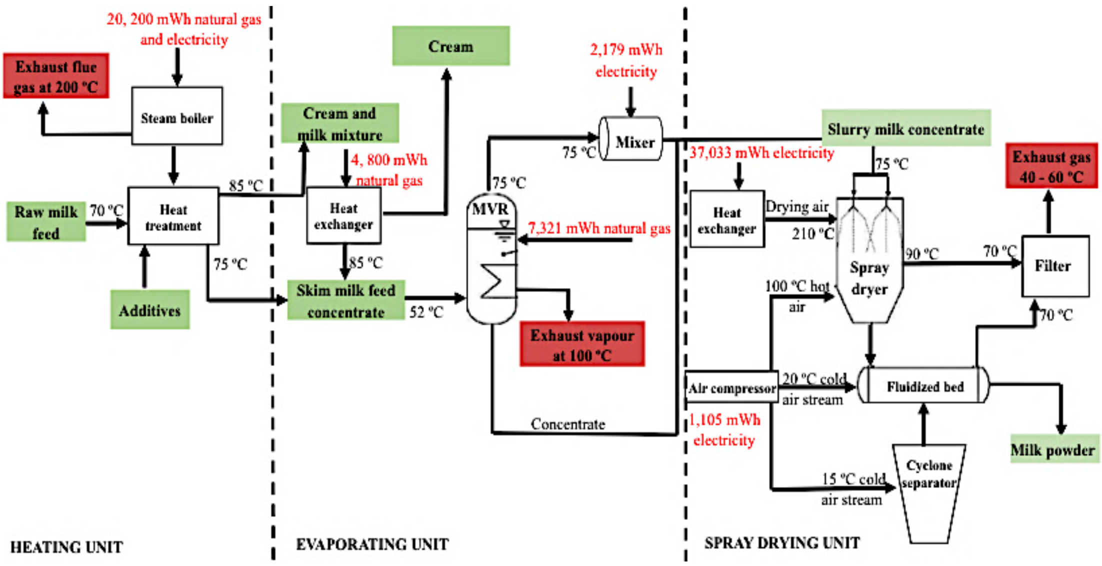

Figure 4.3: A simplified illustration of the process line showing the main energy-intensive units in case study factory A with their respective waste heat sources. MVR represents Mechanical Vapour Recompression.

This case study represents a typical manufacturing area for production from raw material to final product using primarily steam boilers, heat exchangers and air compressors for milk treatment (see Figure 4.3). Given the breakdown of the process-line of the production units that consume the largest amount of energy in case study factory A, it was discovered that the steam boiler system and operations using air compressors and heat exchangers are the main sources of significant low to medium temperature grade waste heat. For instance, the identified waste heat source in the heating processing is exhaust flue gas vented at 200 ^{o}C from steam boilers; from the evaporation unit is exhaust vapour/air at 100 ^{o}C released from the MVR (heat exchanger), and lastly, from the spray drying unit is exhaust gas at 40-60 ºC released from a filtering system.

These sub-findings in case study factory A show that the approach used here is applicable for estimating waste heat recovery opportunities from the generic processing unit in manufacturing industries that conduct operations using air compressors, steam boilers, and heat exchangers. The sub-findings reveal that these particular equipment are sources of potential low-grade waste heat released from exhaust air and vapour, exhaust flue and exhaust gas respectively. Based on the high efficiencies (80 – 85%) reported for large steam boilers, which exceed the efficiencies of other heating systems such as glass furnaces with low efficiency of 30% (U.S. DoE, 2008), numerous large steam boilers are used widely across a range of manufacturing industries (such as paper, agro-processing, refining, chemicals, plastic and metals). However, despite being an efficient heating system; a large number of steam boilers, air compressors and heat exchangers used in generic operation across manufacturing industries suggests a significant amount of low-temperature waste heat losses and opportunities for waste heat recovery (Law et al., 2013).

4.2.3. Estimation of unrecovered waste heat stream

This subsection shows how the identified waste heat stream was quantified using the field measurements of the input and out temperatures for each processing units in the case study A manufacturing site. To quantify the waste heat stream Q_w, the energy content of the waste heat stream is calculated as a function of the waste heat stream mass flow rate ($\dot{m}$ in kg/yr), the density (ρ) of the flue gas (kg/m^3), the specific heat of substances Cp (in J/Kg.ºC) and the heat source temperature change expressed as ΔT ($T_{in} – T_{out}$). This calculated quality of waste heat stream is derived using equation (1) described in chapter two as:

$Qw = \dot{m} \times \rho \times CP \times \Delta T$

Where Qw = quantity of waste heat in Gj per year

$\dot{m}$ = mass flow rate in kg per year

ρ = density of milk in kg per m^3 = 1.035 kg/ m^3

Cp = specific heat capacity for milk in KJ/Kg.ºC = 3.89 KJ/Kg.ºC

ΔT = temperature change expressed as $T_{in} – T_{out}$

For instance, to quantify the waste heat released during treatment of raw milk using the parameters above are used in the equation: mass flow rate =158 kg/year, the density of milk is 1.035 Kg/m^3, specific heat capacity for milk is 3.89 KJ/Kg.ºC and ΔT = 85 – 50 = 35 ºC:

Qw = 158 x 1.035 x 3.89 x 35

= 22264.6 Gj per year

The quantified waste heat stream for each of the heat exchangers in each processing unit (Figure 4.2) and the fluidized drying bed in the spray drying unit are presented in Table 4.2.

Table 4.2: Waste heat data for case study factory A. Note: the parameters used for calculation are basic physics and measurements of matter i.e., specific heat capacity in KJ/Kg.ºC for milk is 3.89; for cream is 3.77; skim milk is 3.97; for water is 1; for air is 1.003; the mixture is 3.77 and for concentrate is 2.22. In the same order, the density in kg/m^3 for each medium are 1.035; 0.994; 1.035; 0.997; 1.225; 1.030; and 1.028 respectively. The change in temperature used is the average between T_{in} and T_{out} for each process. HEX: Heat Exchanger; MVR: Mechanical Vapour Recompression.

Heating	**Equipment**	**Medium**	**T_{in} (ºC)**	**T_{out} (ºC)**	**ṁ (10^6 Kg/yr)**	**Q (Gj/yr)**
Milk treatment	HEX	Raw milk	50	75-85	158	**22.26 x 10^3**
Milk treatment	HEX	Cream	75	85	15	562.1
Milk treatment	HEX	Skim milk	70	75	135	2.77 x 10^3
Milk treatment	HEX	Mixture	80	85	147.4	2.86 x 10^3
Evaporation	HEX	Mixture	75	85	147.4	**5.73 x 10^3**
Evaporation	MVR	Concentrate	52	75	43	**2.26 x 10^3**
Spray drying	HEX	Concentrate	52	75	43	**2.26 x 10^3**
Spray drying	Compressor	Air	23	210	709.4	**16.3 x** 10^4
Milk treatment	HEX	Skim milk	8	5	135	1.66 x 10^3
Milk treatment	HEX	Cream	23	5	150	**10.12 x 10^3**
Milk treatment	HEX	Mixture	10	5	147	2.85 x 10^3
Milk treatment	HEX	Cream	58	23	150	**19.67 x 10^3**
Evaporation	Condenser	Water	98	80	4	71.8
Evaporation	Condenser	Water	52	50	2.5	5
Spray drying	HEX	Air	15	8	71	610.65
Total						**236,695.05**

The quantified waste stream (Q) in bold represent the waste heat with high potentials for being reused. According to the calculations, a total of 236,695.05 Gj of waste heat was released in 2017 to 2018 in case study factory A.

4.2.4. Investigation of the waste heat stream temperature grade

To evaluate the accessible waste heat potential, it is important to investigate the quality based on the temperature ranges of the waste heat sources. This was achieved in consultation with energy experts and the operations manager of the plant. The researcher with the assistance of an energy specialist recorded the waste heat temperatures using temperature recorders and digital thermometer installed on the plant machinery.

The temperature range of the unrecovered waste heat stream is presented in Table 4.3, the work potential of low and medium-temperature waste heat (based on a reference 25°C) reflects the maximum waste heat recoverable if exhaust gases from the heating, cooling, evaporation and spray dryer unit are cooled to room temperature.

Based on a reference temperature of 25°C, approximately 88 % (i.e. the sum of all LT waste heat % in Table 4.3 above: 3.4 + 14.5 + 70.1 = 88%) of the analysed waste heat is of low-temperature grade (below 100 °C), and the rest 12 % is medium-temperature grade waste heat (below 299 °C). Given that the sub-findings identify a significant amount of unrecovered low and medium temperature waste heat, further analysis of the work (Carnot's) potential of the unrecovered waste heat is explored in Chapter 5, which allows for a better comparison of waste heat at different temperatures.

Table 4.3: The temperature ranges for waste heat stream in case study A factory. LT: low temperature; MT: middle temperature and HT: high temperature.

Case study	Waste heat source	Temp. range (ºC)	Temp. code	Unrecovered waste heat (Gj/year) at 25°C reference	% of total waste heat
Milk and dairy production	Exhaust gas Exhaust air Exhaust gas Exhaust gas	160-200 85-100 40-60 40-60	MT LT LT LT	28.46×10^3 8.06×10^3 34.31×10^3 16.59×10^4	12 3.4 14.5 70.1
Total				236,695.05	100

A total of 236,695.05 Gj of unrecovered waste heat of low and medium temperature grade contained in exhaust gas released from steam boilers and during the evaporation, cooling and spray drying process; no high temperature (HT) was released from the processing units.

4.2.5. Analysis of waste heat source in the case study Factory A

The sub-findings from the waste heat stream mapping of case study factory A revealed the following:

- The main source of waste heat in the case study plant (see Figure 4.4) are from the heating/pasteurisation process (flue gas vented at ~200ºC); the evaporation process (exhaust vapour at 100 ºC); and from the spray dryer (exhaust air/vapour at 40-60ºC).
- The bulk (88%) of the waste heat stream released from the process line is of low-temperature grade (< 100 ºC) grade (see Table 4.3).
- The potential for waste heat recovery exists where there is a huge amount of heating, and drying, given that the waste heat sources are channels where these processes are utilized.

- The mapping and estimation of the waste heat revealed that heat treatment, evaporation and spray drying processes conducted through the use of steam boilers, air compressors and heat exchangers yielded a substantial amount of 236, 695.05 Gj waste heat which is equivalent to approximately 65, 748.63 MWh of energy for the year 2017 – 2018 (see Table 4.2). Based on this quantified and qualified low-temperature waste heat stream from case study A factory, the potential for waste heat recovery is very high.

- However, although the vast majority (88%) of unrecovered waste heat stream is low-grade quality, and the fact that low-temperature waste heat has less thermal and economic value compared to high-temperature waste heat, it is available in significant quantities.

- This analysis suggests that unrecovered waste heat stream from generic operation units that use steam boilers, air compressors, and heat exchangers should not be neglected, but rather considered when seeking opportunities for waste heat recovery in manufacturing industries at large. The adoption of currently available technologies may provide significant opportunities for recovery of low-temperature grade waste heat.

The characteristics of the waste heat source in case study factory A is therefore useful for identifying the waste heat sink and selecting recovery techniques that will yield optimum efficiency. Onsite waste heat recovery approach typically involves upgrading the temperature of the waste heat stream to a higher temperature (or in some cases such as in chemical (chilling) and air conditioning units, the conversion to lower temperatures) usually through the use of a heat pump, to use the heat in another processing unit (Hita et al., 2011; IEA, 2011; Hammond and Norman 2014). In situations where the waste heat is too low to be recovered by a heat exchanger or used directly in other onsite processes, like the low- temperature (40 -60 °C) waste heat stream identified in case study A; it could be injected into a heat pump to meet the demand for low temperature (<100 °C) heat by a nearby heat sink (Hita et al., 2011; Hammond and Norman, 2014).

Also, according to Law et al. (2013) and Mukherjee (2017), the recovery and upgrade of low-temperature grade waste heat from exhaust air and gas from manufacturing industries to a higher temperature of > 105 °C yields about 4% savings in fuel consumption. Since the total energy used by the processing units annually is reported as 56, 376.6. MWh/year (see table 4.1), 4% of this amounts to a saving of 2,239.1 MWh of fuel consumption from the total energy consumed by the case study. Thus, the upgrade of low-temperature grade waste heat of 40 – 60 °C to a higher temperature by the use of a heat pump in other recovered waste heat streams from this case study suggests the potential for saving even more energy.

The possible matching of the waste heat end-use or sinks and available recovery techniques for case study factory A is presented in Table 4.4.

Table 4.4: Analysis of the different waste heat sources in case study A and identified end-use and available recovery techniques.

Waste heat source	**Waste heat end-use**	**Recovery technique**
Combustion exhausts from steam boilers (200 °C).	*For preheating boiler feedwater. *For preheating water used for plant clean-up.	Direct reuse requires only pipework and auxiliary equipment
Exhaust gas from the heat exchanger (100 °C).	*For preheating air supplied to the compressor. *For preheating cold milk in the factory. *For heating culture tanks used in cheese production.	Installation of a heat pump between the compressor and refrigerating condenser to recover waste heat.
Exhaust water vapour from air compressors (40-60°C).	*For seasonal space heating. *For other onsite and domestic end-use.	Temperature upgrading via a heat pump.

The estimated low-temperature waste stream is substantial enough for harnessing for onsite use.

These sub-findings from case study factory A, therefore, motivates for the application of this approach for mapping and quantifying waste heat sources in the other energy-intensive manufacturing industries like case studies B and C (which are the rubber/tyre, and pulp/paper manufacturing industries respectively).

However, unlike case study factory A, the researcher was denied access to these other two case study manufacturing plants, hence was unable to conduct a site visit to obtain primary data. Therefore, secondary datasets obtained from academic journals, technical reports and in-plant energy assessment (IPEA) reports from the NCPC-SA was used to supplement the inaccessible primary data.

4.3. Appraisal of production processes of the production processes and energy use in the case study factory B

The total energy use per year accounted for the case study plant B at Laanlaagte is 94,723.2 MWh. On-site energy consumption includes electrical energy, heat, and fossil fuel. The energy consumption begins from the initial stage which is the conversion of latex into rubber sheet, rubber block and crepe. However, this study focuses on energy consumption during the conversion of latex rubber into finished rubber products, as it directly impacts energy demand and carbon emission from the manufacturing plant.

The production process in this manufacturing subsector is mainly centred on generating some of its primary energy onsite, which involves the production of electricity, diesel, Liquefied Natural Gas (LPG). These energy sources are consumed to produce concentrated latex through the centrifugation process, block rubber (STR 20) and ribbed smoked sheet (RSS) (see Figure 4.4). Approximately 90% of electrical energy and ammonia is used to produce concentrated latex, whereas ammonia, diesel and LPG are used for oven drying to produce STR 20 and RSS (Jawit et al., 2010; Conradie, 2018).

The interview with the respondent 1 who conducted the energy assessment for the secondary dataset revealed that the three most energy-intensive processes in the final production stage in case study factory B entail tyre-making, dipping product (the process of thickening rubber products by dipping in latex), and the production of compressed rubber block. The respondent further elaborated that

> *"The production of dipping products, about 70% of steam and 30% electricity are used, whereas, in rubber block production, a larger*

amount of electrical energy is used for driving motors and diesel is used for heat generation used in the drying ovens"[Mrs M].

Likewise, for tyre manufacturing, a large amount of electrical energy is used for driving motors and minimal heat from the steam is mostly used for moulding/extrusion (see Figure 4.5).

Secondary data for case study factory B showed direct or indirect emission of carbon dioxide (CO_2), and minor quantities of methane (CH_4) and nitrogen oxide (N_2O) emissions during its operation (see Figure 4.4). According to respondent 1, the direct emissions were caused by the onsite combustion of fossil fuels such as coal, diesel and natural gas during operations at the processing plant, whereas the indirect emissions were due to the combustion of fossil-fuel such as coal diesel and natural gas for generating electricity used by the rubber processing facility. For this study, the main focus was on both direct and indirect CO_2 emission from the production of raw materials and the conversion of rubber into finished rubber products. The total CO_2 emission per year by this case study factory is approximately 365 kilotons of CO_2 equivalent (NCPC dataset).

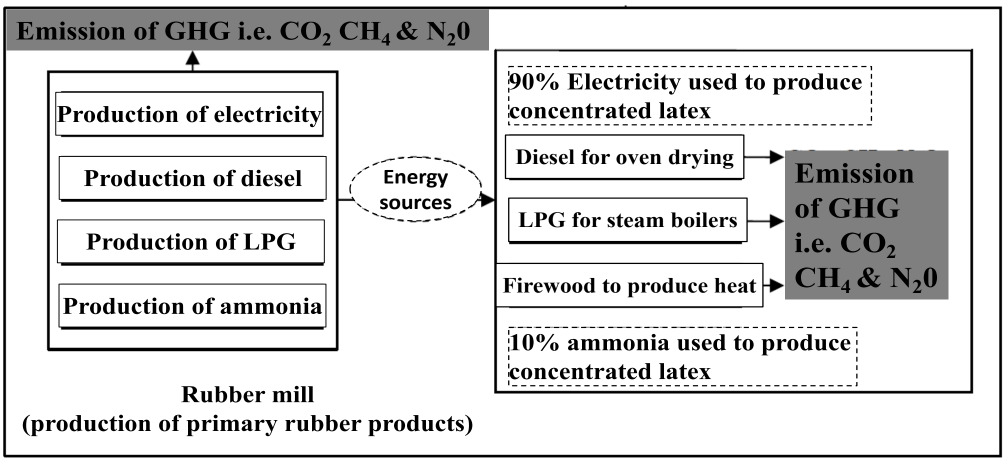

Figure 4.4: The typical main energy source, end-use and major areas of CO_2 emissions in case study factory B (adapted from Jawjit et al., 2010:405). Note: the electricity, diesel, LPG and ammonia are generated onsite and accounts for 50% of the total energy used during production.

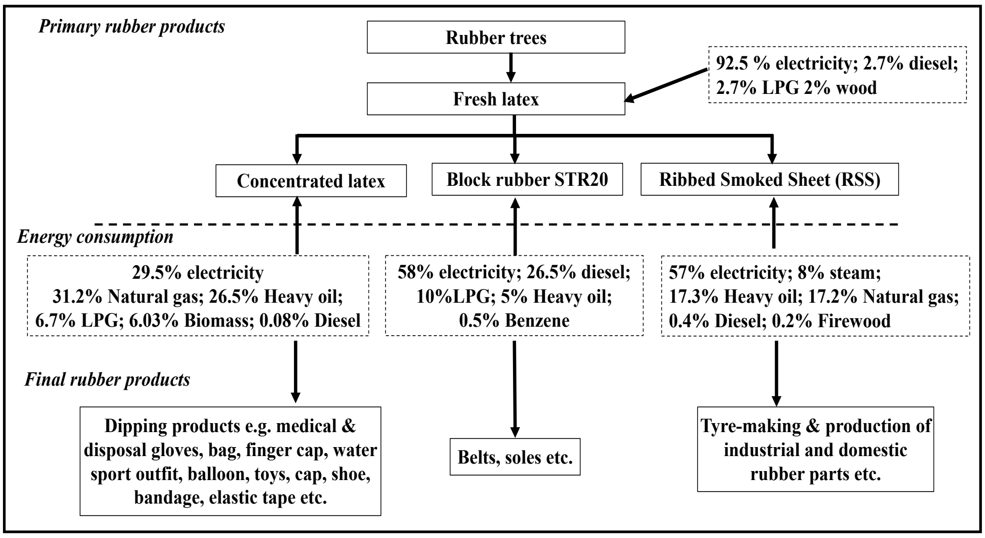

Figure 4.5: The main end-use energy and percent energy consumption in the case study factory B (compiled from NCPC-SA dataset).

Given that the focus of this study is on waste heat recovery during manufacturing activities, the main processing in the case study factory B is steam generation, calendering, extruding, cutting, building and curing (see Figure 4.6). These processes are conducted by heating, cooling and oven drying. The break-down of the total CO_2 emission, the total energy consumption from these production activities in the plant are presented in Table 4.5.

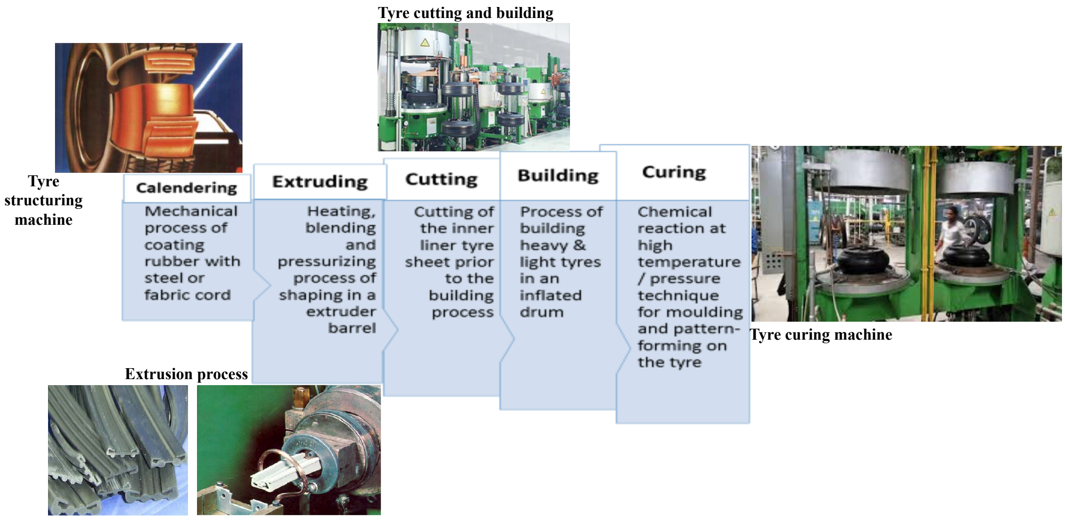

Figure 4.6: Main processes and machinery in a typical rubber and tyre manufacturing plant (adapted from DoAEDE, 2007:14-19).

Table 4.5: Total energy use and CO_2 emission in major processing units in case study B factory; suggesting a high share of fossil fuels in the energy mix.

<table>
<tr><th>Subsector</th><th>Process energy use (MWh/year)</th><th>Total energy use (MWh/year)</th><th>Processing units</th><th>CO_2 emission (ktons of CO_2 equivalent)</th></tr>
<tr><td rowspan="4">Case study B</td><td>9,787.05</td><td>14,744.2 (natural gas, coal)</td><td>Heating</td><td rowspan="4">514</td></tr>
<tr><td>2,109.26</td><td>8, 249.51 (electricity)</td><td>Cooling</td></tr>
<tr><td>6,955.2</td><td>18,309.3 (diesel, electricity)</td><td>Steam Generation</td></tr>
<tr><td>3,466.49</td><td>10,062.3 (diesel, electricity)</td><td>Oven drying</td></tr>
<tr><td>Total annual production: 410,447.4 Kg
43.45% energy used
56.55% energy lost</td><td>22,318</td><td>51,365.31</td><td></td><td></td></tr>
</table>

Footnote: The percentages of energy used are calculated by process energy used per total energy used x 100; while the percentage of energy lost is derived as the (100 – energy used) %.

4.3.1. Mapping of waste heat recovery opportunities

To map the waste heat recovery opportunities, a semi-structured interview was conducted with an energy specialist and project manager, given that primary data could not be retrieved due to lack of access to the plant. According to the respondents, four main processing units that release waste heat were identified as:

- Steam boilers for steam generation
- Gas turbines for energy generation
- Compressed air and vacuum systems;
- Conventional electrical chillers and cooling towers;

In discussion with the energy specialist from NCPC-SA, four main waste heat sources have been identified and considered acceptable for further exploration for waste heat recovery. These are:

- Hot water stream with a mean temperature of 77 ºC and mass flow rate of 139.6 kg/year
- Hot steam with a mean temperature of 116 ºC and mass flow rate of 26.18 kg/year
- Hot exhaust gases released from the heat recovery boiler from the natural gas turbine plant and having a mean temperature of 150 ºC and mass flow rate is of 158.8kg/year
- Flue gas from the drying and curing oven with a temperature of 160 ºC and mass flow rate is of 158.8kg/year.

4.3.2. Estimation of unrecovered waste heat stream

The energy content of the identified waste heat stream is further quantified using the associated parameters which are the waste heat stream Q_w; the waste heat stream mass flow rate (ṁ in kg/s); the density (ρ) of the flue gas (kg/m^3); the specific heat of substances Cp (in J/Kg.ºC); and the waste heat source temperature change expressed as ΔT (T_{in} - T_{out}). These parameters are incorporated into equation (1) described in chapter two as $Qw = \dot{m} \text{ x } \rho \text{ x } CP \text{ x } \Delta T$, and the quantified waste heat is presented in Table 4.6.

Table 4.6: Waste heat data for case study factory B. Note: the specific heat capacity in KJ/Kg.ºC for steam is 2.01; for exhaust gas is 1.063, and for flue gas is 1.0032. While the density in kg/m^3 for steam is 0.6; for exhaust gas at 150 ºC is 1.161; for flue gas at 160 is 0.88 ºC. The change in temperature used is the average between T_{in} and T_{out} for each process.

Process	**Equipment**	**Medium**	**ΔT (ºC)**	**ṁ (10^6 Kg/yr)**	**Q (Gj/year)**
Heating	Steam boilers	Hot water steam	77	139.6	**129,965.6**
Cooling	Electrical chillers	Hot air	116	26.18	3,662.5
Energy generation	Gas turbine	Hot exhaust	150	158.8	**29,397.3**
Oven drying	Drying/curin g ovens	Flue gas	160	158.8	2,430.6
Total					**165,456**

Footnote: The quantified waste stream (Q) in bold represent the waste heat with high potentials for being reused for work as well as reveal the processing unit with the most relevant amount of waste heat that could be harnessed. A total of 165,456 Gj of unrecovered waste heat contained in hot steam, exhaust and flue gas was released from 2017 to 2018.

4.3.3. Investigation of the grade of waste heat stream temperature

The quality of the unrecovered waste heat stream is presented in terms of the temperature grades of the unrecovered waste heat stream in Table 4.7. The work potential of low and medium temperature waste heat (based on a reference 25°C) reflects the maximum waste heat recoverable if hot steam, exhaust and flue gases from the steam boilers, gas turbines and drying and curing ovens are cooled to room temperature.

Table 4.7: The temperature ranges for waste heat stream in case study factory B. LT: low temperature; MT: middle temperature and HT: high temperature.

Case study	Waste heat source	Temperature range ºC	Temperature code	Unrecovered waste heat (Gj/yr) at 25 °C reference	% of total waste heat
Rubber and tyre production	Hot water steam Exhaust air Exhaust gas Flue gas	60 – 77 100 - 116 140 - 150 150 - 160	LT MT MT MT	12.99.6 x 10^4 3.66 x 103 29.39 x 10^3 2.43 x 10^3	78.55 2.21 17.77 1.47
Total				165,456	100

Footnote: A total of 165,456 Gj of unrecovered waste heat of low and medium-temperature grade contained in steam, exhaust and flue gas released from steam boilers, gas turbines and ovens; no high temperature (HT) was released from the processing units.

4.3.4. Analysis of waste heat source in the case study Factory A

The sub-findings from the waste heat stream mapping of case study factory B revealed the following:

- The main source of waste heat in the case study plant (see Figure 4.6) are from the steam boilers (hot water steam vented at ~77 ºC); the cooling process (hot air at 116 ºC); the gas turbine (hot exhaust at 150 ºC) and from the drying oven (flue gas at 160 ºC).
- The bulk (78%) of the waste heat stream released from the process line is of low-temperature grade (< 100ºC) grade (see Table 4.7).
- The potential for waste heat recovery exists where there is a huge amount of heating, and drying, given that the waste heat sources are channels where these processes are utilized.
- The mapping and estimation of the waste heat revealed that heat treatment, cooling and oven drying processes conducted through the use of steam

boilers, electric chillers and curing ovens yielded substantial amounts of 165,465 Gj waste heat which is equivalent to approximately 45,962.5 MWh of energy for the year 2017 – 2018 (see Table 4.6). Based on this quantified and qualified low-temperature waste heat stream from case study B factory, the potential for waste heat recovery is also very high.

- The vast majority (78%) of unrecovered waste heat stream is low-temperature grade quality, in the form of 129,900 GJ of hot water steam. The rest waste heat is release as medium temperature grade exhaust air, gas and flue gas (see Table 4.7).

- This analysis suggests that unrecovered waste heat stream from generic operation units that use steam boilers, electric chillers, and drying ovens should not be neglected, but rather considered when seeking opportunities for waste heat recovery in manufacturing industries at large. The adoption of currently available technologies like heat pumps or heat exchangers may provide significant opportunities for harnessing the low-temperature grade waste heat.

4.4. Appraisal of the production processes and energy use in case study factory C

Case study C manufacturing industry is located in Elandsfontein. According to the semi-structured interview with respondent 1, case study factory C is very energy and heat intensive. The total energy use per annum for this case study factory is 158,798.9 MWh (see Table 4.7). The main energy supply in this subsector is mainly from a combination of external electricity supply from the grid; internal heat and power generation; combustion of heavy oil, fossil fuel (coal); biomass fuel (bark); and combustion of the black liquor in the alkali recovery boiler to generate steam at high pressure (Zhao, et al., 2019).

The main processing units in case study factory C are wood chipping, pulping, bleaching, alkali recovery, calcination in lime kilns, paper making, and wastewater/sludge treatments (see Figure 4.7 for a sequence of the process). Large amounts of steam and electricity are used to conduct these processes. However, case study factory C is unlike other selected case studies, as this subsector generates over 50% of the energy used for production from by-products and biomass residue (Galitsky, 2009). Albeit this practice is not fully explored in South Africa.

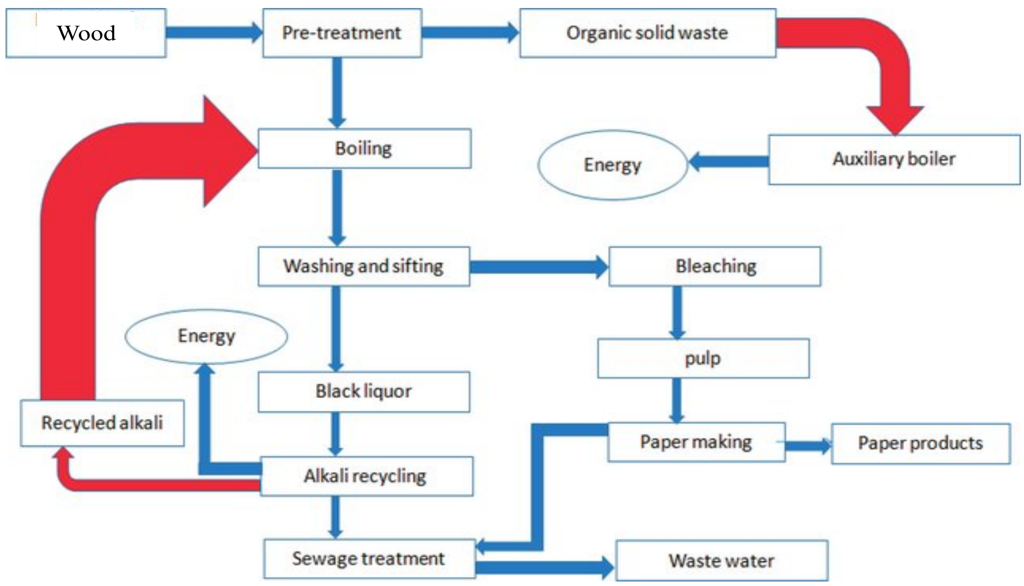

Figure 4.7: Process flow of a typical pulp and paper mill (adapted from Azeez, 2018:74).

The energy consumption and combustion of biomass and fossil fuel (such as coal, natural gas, bark and wood residual, black liquor and heavy oil) in each production process resulted in the generation of thermoelectric energy and associated loss of steam during distribution. This generated energy and steam loss results in excessive CO_2 emissions from the plant. Secondary thermoelectric energy is generated when fuel is combusted in steam boilers, and a large amount of CO_2 is emitted (see Table 4.8). The fossil fuel (natural gas and coal) to thermal energy conversion power station involved in steam generation was identified as the largest source of CO_2 emission, and the total emission from all processing units are approximately 514 kilotons of CO_2 equivalent.

Table 4.8: Summary of the total energy use and CO_2 emissions for the main processing units in case study factory C.

Subsector	Processing units	CO_2 emission (ktons of CO_2 equivalent)	Process energy use (MWh/year)	Total energy use (MWh/year)
Pulp and paper	Boiler system	121	37,107.1	65,138 (Natural gas, coal, sulphur)
	Papermaking unit	103	10,527.62	20,358.3 (thermal, electricity)
	Pulping process	96	29,765.3	57,950 (thermal, electricity)
	Alkali recovery	5	1,513.31	2516.8 (thermal, electricity)
	Pulpboard	77	4,689.2	7125 (electricity, fuel)
	Paper machine hot air system	12	2,181.5	5710.8 (thermal, electricity)
Production: 510, 692 Kg 55.28% energy used 44.72% energy lost	Total	414	87,784.03	158,798.9

Footnote: The energy use is per-process unit and total energy consumption presented is for the total annual production at the plant.

4.4.1. Mapping of waste heat recovery opportunities

The primary energy source of onsite heat and electricity generation in case study manufacturing plant C are mainly electricity, coal, bark and black liquor, coupled with the use of natural gas and heavy oil as supplementary fuel. The combined heating and power units in the case study factory C uses fossil and biomass fuels to produce steam and electricity, which according to the energy specialist, is partly used in the production process, while the rest lost as waste energy (see red arrows in Figure 4.8).

In addition, four main waste heat sources have been identified and considered acceptable for further exploration for waste heat recovery. These are:

- Hot water stream from the bleaching and pulping unit with a mean temperature of 77 ºC and mass flow rate of 26.8 kg/year (based on the secondary dataset).
- Hot steam from the paper making unit with a mean temperature of 116 ºC and mass flow rate of 139.6 kg/year (based on the secondary dataset).
- Hot exhaust gases released from the heat recovery boiler from the natural gas turbine plant and having a mean temperature of 150 ºC and mass flow rate of 158.8 kg/year (based on the secondary dataset).
- The lime calcination unit that does not use steam but fire for heating; hence is not considered in this research report for waste heat recovery.

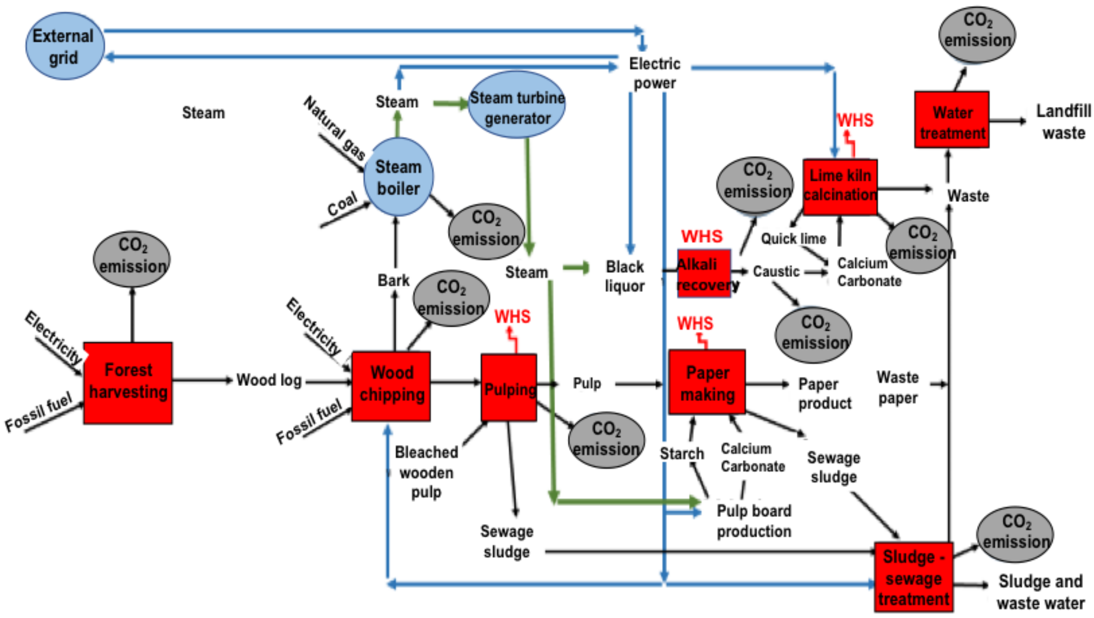

Figure 4.8: Schematic illustration of the main processing units, and associated energy sources, waste heat sources and CO_2 emissions of case study factory C. The red squares represent the main processing units; black arrows indicate the corresponding physical and chemical changes in the processes; the grey circles represent the numerous avenues at which CO_2 is emitted; the blue arrows indicate electricity flow, and the green arrows represent thermal energy flow; WHS represent the identified waste heat sources in this study.

4.4.2. Estimation of the grade of unrecovered waste heat stream temperature

The energy content of the identified waste heat stream highlighted above is further quantified using the associated parameters namely: waste heat stream Q_w; the waste heat stream mass flow rate (ṁ in kg/s); the density (ρ) of the flue gas (kg/m^3); the specific heat of substances Cp (in J/Kg.ºC); and the waste heat source temperature change expressed as ΔT (T_{in} - T_{out}). These parameters are incorporated into equation (1) described in chapter two (Qw = ṁ x ρ x CP x Δ). The quantified waste heat streams are presented in Table 4.9.

Table 4.9: Estimate of waste heat in case study factory C. Note: according to basic physics and measurements of matter, the specific heat capacity in KJ/Kg.ºC for steam is 2.01; for exhaust gas is 1.063. While the density in kg/m^3 for steam is 0.6; and for exhaust gas is 0.995. The change in temperature used is the average between T_{in} and T_{out} for each process.

Process	**Equipment**	**Medium**	**T_{in} (ºC)**	**T_{out} (ºC)**	**ṁ (10^6 Kg/yr)**	**Q (Gj/year)**
Pulping	Steam heated digesters	Pulp	85	95	139.6	**15, 152.2**
Bleaching	Steam heated bleaching towers	Pulp	50	70	139.6	10, 102.5
Paper drying	Dryer/Compressor	Pulp/paper	150	200	312	**57, 749.6**
Alkali recovery	Recovery boiler	chemicals	85	95	158.8	**17, 236.1**
Total						100, 240.5

Footnote: The paper drying process is observed as releasing the largest amount of waste heat stream.

4.4.3. Investigation of the waste heat stream temperature grade

The same technique used to determine the temperature grades of the waste heat streams in case studies factory A and B was adopted in the investigation of the waste heat stream temperature in case study factory C, and the results are presented below in Table 4.10.

Table 4.10: Main processes used in case study manufacturing factory C presented with their corresponding temperature range. LT: low temperature; MT: middle temperature and HT: a high temperature; the selected processes used to calculate the waste heat potential are in bold.

Case study	Waste heat source	Temperature range °C	Temperature code	Unrecovered waste heat (Gj/year) at 25 °C reference	% of total waste heat
Pulp & paper	**Exhaust vapour**	85-95	LT	15, 152.2	15.11
	Exhaust gas	50-70	LT	10, 102.5	10.07
	Exhaust gas	150-200	MT	57, 749.6	57.6
	Exhaust vapour	85-95	LT	17, 236.1	17.2
Total				100, 240.5	100

Footnote: The investigation of case study C revealed predominantly low-temperature grade unrecovered heat in the form of steam from the pulping, bleaching and alkali recovery units, and medium grade waste heat in the form of exhaust gas from the paper drying process.

4.4.4. Analysis of waste heat source in the case study Factory A

The sub-findings from the waste heat stream mapping of case study factory C revealed the following:

- The main source of waste heat in the case study plant (see Figure 4.10) are from the dryer/air compressor (exhaust gas released at 150-200 ºC); the boiler system (exhaust vapour at 85-95 ºC); the steam heated digesters (exhaust vapour at 85-95 ºC) and from the steam heated bleaching towers (exhaust gas at 50-70 ºC).
- The bulk (57.6%) of the waste heat stream released from the pulping process line is of medium grade temperature (>160ºC) grade (see Table 4.9).

- Given that the waste heat sources are channels where heating and drying processes are utilized, thus the potential for waste heat recovery exists in these process lines.

- The mapping and estimation of the waste heat revealed that the heat treatment and drying processes conducted through the use of steam-heated digesters, bleachers and boilers, and dryers yielded a substantial amount of 100, 240.5 Gj waste heat which is equivalent to approximately 27,844.4 MWh of energy for the year 2017 – 2018 (see Table 4.10). Based on this quantified and qualified low-temperature waste heat stream from case study factory C, the potential for waste heat recovery is also very high.

- The vast majority (57.6%) of unrecovered waste heat stream is medium temperature grade quality, in the form of 57,749.6 GJ of exhaust gas. The rest waste heat is released as low-temperature grade exhaust vapour (see Table 4.9).

- This analysis suggests that unrecovered waste heat stream from generic operation units that use steam boilers, compressors and dryers should not be neglected, but rather considered when seeking opportunities for waste heat recovery in manufacturing industries at large.

4.5. Analysis and interpretation of key findings

This substantive chapter quantified and qualified the waste heat streams from selected processes of energy-intensive processing units in case study A, B and C manufacturing plants. The analyses presented in sections 4.2 – 4.8 shows sub-findings for case study A which includes waste heat streams from the heating unit, evaporation unit, and spray dryer unit; case study B which includes waste heat stream from the calendaring, extrusion, cutting and building, cutting and curing; and case study C which include waste heat stream from the pulping, bleaching, alkali recovery, and paper drying process.

The waste heat streams from each selected case study were quantified by considering total energy consumption of each case manufacturing subsector and qualified into different waste heat temperature grades (LT, MT and HT). The sub-findings in this research study, although preliminary provides: (a) insights into the main processing units used in the case study manufacturing subsectors in Johannesburg, and b) highlights the associated temperature ranges of the analysed waste heat streams for each case study. These obtained temperature grades represent the waste stream that could potentially be recovered and harnessed.

Case study – Factory A

In Table 4.1, of the 80,468 MWh per year of total energy use reported for case study A, only about 56,327.6 MWh per year (70%) was used during production, and around 30 % was lost mostly as waste heat in exhaust gases, based on a reference enthalpy of 25 °C. Analysis of the total waste heat largely depends on energy consumed by each processing unit and on the temperature grade at which the waste heat is released. For instance, Table 4.3 shows that the heating, evaporation and cooling units are significant sources of waste heat; however, 88% of this waste heat is at low (< 100°C) and medium (less than 299°C) temperature grades.

Given the numerous low-temperature processes and consistently high demand and production that characterises this subsector (Law et al., 2013), the significant sub-finding of 236, 695.05 Gj (equivalent to approximately 65, 748.63 MWh per year) of unrecovered low-temperature heat stream (see Table 4.3) presents huge potential for waste heat recovery.

Case study – factory B

Meanwhile, Table 4.4 above reveals that of the 51, 365 MW/ year of total energy consumed by the case rubber and tyre manufacturing plant, only 22, 318 MW/year is used during manufacturing processes and about 56.55 % (29, 047.31 MW/year) was lost mostly as waste heat from the main processing units i.e. drying ovens, steam boiler and gas turbines for energy generation). Analyses revealed that 165, 456 GJ (equivalent to 45, 960 MWh) of low (78.55 %) to medium temperature

(21.45%) grade waste heat stream remains unrecovered (see Table 4.3). This, therefore, present an opportunity for waste heat recovery.

Case study – factory C

Lastly, Table 4.8 revealed that in the pulp and paper manufacturing plant, of the 158, 798.9 MW/year total energy consumed, approximately 55.3% is lost (71, 014.9 MW/ year) is lost mostly as waste heat from the pulping, bleaching, paper drying, steam boilers and alkali recovery processing systems. The estimated unrecovered waste heat stream of 100, 240.5 GJ (equivalent to 27, 844.58 MWh) are of low (42.38%) to medium temperature (57.62%) grades (see Table 4.10) and also provides tremendous opportunities for waste heat recovery.

The unique element in this analysis of the potential for waste heat recovery is that it allows for a better comparison of waste heat at different temperatures for various manufacturing industries. Firstly, each case study factory was discovered to have homogenous and generic processing units that typically consume a high amount of energy (i.e. the use of steam boilers in their operations, heating and drying processes). Secondly, the quality of the waste heat streams for all the case studies are characterised as low to medium grade temperature from exhaust gases, waste vapour steams and a few exhaust flue gases, with about 70% of the recoverable waste heat with exergy content being of low-temperature grade

These above-listed sub-findings suggests excessive emission as well as significant potential for waste heat recovery. However, during discussions with respondent 2, it was revealed that most of the manufacturing sites show limited interest in embarking on the recovery of waste heat. In this regard, the respondent disclosed that:

> *"Most factory operations managers place importance on profit-making above environmental concerns over CO_2 emissions" [Mrs. M].*

The respondent further claims that continuous production was the ultimate driver of energy consumption, while all other decisions were made subordinate in manufacturing industries. These findings indicate the reluctance of SMMEs to prioritise reducing GHG emission, and further confirms the 2014 South African Department of Environmental Affairs GHG report that shows the manufacturing sector is responsible for a significant portion of energy consumption and GHG emissions. This disparity implies a mismatch between the mindset of energy policy-makers and the understanding of operations managers on the important factors for achieving reducing carbon footprints and improving energy efficiency in their manufacturing plants (Solnørdal and Foss, 2018). Thus, energy policies should be implemented with regards to these issues. These policies should serve to motivate the interest of SMMEs to want to invest in projects to reduce GHG emissions, and on the other hand, these policies should challenge and stimulate the competence of the management of the factories as well as provide economic incentives for compliance toward reducing GHG emissions. An instance of such a policy is the Carbon tax that is slowing being phased into South Africa.

4.6. Synthesis of the waste heat recovery potential with available waste heat recovery techniques

The characteristics of the waste heat source and identified heat sink play a major role in the selection of recovery techniques that will yield optimum efficiency. Certain important parameters such as the waste heat source temperature categorized as low, medium-high-temperature grades determine the overall waste heat quality and effective matching of the source to sink; and the waste heat source mass flow is also crucial for determining and possible heating applications (Law et al., 2013). In this context, a comprehensive review is presented for waste heat recovery techniques suitable for harnessing waste heat from the identified sources in the case study factories. This subsection provides answers to sub-question 3 which is " What technically viable and practical ways are applicable for harnessing the identified waste heat?. This is achieved by appraising the most suitable and available recovery technique based on a comparison or review of feasible and available technology and criteria such as the heat transfer mechanism for low to medium temperature grade waste heat. The identified waste heat sources in the case study factories are matched to sinks and selected recovery technique.

Results from the thermal energy mapping revealed that the main source of waste heat in case study A factory (see section 4.3). The quantifying and screening of the potential waste heat revealed that heat treatment, cooling and evaporation processes through heat exchangers yield large amounts of waste heat (15.36 – 19.6 Gj per year**).** These avenues serve as a potential waste heat source that can be used to preheat the air supply for each of these processing units.

For instance, the waste heat released from the pasteurisation (heating unit) and cooling unit can be harnessed, and the temperature upgraded through a heat exchanger or heat pump for preheating cold milk in the regenerator. The low-temperature waste heat (60 – 90°C) from the refrigeration condensers in the cooling unit can be harnessed by first installing a heater or heat pump between the compressor and condenser to recover waste heat, and then re-using the recovered heat for several purposes, such as to produce hot water needed for plant clean-up; for preheating feed water for steam boilers; or to heat culture tanks for cheese production.

To explore the applicability of the approach of quantifying waste heat and screening of waste heat sources used in the case study factory A in this research, the processing units of similar food processing industries such as the egg processing, fruit and vegetable processing and confectionaries (baking) industry are considered. The egg production industry also conducts a pasteurisation, refrigeration and drying process, hence the release of waste heat from both units is expected. Waste heat from the pasteurization can be passed onto a regenerator to produce heat for preheating cold egg products. Whereas the exhaust air from the egg drying process can also be recovered for preheating steam boiler feed water, for heating water for washing the egg and for preheating air supplied to the dryer.

The main operations in the fruit and vegetable processing industry are freezing, washing and canning processes. Waste heat from the freezing operations is released from the condenser in the refrigerating unit, whereas for the washing and canning operations, waste heat is released from wastewater and retort vents. The waste heat released from the hot refrigerant can be harnessed for heating water needed for can washing, plant clean up and feed water for the steam boiler. While wastewaters with temperatures higher than ambient temperature can be harnessed to supply household heating, generate steam and reduce electricity use (Stafford et al., 2013).

In the confectionaries or bakery industry, the major waste heat is flue vent gases (similar to the milk and dairy production) released from the ovens, fryers, pan washers and steam boilers. This waste heat can be recovered and passed through an air-preheater and used for heating water needed for plant clean-up. The effectiveness of this waste heat recovery technique explored by Mukherjee (2017), showed that by increasing the exhaust air from ovens to 105ºC, 4% savings in fuel consumption by the oven and at least £4,200 of running cost is achievable.

The identified processing unit-specific sources of low-temperature grade waste heat identified in this case (Figure 4.2 and Table 4.1), as well as the several matched heat sinks (in section 4.5), requires innovative and technologically advanced energy recovery heat exchangers available for a waste heat source to sink heat transfer and the generation of electricity and refrigeration purposes. However, in the recovery of low-grade temperature range from exhaust gases, there is the possibility of contamination due to corrosion, hence this heat cannot be transferred back to the same process but can be useful for space heating or used in other areas of the manufacturing plant.

Therefore, based on the investigation done and the nature of the identified waste heat sources, suggested recovery methods in this instance include space and domestic water heating; temperature upgrading via heat pumps for combustion, process preheating or steam generation. There is also the possibility of converting the waste heat to electricity mostly using organic Rankine cycle technology, however, the most economical waste heat recovery technique is by heat pump/direct re-use to a nearby heat sink, and several different heat exchange systems are well-developed and economically available for commercial applications (Hammond and Norman, 2014). These recovery techniques are further discussed below.

4.6.1. Onsite waste heat recovery

Onsite waste heat recovery approach typically involves upgrading the temperature of the waste heat stream to a higher temperature (or in some cases such as in chemical (chilling) and air conditioning units, the conversion to lower temperatures) usually through the use of a heat pump, to use the heat in another processing unit (Hita et al., 2011; IEA, 2011; Soroka, 2011; Hammond and Norman 2014). In situations where the waste heat that is too low to recovered by a heat exchanger or used directly in other onsite processes, like in the case of the milk and dairy products plant investigated in this research, the low temperature (<80 °C) waste heat could be injected into a heat pump to meet the demand for low temperature (<100 °C) heat by a nearby heat sink (Hita et al., 2011; Hammond and Norman, 2014).

This technique is most suitable to harness the identified waste heat released at 60 ºC as exhaust air and vapour from the spray dryer and cooling units in the case milk and dairy production plant (see Figure 4.3). Since the cooling unit is a crucial processing unit and constitutes a major energy end-use in this case study, the refrigerant's condensers supply a large stream of waste heat into the air that could be transferred into a heat pump and injected into the nearby evaporating unit that requires heat at 75ºC. This effectiveness of this waste heat recovery technique is supported by calculations of the CoP of a heat pump conducted by Hita et al. (2011) shown in Table 4.11 that reveals that heat pumps tend to be most effective in its application with lower temperature waste heat.

Table 4.11: Calculation of the CoP of a heat pump conducted by Hita et al. (2011). The waste heat source to sink temperature matched in this case study from the cooling and spray drying unit to evaporation unit in the milk and dairy products manufacturing is indicated in bold (from 60 – 75ºC).

Temperature of Waste heat source T_S (ºC)	30-60	30-60	30-60	30-60	30-60	30-60
T_S* = T_S mean - 5 (ºC)	40	40	40	40	40	40
Temperature of Waste heat sink T_D (ºC)	60-70	70-80	80-90	90-100	100-120	120-140
T_D* = T_D mean - 5 (ºC)	70	80	90	100	110	135
Coefficient of Performance (CoP)	6.29	4.85	3.99	3.42	2.85	2.36

4.6.2. Conversion of waste heat to electricity using Rankine cycles

The Rankine cycle mechanism is a thermodynamic cycle which converts heat to mechanical energy for the eventual generation of electricity. This technique typically uses fuel to produce heat from a steam boiler which is then injected into a turbine to produce energy useful for work (Dincer and Bicer, 2020). This mechanism of waste recovery could apply to the milk and dairy case study with the steam boilers, cooling units and spray dryers utilize some amount of electricity as its source of electricity to operate (see Figure 4.3).

In addition, the electricity utilized in these processing units add to the total demand for grid electricity on the plant per year, hence, application of the Rankine cycle to generate electricity through the supply of waste heat stream heat could serve to supply the manufacturing plant's electricity and reduce its demand on the grid and electricity cost. According to the World Data information report for 2020, the current total energy consumption of electric energy per year in South Africa is estimated at 207.10 billion kWh, which is an average of 3,584 kWh per capita compared to an average 5,520.65 kWh for Europe. Furthermore, South Africa is reported to have undergone a seven-fold rise in CO_2 emissions since 1950, with 80 - 90% of the emissions ascribed to electricity generation from coal and combustion of fossil-fuel (Boden et al., 2011). As of 2018, the greenhouse gas emissions from

South African industries is reported as ~ 5.45 x 10^{11} kg CO_2 equivalent (Thambiran and Diab, 2011; DEA, 2014). Even with the White Paper policy, anticipations of South Africa's GHG emissions' peak, plateau and decline trajectories is predicted to peak at 6.1x10^{11} kg CO_2 equivalent between 2020 and 2025 (Feig et al., 2017).

In light of this development, with adequate investment in this recovery mechanism, and with a surplus supply of waste heat from a centralised unit by a cluster of manufacturing industries in Johannesburg or other parts of South Africa could generate enough electricity to supply the surrounding households, and eventually reduce the dependence on coal for electricity generation and total annual CO_2 emissions for that particular area (Figure 4.9).

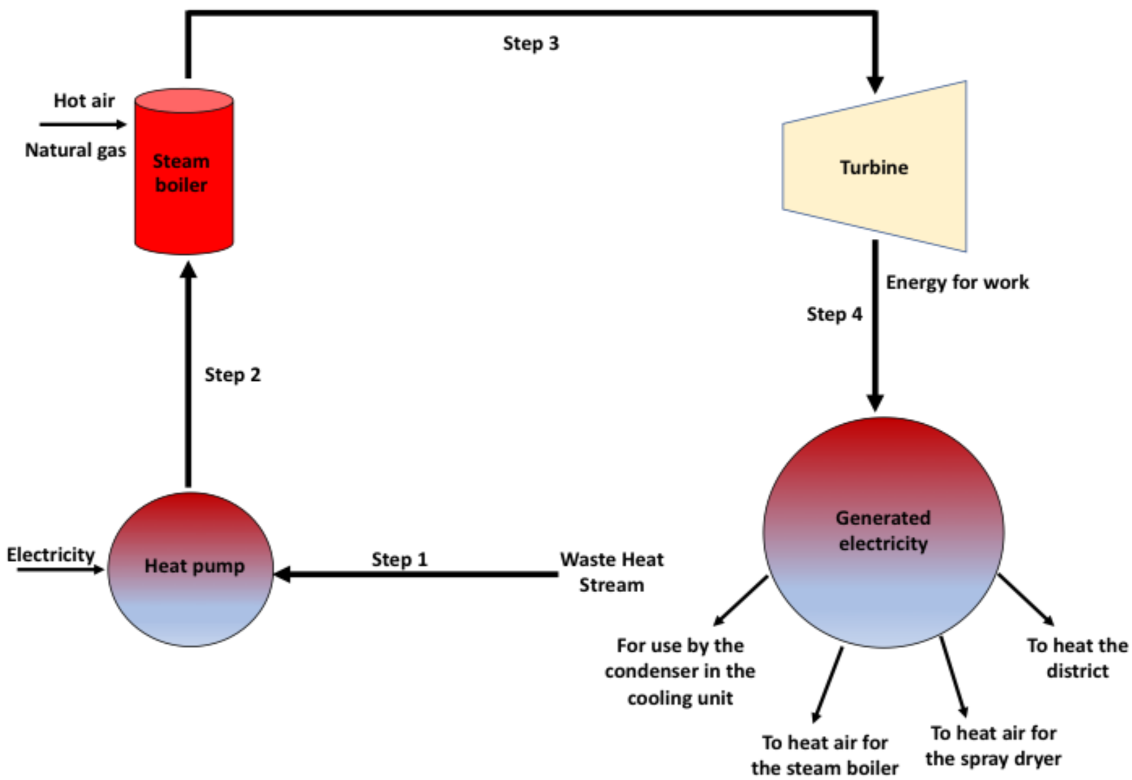

Figure 4.9: Waste heat recovery for electricity generation using Rankine cycles. Note the applicability of this technique for reduction of demand in grid electricity for both manufacturing plants and districts (households and neighbourhoods).

4.6.3. Waste heat recovery to supply an off-site heat demand

This waste heat from the case study manufacturing industries can be harnessed and transported to supply heat outside of the operating plant. This technique is applicable based on the establishment of a heat network, quite similar to the electricity supply network operated and regulated by Eskom whereby multiple end-users benefit from harnessed waste heat from manufacturing industries. The applicability of this proposed heat network to manufacturing industries across South Africa is if it is developed in major provinces that show industrial clusters and good potentials in this instance (Hammond and Norman, 2014) such as Johannesburg with multiple manufacturing and industrial sites. Implementation of this heat network, manufacturing plants could serve as both a heat end-user and supplier. Alternatively, this proposed heat network could also be used for district heating for the benefit of residential and commercial users, in such a way that with optimum usage in a particular district, electricity cost is reduced across for all users (Ibid).

4.7. Conclusions

This substantive chapter has presented the analysis of waste heat potential in selected manufacturing industries. Thereafter, a systematic approach of identifying the sources, quantifying and qualifying the waste heat in key equipment (such as steam boiler systems, air compressors and heat exchangers) and operating unit (namely heating, steam boiler systems and drying). Given that this procedure addressed widely used processing systems, it demonstrates its applicability and effectiveness for investigating waste heat recovery potential in other kinds of manufacturing subsectors.

Analysis of the waste heat stream from the exhaust gas and air from generic processing units such as boiler systems, heating and drying units in the case study manufacturing plants can be implemented in most manufacturing plants. The quantified and qualified waste heat for each case study suggests that there is significant potential for waste heat recovery in the manufacturing subsectors in Johannesburg.

For these specific manufacturing operations and identified waste heat sources such as waste vapour from air compressors, flue gas vents and exhaust air from steam, the most suitable recovery techniques recommended are the use of a heat pump or an internally incorporated heat exchanger for combined waste heat recovery and hot water generation. These techniques could serve as effective ways of reducing total energy cost incurred for production in a wide range of manufacturing industries.

CHAPTER FIVE: CONTRIBUTION OF WASTE HEAT RECOVERY TO THE MITIGATION OF CARBON DIOXIDE EMISSIONS FROM THE CASE STUDY FACTORIES.

5.0. Introduction

This chapter provides answers for sub-question 2 which is: "How can waste heat recovery in manufacturing industries contribute to the mitigation of greenhouse gas GHG in Johannesburg?" This analysis builds upon the temperature grade of the quantified waste heat stream in chapter Four for the case study factories. After quantifying and qualifying the waste heat stream in Chapter Four, it is important to derive the amount of the waste heat stream to be re-used for work (Panayiotou et al., 2017). This is the exergy content of the waste heat stream for each case study.

The initial step is to derive the Carnot's factor (i.e., η_C) for the portion of the quantified waste heat that could still be useful for work, rather than just being emitted along with associated carbon emission to the atmosphere as waste heat. This method also verifies the theory that only about half of the waste heat in an exhaust stream is considered technically recoverable (Miró et al., 2018). This allowed for detailed modelling of the selected case studies and the assurance of the achievement of results with a good degree of confidence.

Secondly, an estimation of the work (i.e., Carnot's) potential of the waste heat stream (WH_T) was calculated based on the factory data i.e. the total CO_2 emission from the case study factories (i.e., C_T); the calculated Carnot's factor (η_C) for each waste heat temperature grade in the case study subsectors; and subsector-specific data. To further reduce the uncertainty associated with the subsector specific activity data and ensure higher accuracy in results, the calculations for the waste heat (Carnot's) potential (WH_T) are based on the following assumptions:

- Only physical exergy at atmospheric pressure was used in this study. Other exergy contributions, such as chemical, kinetic and potential exergy, were neglected.
- The heat media temperature was taken as the mean of the estimated temperature range.

- The reference conditions for the calculation was established at atmospheric pressure and a temperature of 25 °C (US DoE, 2004).
- It was presumed that liquids and gases could be cooled down in practice to the reference temperatures of 25 °C for liquids and 40 °C for gases.

5.1. Estimation of Carnot's factor (η_C) for the waste heat stream from the case study factories

This analysis involved using the temperature grade of the quantified waste heat stream in Chapter Four to derive the amount of the quantified waste heat stream that is reusable for work. This portion of the waste heat stream is known as the Carnot's factor (η_{max} or η_C) and is derived from equation 3 in section 2.6.3. in Chapter Two. Which is:

$$\eta_{max} = \eta_C = 1 - \frac{T\ low}{T\ high}$$

where

η_{max} or η_C is the Carnot's potential (the amount of reusable waste heat)

T_{low} is the ambient temperature (assumed as the reference temperature of 25°C)

T_{high} is the average of the waste heat temperature grade (mean of the range e.g. mean of 40-60 ºC = 50 ºC).

For instance, the Carnot's factor (η_C) for low-temperature grade waste heat (40 - 60 ºC) in case study factory A = $1 - \frac{Tlow}{Thigh}$

$$= 1 - \frac{25}{50}$$

$$= 0.5$$

This indicates that 0.5 or half of the waste heat stream at a low-temperature of 50 ºC has the potential to be useful for technical work.

The Calculations for the Carnot's factor (η_C) for medium-temperature grade waste heat (160 -250 ºC):

$$\eta_C = 1 - \frac{25}{205}$$

$$= 0.5$$

This indicates that 0.5 or half of the waste heat stream at a medium-temperature of 205 ºC has the potential to be useful for technical work.

5.2. Estimation of waste heat Carnot's potential (WH_T) based on Carbon dioxide emission from case study factories

The waste heat Carnot's potential (WH_T) based on the CO_2 emissions for each case study manufacturing subsector is derived by using the Carnot's factor (η_C) derived for each case study in section 5.1, the total CO_2 emission for each case study and a compilation of the subsector specific parameters in equation 4 in section 2.6.4. in Chapter Two, which is:

$$WH_T = \frac{RF .CT.FCi \ \eta Ci}{KCi .LiL}$$

Where

R_F is the heat recovery fraction for any equipment = 0.5 (given that only about half of the waste heat is recoverable);

C_T is the reported total CO_2 emission (Kilotons/year) for each case study manufacturing plant;

F_{Ci} is the combustion emission fraction for each case study manufacturing subsector;

η_{Ci} is the calculated Carnot factor for each temperature range in each case study

K_T is the overall emission factors in each case study manufacturing subsector = 0.957

L_{il} is the load factor each case study manufacturing subsector = 0.96

The subsector-specific data used in the equation are presented in Table 5.1 and allowed for detailed modelling of the selected case study factories to ensure the achievement of results with a good degree of confidence.

Table 5.1: Subsector-specific parameters used to estimate the waste heat work potential based on CO_2 emission. The pages where the definition of the variables are stated in the report are in parenthesis.

Variables	Description	Value	Source
R_F	Heat recovery fraction (see p. 344)	*Case 1: 10% (low) *Case 2: 20% (high) Thus ration = 10:20	Miró et al. (2018); McKenna and Norman (2010); McKenna (2009)
F_C	Subsector's combustion emission fraction+ (see p. 44)	Food processing 0.98[a] Pulp and paper 0.6 [a] Chemicals 0.44 [a]	Lozynskyy et al. (2014)
η_C	Carnot factor (η_C) (see p. 38)	Calculated for each waste heat temperature grade	The case study subsectors
L_F	Subsector's load factor (see page 30)	Food processing 0.96 Pulp and paper 0.96 Chemicals 0.96	Eskom schedule of standard prices SC0207 (mega flex general tariff - 2018/19 page 24)
K_T	Subsector's overall emission factor	0.957[b]	Spalding-Fecher (2011)

Footnote: * For R_F the ratio of low to high is considered as 0.5 since typically, only about half of the waste heat in an exhaust stream is considered technically recoverable (Miró et al., 2018). [a]These values represent a fuel benchmark related to the mean fuel combustion emission factor for South African manufacturing industry based on the World bank's 2014 technical support study on GHG emissions intensity benchmarks for South African carbon tax. [b]The indicated manufacturing subsector's overall emissions fractions represents the carbon emission factor for the manufacturing sector in South Africa. This value is derived from the total fuel combustion and process combustion for all manufacturing subsectors. The overall reliability of the compiled combustion emission fraction is based on energy balance sheets and sourced facility-level activity data collected by the NCPC-SA.

For instance, the calculation for the waste heat Carnot's potential (WH_T) for low and medium temperature grades in case study factory A using equations (4) from chapter 3 is explained below:

For low temperature grade: $WH_T = \frac{RF \cdot CT \cdot FCi \cdot ŋCi}{KCi \cdot Li}$

$$WH_T = \frac{0.5 \; x \; 619 \; x \; .0.98 \; x \; 0.5}{0.957 \; x \; 0.96}$$

$$= 165.07$$

Then derive the total fuel use $= CT + FCi + K_T$ (KWh/year)

$$= 619 + 0.98 + 0.96 = 620.94$$

Expressed as a % of total fuel use $= \frac{287.22 \; x \; 100}{620.94}$

$$= 26.6 \%$$

This suggests that 26.6 % of the total emitted low-temperature waste heat stream contained in exhaust air from case study factory A has the potential to be reused for work.

For medium temperature grade: $WH_T = \frac{RF \cdot CT \cdot FCi \cdot ŋC}{KCi \cdot Li}$

$$WH_T = \frac{0.5 \; x \; 619 \; x \; .0.98 \; x \; 0.88}{0.957 \; x \; 0.96}$$

$$= 290.52$$

Expressed as a percent of total fuel use $= \frac{290.52 \; x \; 100}{620.94}$

$$= 46.8\%$$

This suggests that 46.8 % of the total emitted medium temperature waste heat stream contained in exhaust air has the potential to be used for work.

Miró et al. (2018) emphasize that the combination of the manufacturing subsector's "emissions (C_T), the combustion emission fraction (F_C) and the overall emission factor (K_T)" signifies the total fuel consumption for the particular case study in question. Lastly, the load factor (L_F) signifies the annual working time expressed as the average capacity utilized. The derived results along with the Carnot's factor (η_C) and waste heat Carnot's potential (WH_T) presented below in Table 5.2.

Table 5.2: Derived Carnot's factor and waste heat (WH_T) potential for the case study manufacturing plants at their corresponding waste heat temperature grades. The total CO_2 emissions and emission factor for each case study are presented per year.

Subsector specific parameters	Case study A	Case study B	Case study C
Temperature grade (ºC)	LT: 40 – 60 LT: 40 - 60 LT: 85 - 100 MT: 160 – 250	LT: 60 – 77 MT: 100 - 116 MT: 140 - 150 MT: 150 - 160	LT: 70 – 77 LT: 85 - 95 MT: 50 – 70 MT: 150 – 200
Carnot factor (η_C)	LT: 0.5 LT: 0.5 LT: 0.73 MT: 0.88	LT: 0.63 MT: 0.77 MT: 0.83 MT: 0.84	LT: 0.72 LT: 0.72 MT: 0.58 MT: 0.86
Carbon emission (kilotons CO_2/year)	619	514	414
Subsector's combustion emission fraction (F_C)	0.98	0.44	0.6
Total fuel = $C_T + F_{Ci} + K_T$ (KWh/year)	620.94	515.4	415.56
Waste heat potential (%)	LT: 26.6 LT: 26.6 LT: 38.8 MT 46.8	LT: 21.1 MT: 25.8 MT: 27.9 MT: 28.2	LT: 17.3 LT: 17.3 LT: 14 MT: 20.7

As observed in Table 5.2, the waste heat Carnot's potential percent calculated for all the case studies increased with temperature grades. Given that the waste heat Carnot's potential is an accurate indication of the portion of the waste heat that could still be reused for technical work and is expected to increase with temperature (Panayiotou et al., 2017; Miró et al., 2018), the calculated Carnot's potential in this research report are valid. The relationship of the waste heat work potential for each case study manufacturing subsector and their waste heat sources identified in Chapter 4 is further presented in Figure 5.1.

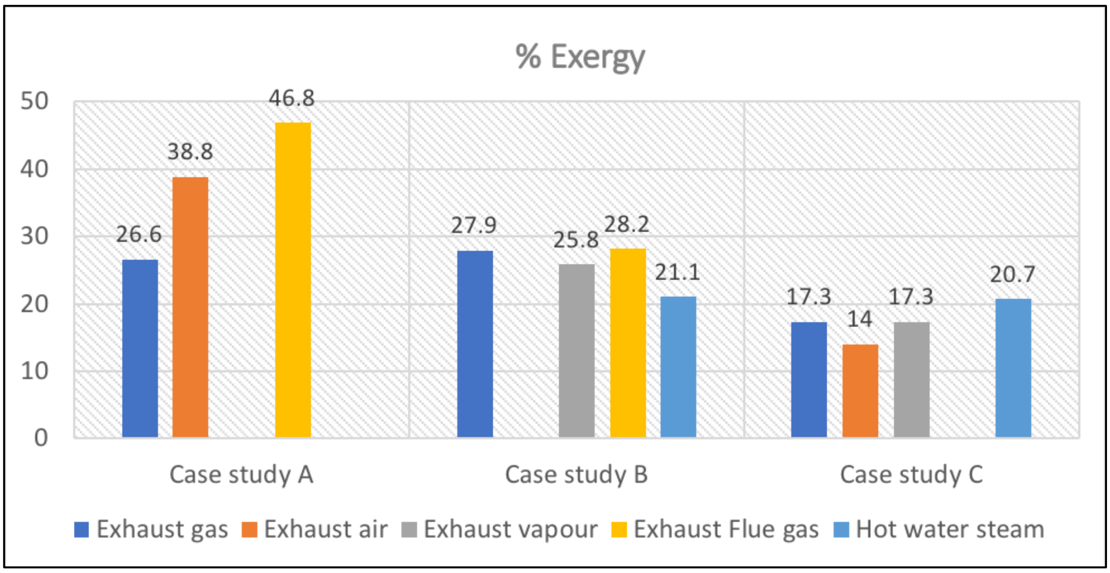

Figure 5.1: Waste heat Carnot's (work) potential for the waste heat streams corresponding temperature ranges (LT and MT) for each case study. The respective waste heat sources for each case study factories were identified in Chapter 4.

Analysis of the Carnot's potential derived for the respective waste heat stream for each temperature range suggests that there is a significant amount of exergy (i.e. reusable energy content) in the waste heat emitted from the process units of each case study manufacturing plant. Between 14 - 46.85 % of the waste heat streams quantified for each case study in Chapter 4 (i.e., between 100, 240.5 - 236, 695 GJ) have the potential to be reused for onsite work.

A breakdown of the amount of energy that could be used for work is further presented in Table 5.3 below:

Table 5.3: Analysis of exergy content (in GJ/year) in unrecovered waste heat stream in the period of 2017-2018 for selected case studies.

Case study	Waste heat source	Temp code	Unrecovered waste heat (Gj/year)	% waste heat Carnot's potential	Exergy content in waste heat (GJ/year)	Exergy as % of total waste heat stream
A	Exhaust flue gas Exhaust air Exhaust gas Exhaust gas	MT LT LT LT	28,464 8,061.4 34,309 165,860.65	46.8 38.8 26.6 26.6	13,321.15 3,087.52 9,126.2 44,118.93	
Total			236,695.05		69,653.8	29
B	Hot water steam Exhaust air Exhaust gas Flue gas	LT MT MT MT	129,965.6 3,662.5 29,397.3 2430.6	21.1 25.8 27.9 28.2	27,422.74 944.93 8,201.85 685.43	
Total			165,456		37,254.95	22
C	Exhaust vapour Exhaust gas Exhaust gas Exhaust vapour	LT LT MT LT	15,152.2 10,102.5 57,749.6 17,236.1	17.3 14 20.7 17.3	2,621.33 1414.35 11,954.17 2,981.84	
			100, 240.5		18,971.69	19

Footnote: Unrecovered heat is quantified at 25°C reference.

Table 5.3 shows that the case study A which is the milk and dairy products manufacturing subsector has the highest energy content of 29 % for low to medium temperature grade waste heat stream, given that this case plant emitted the largest CO_2 emission for the year 2017 to 2018 (see Table 5.2). An estimated energy content of 23 % is derived for the total waste heat stream from case study factory B which is the rubber and tyre manufacturing plant, and 19 % of energy content is present in the unrecovered waste heat stream from case study C which is the pulp and paper production subsector.

Although the waste heat streams from all the case studies are restricted to low and medium temperature grade, which is considered a lower quality waste heat, these analyses show that it is present in large amounts in the all the subsectors. The derived work potential of between 19 to 29 % represents about one-fifth to a third (20 - 30 %) of the total estimated waste heat streams for all three selected manufacturing case studies.

5.3. The link between carbon emission and energy loss in the case study

The link between carbon emission and energy loss in the case study factories is developed on the basis that waste heat is released from energy-related processes involving fossil fuel combustion during manufacturing activities. The carbon emissions (in kilometric tons of carbon equivalent – KTCE) associated with energy losses in the selected case study are shown in Table 5.4. These add up to nearly 15.47 x10^2 KTCE, which represents a significant amount of carbon emissions from the manufacturing sector (2015 National GHG inventory: DEA, 2014; 2019) in South Africa from anthropogenic (manmade) sources. The carbon emissions shown in Table 5.4 are generated by fossil fuel combustion, steam conversion losses and energy conversion and losses that occur during process operations, and also the end-of-process losses.

These energy losses from manufacturing processes are contained in hot exhaust flue gases, air and vapour released from compressors, coolers, dryer vents and condensers to the environment. Given that the waste heat stream is released with associated carbon emissions from fossil fuel combustion during manufacturing activities; the adoption of fuel switching to recovered waste heat to provide useful energy will reduce overall fossil fuel combustion and associated carbon emissions from the factories.

Table 5.4: Energy use and losses of case study factories. CO_2 emissions are derived from secondary data.

Case studies	Processing units	CO_2 emission (Ktons CO_2 equivalent)	Process energy loss (MWh/yr)	Process energy use (MWh/yr)	Total energy use (MWh/yr)
Case study A: Milk and dairy products factory	Heating	206	3,745	16,455	20,200
	Cooling	171	876.2	6,953.8	7,830
	Evaporation	136	781.46	13,518.54	14,300
	Spray dryer	106	18,737.74	19,400.26	38,138
70% energy used 30% energy lost	Total	619	24,140.4	56,327.6	80, 468
Case study B: Rubber and tyre production	Steam boilers	514	6,140.25	2,109.26	8, 249.51
	Electrical chillers		4,957.15	9,787.05	14,744.2
	Gas turbine		11,354.1	6,955.2	18,309.3
	Drying/curing ovens		6,595.81	3,466.49	10,062.3
43.5% energy used 56.6% energy lost	Total		29047.31	22, 318	51, 365.31
Case study C: Pulp and paper production	Boiler system	121	28,030.9	37,107.1	32,569
	Papermaking unit	103	9,830.68	10,527.62	10,179.15
	Pulping process	96	28,184.7	29,765.3	28,975
	Alkali recovery	5	1,003.49	1,513.31	1258.4
	Pulpboard	77	2,435.8	4,689.2	3562.5
	Paper machine hot air system	12	1,529.3	2,181.5	2855.4
55.3% energy used 44.7% energy lost	Total	414	71,014.87	87,784.03	*79399.45

Footnote: *Case study factory B and C conducts onsite energy generation which contributes about 50% to the primary energy used in production and is not included in the totals.

As shown in Table 5.4, case study A, B and C records 30 %, 57 % and 45 % energy loss from their process units respectively. These energy losses from each processing unit are presented as percentages of the total annual energy loss for each case study in Figures 5.2 - 5.4. The chart shows that the largest energy losses occur in processes involving the use of steam boiler systems, heating and drying units. Collectively, the losses from the steam boiler system are the highest, accounting for approximately 39% of all individual energy systems in all the case studies, followed by the drying units which accounts for 31 % of the total energy loss.

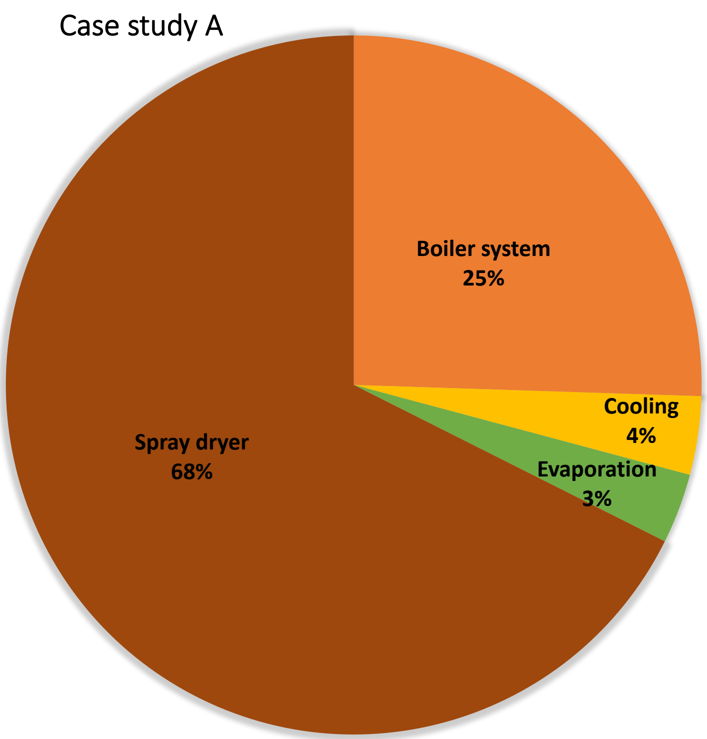

Figure 5.2: Percent of energy losses from the main processing unit in case study A.

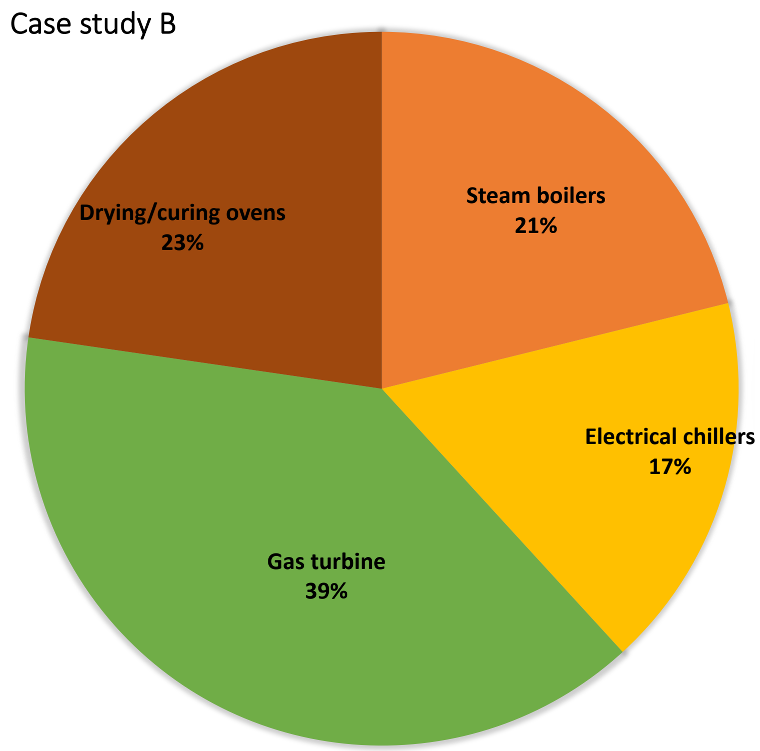

Figure 5.3: Percent of energy losses from the main processing unit in case study B.

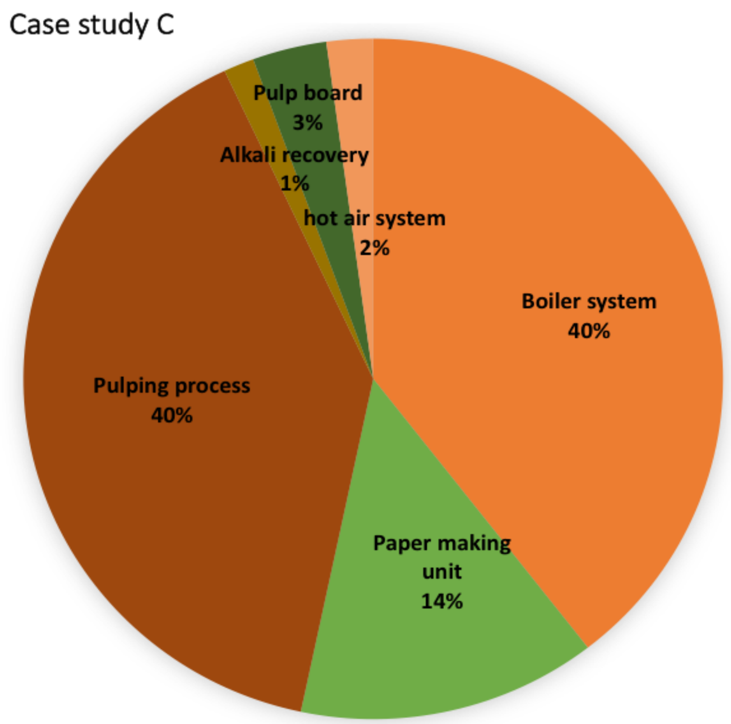

Figure 5.4: Percent of energy losses from the main processing unit in case study C.

In light of these sub-findings, it is logical to state that if waste heat contained in the exhaust gas, air or vapour from steam boilers, air compressors, dryers and condensers are recovered on site, there would be a resultant reduction in energy demand, and in turn, a significant reduction in carbon emission from the respective manufacturing activities.

5.4. Benefits of waste heat recovery and reduction of carbon emission for the case study factories

This section provides substantive answers to sub-question three which is "In what ways can waste heat recovery contribute towards the reduction of GHG emission for manufacturing industries?". The sub-findings presented in this section further highlights the potential savings on energy use and cost based on the estimated energy content available in the waste heat streams of each case study manufacturing plant.

5.4.1. Energy saving and carbon emission reduction

The secondary data derived from the NCPC-SA on total energy consumption and CO_2 emissions for each case study for the period of 2017-2018 were used to deduce the significant potential savings to the case study energy usage and reductions in CO_2 emissions based on harnessing the quantified waste heat stream from each case study. The Eskom tariff baseline for 2018 was used to calculate the total costs and the figures presented in Table 5.5 below provide a basis for deducing potential energy-use and costs saving based on the recovery of the analysed waste heat. The conversion rate of 3.6 GJ equal to 1 MWh was applied to the total energy consumption (in MWh/year) to obtain the energy use in GJ in order deduct the energy content in the unrecovered waste heat stream and achieve the potential energy savings presented in Table 5.5.

Table 5.5: The potential savings on energy consumption and cost based on the quantified exergy content in waste heat streams for case study factories for the year 2017-2018.

Case study	Total Energy use (GJ/year)	Quantified energy content in waste heat (GJ/yr)	% energy saved	Energy cost (Rands/yr)	Energy cost savings (Rands/yr)	CO_2 reduction (kg CO_2 year)
A	289,684.8	69,695.8	24	73,225,880	17,423,946	68,789.75
B	184,915.12	37,254.95	20.15	46,742,432.1	9,417,226	36,770.63
C	285,838.02	18,971.69	6.64	144,506,999	4,742,919	18,725.06
Totals	**1,046,275.92**	**125,922.44**		**264,475,311**	**31,584,091**	*** 124,285.44**

Footnote: The Eskom's 2018 tariff of R 0.91 per Kilowatt/hour was used to determine the amount in Rands spent on electricity in each process units. The CO_2 emission reduction is derived by multiplying the energy saved in GJ by the carbon emission factor of 0.987 for the manufacturing sector in South Africa (Spalding-Fecher, 2011) explained in Table 5.2. * The sum of CO_2 emission reported for all case study converted to kg per year is 20. 85 x 10^4 kg per year.

Although a clear outlook of energy cost savings is typically done by comparing the waste heat recovery technique and the investment cost of the upgrade in the case study factories, Table 5.5 reveals that the large amount of energy consumption reported by the case study factories results in a high amount of waste heat streams. Table 5.5 also shows that recovery of waste heat can significantly reduce energy use and in turn, costs and CO_2 emissions for the case study factories. Highlights of these savings and reductions are presented as:

- A potential saving of 24% of total annual energy consumption and a CO_2 emission reduction of 68,789.75 kg per year can be achieved for case study A.
- A potential saving of 20.15 % of total annual energy consumption and a CO_2 emission reduction of 36,770.63 kg per year can be achieved for case study B.
- A potential saving of 6.64 % of total annual energy consumption and a CO_2 emission reduction of 18,725.06 kg per year can be achieved for case study B.
- Lastly, a potential total reduction in CO_2 emission of 124,285.44 kg can be achieved, which is a 59.6 % reduction from the total CO_2 emission reported for the case studies.

The evaluation of potential energy savings and costs, as well as CO_2 emission reduction revealed case study A as showing the highest values across. However, given that substantial savings can still be achieved in all selected case study factories, the adoption of waste heat recovery promises potential energy consumption and costs savings and reduction of CO_2 emission from all manufacturing activities in general.

South Africa has a long history of high carbon emission caused by the dependency on coal for power generation, and micro-level reduction of carbon emission of specific manufacturing subsectors could substantially contribute positively to the fight to reduce GHG emission and mitigate climate change. In addition, CO_2 emission is gradually becoming a mandatory reporting issue, and the country is gradually phasing in additional stages of the ongoing Carbon Tax regime. Thus, the recovery of waste heat from exhaust pipes of manufacturing SMEs offers potential for organizations to benefit reduced carbon tax and rebates. These pressing issues are likely to motivate manufacturing plants to adopt waste heat recovery in their facilities.

Further benefits associated with waste heat recovery from the identified waste heat sources can be highlighted as follows:

- Potential reduction of capacity requirements for the machinery used in production due to the recovery of a significant amount of unrecovered low-temperature heat contained in several product streams.
- Potential reduction in incurred energy costs and overhead cost for the manufacturing plants themselves.
- Based on a reduction in energy use, there will be a reduction in demand on the grid by the manufacturing industries.
- Potential reduction in fuel combustion during energy-intensive operations and the associated carbon emission released through the exhaust pipes of machinery used.
- A significant contribution to the improvement in industrial energy efficiency and cleaner production in Johannesburg.

5.5. Analysis and interpretation of key findings in relation to the manufacturing sector.

The sub-findings presented in this chapter is the analysis of the potential of reusing the quantified waste heat from each case study. The estimated waste heat work potential in Section 5.2 represents the exergy (useful energy content) available in the unrecovered waste heat at their different temperature grades. The graph of exergy percent (Figure 5.1) indicates that the majority of waste heat losses (based on a 25°C reference) spread across low and medium temperature grades and contained in exhaust gases and air, steam, flue gas and hot water steam.

The analysis in Table 5.3 shows the following sub-findings:

- The unrecovered waste heat stream from case study A which has approximately 69,655.8 GJ exergy (reusable energy) content. This is about 30 % of the total annual waste heat (236,695.05 GJ) estimated for this factory.
- For case study B, there is approximately 37,254.95 GJ exergy (recoverable energy) content in the unrecovered waste streams; and this amounts to 22.5% of the total annual waste heat (165,456 GJ) estimated for this factory.

- Lastly, the energy content of 18,971.69 GJ is contained in the unrecovered waste heat stream from case study C, and this amounts to 18.93% of the total annual waste heat (100, 240 GJ) estimated for this factory.

The analysis further reveals that the waste heat stream from case study factory A has the highest energy content (29.4% of the total subsector's emissions). However, it can be concluded that the energy contents in the waste heat streams for each of the case studies are relatively close. This sub-finding indicates the effect of similar processing units involving boiler systems for heating and drying in all the case studies. Given that these units are standard or generic units common to a wide range of manufacturing industries, it is logical to expect a similar amount of energy contents to be contained in the unrecovered waste heat streams emitted from several manufacturing industries in Johannesburg.

Furthermore, given that the identified the waste heat sources in the study are from exhaust air and gases, and flue gas, a significant portion is fuel-related emissions resulting from the combustion of fossil fuel mixed with some non-condensable gases (Kirova–Yordanova, 2015). Hence, waste heat recovery at low and medium temperature grade provides a means for these case study manufacturing industries to significantly reduce their energy and fossil fuel consumption, which in turn reduces the associated operating costs, pollution caused by CO_2 emissions due to fossil fuel combustion.

5.6. Scale up benefits of the reusable energy

According to Fragkias et al. (2013), over 66% of the world's energy is used up in urban areas and these areas are responsible for over 70% of the world's GHG emissions. Also, given that energy consumption evolves around producing more CO_2 that is emitted into the air, causing natural damage and climate change. The findings on the waste heat Carnot's potential which denotes the portion of reusable waste heat could result in CO_2 emission reduction. This serves as actions towards achieving the national reduction goal and mitigating climate change. Thus, it is important to present the possible scale-up benefit of the derived exergy content in the case study factories.

These are classified as direct and indirect benefits:

Direct Benefits:

- Economic and resource saving (i.e., fuel consumption) saving. This involves improved energy efficiency in the production process, which is reflected by reduced energy demand, consumption and costs, as well as reduction in capital investment cost associated with the installation of new process facilities.
- Transformation of waste heat to useful forms of energy.

Indirect Benefits:

The indirect benefits of reusing energy recovered from waste heat includes

- **Life-cycle climate benefits**: Low carbon energy is used in production as opposed to manufacturing of products with higher life-cycle emissions
- **Reduced air pollution:** Recovered heat could significantly reduce the emission of carbon, GHG and other toxic gases to atmosphere; which in turn results in reduced environmental pollution levels.
- **Reduced equipment sizes:** Recovered waste heat results in reduced fuel consumption, which yields reduced production of flue gas. This results in reduced sizes of all equipment that handle flue gas such as fans, burners, stacks etc.
- **Reduced consumption of auxiliary energy:** A reduction in equipment size is achieved yields additional benefits such as reduced auxiliary energy usage like electricity for fans, pumps etc..
- **Development of methods** needed to inform future energy policies and investment decisions by the manufacturing industries themselves

5.7. Conclusions

This chapter shows the result for the potential for the estimated waste heat in chapter four to be useful for onsite work. The estimated waste heat stream and their corresponding temperature grades in the case study were found to be released in the form of exhaust air or gases of major operating units. The case studies showed fairly consistent values for waste heat Carnot's potential, suggesting that at any temperature range, there is potential for waste heat recovery and re-use for work. Based on the sub-findings from chapters four and five, considerable potential exists for recovering some of the wasted energy in the manufacturing sector of the economy. In conclusion, the substantial portions of waste heat potential to be used for work (Carnot's potential) as quantified in this chapter, suggests that implementation of recovery techniques in manufacturing industries in Johannesburg would significantly reduce CO_2 emissions and energy costs. The values derived from the analysis of potential energy savings and CO_2 reduction in the case study factories range from 7 - 24 % savings in energy consumption and between 18725 – 68,789.75 Kg reduction in CO_2 emissions per year. Approximately a potential total reduction in CO_2 emission of 124,285.44 kg can be achieved, which is a 59.6 % reduction from the total CO_2 emission reported for the case studies.

Considering the rising energy prices, manufacturing industries are forced to reconsider their energy usage and seek measures to reduce usage and incurred cost. The approach used in this study could serve in providing operations managers with the opportunities to make informed decisions for improving the operations processes in their factories.

CHAPTER SIX: CONCLUSION AND RECOMMENDATIONS

6.0. Overview and approach to consolidation

The study has explored the opportunities for waste heat recovery by investigating the key waste heat sources from the main process units from selected case study manufacturing plants. The study also estimated the identified waste heat streams and analysed the work potential of the unrecovered waste heat based on the temperature grade at which the heat is emitted to the atmosphere. This analysis was useful for determining the potential of achieving energy savings and reduction of CO_2 emission from waste heat recovery in manufacturing industries.

The study was structured around three research sub-questions which are:

- What potential exists for waste energy recovery in selected manufacturing industries in Johannesburg?
- What are the key points of energy loss and waste heat channels in manufacturing processes?
- In what ways can waste heat recovery contribute towards the reduction of GHG emission for manufacturing industries?

Each of the sub-questions substantiated on different aspects of the overall research question which investigated the extent at which waste heat recovery in manufacturing industries could contribute to the mitigation of GHG emission and related climate change due to the ongoing global warming.

The primary aim of the study was to investigate the key points at which waste heat is released during manufacturing processes and the opportunities for recovery and onsite use as an energy source, to contribute towards the goal of achieving sustainable energy for the city of Johannesburg,

The study finds that waste heat streams are contained in exhaust gases, air and vapour emitted from the steam boiler system, heating, air compressors, and drying processing units; which are generic processing units widely used in manufacturing industries and typically consume a high amount of energy. Secondly, the quality of the waste heat streams for all the case studies are characterised as low to medium grade temperature that provides tremendous opportunities for waste heat recovery. However, although low and medium temperature grade waste heat is considered to be of lower quality, the analysis shows that about 125,922.44 GJ is present with a work potential of between 18.93 to 29.4% representing about one-fifth to a third (20 - 30 %) of the total estimated waste heat streams for all three selected manufacturing case studies. In addition, given that this waste heat stream is released with associated carbon emissions from fossil fuel combustion during manufacturing activities via commonly used processing unit (i.e. steam boiler systems, dryers, ovens, air compressors); the study finds that the recovery of waste heat promises significant potential energy savings ranging from 7 - 24 % and CO_2 emissions reduction ranging from 18,725 – 68,789.75 Kg for manufacturing industries that use these processes.

6.1. The main waste heat sources during manufacturing processes

Manufacturing processes involve processing raw materials into finished products, and this is achieved by the action of generic processing units namely: steam boiler systems, heating, and drying actions, ovens or air compressors. The study finds that these processing units typically consume a high amount of energy and are responsible for significant energy losses of around 30-56 % as a result of losses associated with steam conversion, energy conversion, losses that occur during process operations, and also end-of-process losses. The sub-findings from this study reveals that the energy losses are mostly released as low to medium temperature (< 299 °C) waste heat streams contained in exhaust gases, vapour and a few flue gases ejected into the environment.

Waste heat, therefore, represents an important, but yet to be fully exploited energy source. Thus, waste heat recovery and its reintegration into production processes or re-use for other onsite purposes such as the factory's heat demand is an emission-free energy source that reduces the intensity of expensively priced fossil fuels or electricity usage, that also offers public benefits like a significant reduction on energy demand on the grid, reduced GHG emission and overall environmental degradation.

6.2. The estimation of waste heat potential

The estimation of waste heat potential is a pivotal step towards better management and utilization of waste heat. This crucial step was conducted in the study and it involved quantifying waste heat released from the identified sources in GJ per year and the temperature grades at which the heat is released. This analysis was conducted in this study using sector-specific parameters for the waste heat stream such as the media; the mass flow rate (Kg/year); the temperatures (ºC) at inlet and outlet points in the equipment; and the quantified CO_2 emissions from individual processing units.

The quantified waste heat stream based on a reference temperature of 25°C in the three case study factories in the study estimated as 100, 240.5 - 236, 695.05 Gj for case study A, B and C respectively reveals that there is substantial potential for waste heat recovery in manufacturing industries. The work potential based on Carnot efficiency for energy conversion (mechanical or electrical) was derived for the estimated waste heat stream. This evaluation of the energy content in the quantified energy stream allowed for a better comparison of waste heat with different exhaust temperatures. The study finds that the portion of the waste heat that could still be reused for technical work increased with temperature, and between 18.93 to 29.4% (which represent about one-fifth to a third i.e., 20 - 30 %) of the total estimated waste heat streams for the three case studies could still be utilized.

The study also finds that approximately 70% of the recoverable waste heat stream with exergy content is of low-temperature grade due to the significant amount and mass flow rate of these low-temperature waste heat streams. Therefore, based on the analysis on widely used processing units namely boiler systems, heating and drying units common to a wide range of manufacturing industries, it is logical to expect a similar amount of energy contents to be contained in the unrecovered waste heat streams emitted from several manufacturing industries in Johannesburg.

6.3. Potential savings in energy costs and GHG emissions reduction from waste heat recovery

Given that energy is lost during manufacturing activities as waste heat stream from processing units, and these waste heat streams are released with associated carbon emissions from fossil fuel combustion during manufacturing activities; it is reasonable to argue that the adoption of fuel switching to harnessed waste heat to provide useful energy would reduce overall fossil fuel combustion and associated carbon emissions from the factories.

The findings from this study revealed records of about 30 – 56.6% energy losses from the case study factories with the largest energy losses occurring in processes involving the use of steam boiler systems, heating and drying units, which have been identified in the study as the main sources of waste heat. The study findings further revealed that recovery of the waste heat streams from the case studies could yield about 7 - 24 % potential savings in energy consumption and about 59.6 % reduction in CO_2 emissions per year.

The investigation of the exergy content which is the energy content in the waste heat stream which typically was expelled into the environment and contributes to the carbon footprint of the case study manufacturing industries presents the unique opportunity for reducing carbon emission. In light of the finding from the study, it is logical to state that if waste heat contained in the exhaust gas, air or vapour from steam boilers, air compressors, dryers and condensers are recovered, there would be a resultant reduction in energy demand and cost, as well as a significant reduction in carbon emission from manufacturing industries.

6.4. How waste heat recovery in manufacturing industries can reduce energy demand and GHG emission towards mitigation of related climate change due to the ongoing global warming.

The sustainable development of a city is unattainable without sustainable energy (SEforALL, 2012). In this context, one of the main focuses of the United Nation's Sustainable Energy for All (SEforALL) 2012 framework for action is the environmental dimensions of sustainable development which proposes international actions towards improving energy security and promoting energy efficiency improvement in energy-intensive sectors by 2030. The proponents of the SEforALL (2012) action framework is aimed at realising these considerable benefits to countries, industries and communities. This objective targets reduction and recovery of waste energy as well as the reduction of carbon footprint and pollution due to greenhouse gas emissions. This aligns with the scope of this study which is waste heat recovery in manufacturing plants in Johannesburg.

Despite the installation of thermal insulation improvements in manufacturing facilities and process optimization, heat energy losses expelled through exhausts gas, air and vapour are unavoidable. In addition, besides being a wasted energy source, GHG emissions and other harmful pollutants generated from fossil fuel combustion are associated with the resultant waste heat streams. Furthermore, it can be argued that the continuous expulsion of waste heat into the atmosphere especially in urban areas like Johannesburg could raise the city's temperature higher than that of surrounding rural areas, causing the need for more energy for cooling during hot summer seasons.

In addition, with the recent Carbon Tax levied against all economic sectors in South Africa, the study finding reveals large room for improvement for the manufacturing sectors with regards to reducing energy intensity while at the same time reducing carbon emission through waste heat recovery. The study finds that case study factory A showed the highest percentage of potential energy savings of 24 % (69,695.8 GJ estimated usable waste heat) and 59.6 % reduction in CO_2 emissions (68,789.75 Kg of CO_2). The case study is a milk and dairy production factory belonging to the food and processing subsector which showed by far, the highest year on year production growth at 9.96% in 2019 above all other subsectors. In addition, according to the 2016 CCRED report, 108 food processing firms were identified across the City of Johannesburg. The collective harnessing of waste heat from these industrial cluster or manufacturing nodes would thus result in a hundred-folds of the findings in this research report in relation to the total of mitigation of CO_2 emissions and related climate change.

The focal point of this analysis was to characterize the quantity of the waste heat stream and the amount of energy that was embedded in the emitted waste heat with a consideration of the available technology opportunities for capturing and reusing this energy. The extent to which waste heat recovery in manufacturing industries can contribute towards a reduction in energy consumption and GHG emissions towards climate change mitigation is illustrated in the conceptual diagram below (see Figure 6.1). This projection of mitigation of CO_2 emissions based on one manufacturing subsector makes it apparent that the recovery of waste heat in other manufacturing subsectors that use steam boilers, air compressors, dryers or ovens and any heating utilities, has the potential to yield a significant reduction in energy demand and mitigation of CO_2 emissions.

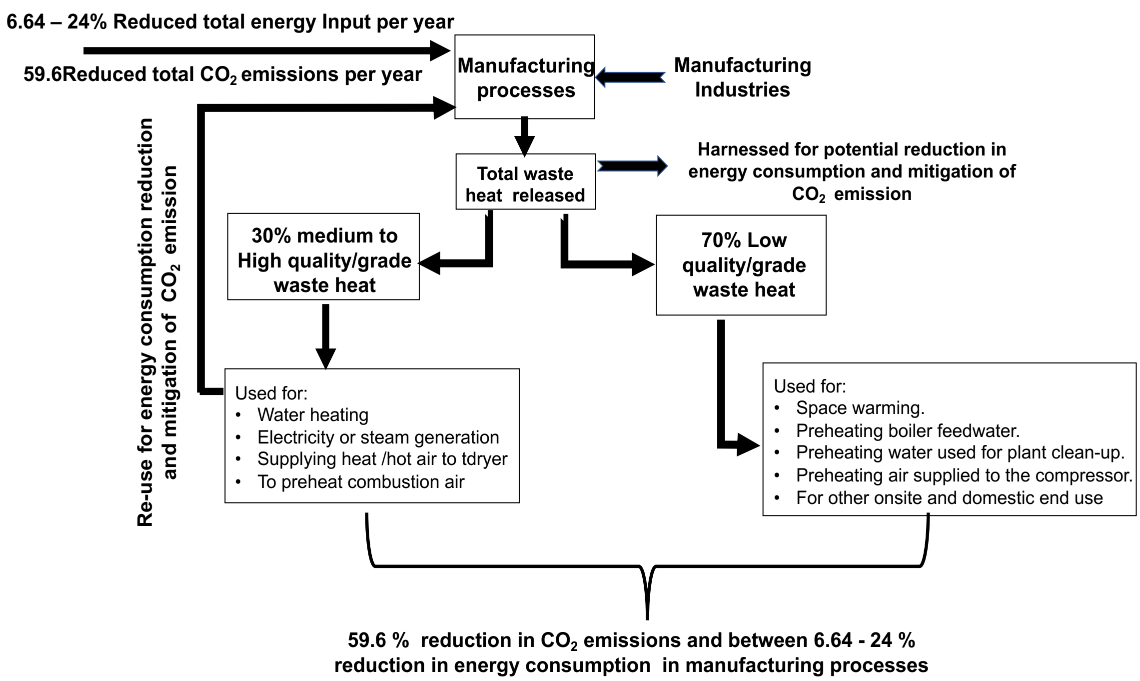

Figure 6.1. Conceptual diagram of the extent at which waste heat recovery in the case study factories can contribute towards a reduction in energy consumption and GHG emissions towards climate change mitigation.

In the course of the study, it was recognised that importance was placed on profit-making above environmental concerns and CO2 emissions. Continuous production was the ultimate driver of energy consumption, while all other decisions were made subordinate. However, "the omission of productivity benefits in the evaluation of energy-efficiency measures" like waste heat recovery has resulted in "an underestimation of the cost-effective savings potential" across manufacturing industries (Worrell, 2003:1083). This production-centred mindset of manufacturing industries has resulted in the continual expulsion of waste heat and GHG into the environment, which has contributed to the carbon footprint in the surroundings around the facilities. Nevertheless, the study finds that there has been a limited recommendation on waste heat recovery to manufacturing industries.

It is possible that the manufacturing plants are not adequately equipped with information or detailed inventory that could provide a detailed understanding of the environmental impacts of their emissions due to production. This plausible explanation is beyond the scope of this study, however, the findings from this study could thus guide them in making informed decisions on waste heat recovery and facilitate inter-sectoral interventions to mitigate environmental degradation.

The identified processing unit-specific sources of low-medium temperature grade waste heat identified in the study, as well as the several matched heat sinks, requires technologically available waste heat recovery techniques that could effectively achieve waste heat source to sink heat transfer and serve as effective ways of reducing total energy cost incurred for production. However, in the recovery of low-grade temperature range from exhaust gases, there is the possibility of contamination due to corrosion, hence, although this heat may not be transferred back to the same process, it can be useful for space and feedwater heating or direct re-use in a nearby heat sink in the manufacturing facility. Therefore, based on the investigation done and the nature of the identified waste heat sources, the most suitable and economic recovery techniques recommended are the use of heat pumps or internally incorporated heat exchangers for combined waste heat recovery and temperature upgrade for commercial applications (Hammond and Norman, 2014). There is also the possibility of converting the medium temperature grade waste heat to electricity mostly using organic Rankine cycle technology.

6.5. Recommendation for further research

The approach of using facility level as data adopted in this study to quantify waste heat potential should be used on numerous factories on a country-wide or regional scale and over a longer period of years to estimate the maximum waste heat potential and identify temporal changes of the potential in South Africa. In addition, in the study, not all processing units are included, therefore, the work potential estimated in this research report is expected to be lower than the actual potential. Further studies covering all processing units in manufacturing facilities should therefore be conducted to derive the maximum work potential possible from waste heat streams in manufacturing industries.

With the collation of more detailed data and thorough investigation, a comprehensive release of more research findings on the benefits of waste heat recovery that cover the cogent points below can assist in creating awareness. A part of government interventions on this issue include awareness by the NCPC-SA which focuses on demonstrating that energy efficiency in manufacturing plants does not just involve reducing utility expenses, rather it also boosts revenue through improved cleaner productivity. The strategy used by the NCPC-SA involves performing energy assessment of the operating plants of manufacturing industries and presenting the findings obtained from this exercise to the companies with guidelines and recommendations on areas to implement energy efficiency practices.

Increased energy efficiency: The implementation of waste heat recovery in large manufacturing facilities and production plants to serve as a measure to achieve large scale improvement in energy efficiency, based on evidence that the installation of a waste heat recovery systems can yield large scale and profound impacts on efficiency at an industry level.

Conservation of resources: More emphasis should be placed on the importance of reusing waste heat as a way for manufacturing facilities to contribute to the conservation of resources. This can be achieved by demonstrating that the implementation of a recovery system is key to reducing the use of another heat source, which can thus make significant progress towards conserving resources like coal and natural gas.

Reduction of waste and dangerous GHG emissions: Although waste heat from manufacturing plants is inevitable, efforts should be focussed on demonstrating that waste heat from manufacturing processes is an alternative energy resource that has the potential to be harnessed for technical work rather than being discarded. In addition, it should also be explained that unrecovered waste heat containing toxic waste gases are expelled directly into the atmosphere, hence, waste heat recovery serves to repurpose these dangerous emissions for reduced GHG emissions and increased productivity of the facility.

Reduction of energy consumption and operating cost of a plant: Especially with the constant rise in energy costs and the need to further increase in profit margin through decreased expenditures, facility managers should be recognized that the installation of a waste heat recovery system promises potential savings in energy consumption of between 6.64 to 24% (based on the study findings) or even higher, which would result in the reduction of energy costs.

Finally, to achieve widespread use of waste heat recovery, future work should be conducted on the economic feasibility assessment aspect of it, consisting of an exhaustive economic analysis of each case manufacturing industry, with consideration of the current and envisaged future energy prices to thoroughly analyse the feasibility of implementing waste heat recovery systems and technologies.

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Appendix 1: Supplementary data

Case study subsectors used in the assessment based on a dataset from NCPC-SA (2017-2018).

Energy consumption in 10^6x Gj/yr. for pulp and paper manufacturing

Processing unit	Heat energy consumption
Pulping	1.6
Alkali recovery	3.8
500 kT of Pulpboard	1.4
250 kT of high-quality paper	1.8
Paper machine hot air system	0.6
250 kTof high-quality packaging paper box	1.8

Total energy consumption: 285,838.02 GJ/year

Energy consumption in 10^6 x Gj/yr for milk and dairy products manufacturing

Processing unit	Heat energy consumption
Heating system	1.13
Evaporation	5.09
Cold system	
Spraying drying	14.69

Total energy consumption: 289,684.8 GJ/year

Energy consumption in 10^6 x Gj/yr for rubber products and tyre manufacturing

Processing unit	**Heat energy consumption**
Calendering	0.23
Extruding products	0.50
cutting and building	1.58
Curing	1.95

Total energy consumption: 184,915.12 GJ/year

CO_2 emission threshold for selected manufacturing subsectors:

NCPC-SA dataset nomenclature	Production capacity threshold (kt/day)	CO_2 emission threshold from processing (kilotons /yr)	Study nomenclature
Agro-processing Heating system Evaporation Cold utility system Spray drying	500	206 136 171 106	Milk and dairy production
Pulp and paper Steam boiler system Alkali recovery process Papermaking process Pulping process Pulpboard	500	121 5 103 96 77	Pulp and paper production
Rubber Processing of raw materials to finished goods	500	514	Rubber and tyre production

Appendix 2: Copy of Ethics clearance statement

SCHOOL OF ARCHITECTURE AND PLANNING
HUMAN RESERCH ETHICS COMMITTEE

CLEARANCE CERTIFICATE
PROTOCOL NUMBER: SOAP054/06/2019

PROJECT TITLE:	ENERGY-EFFICIENCY IMPROVEMENT STUDY: A CASE STUDY OF WASTE HEAT RECOVERY IN FOOD INDUSTRIES
INVESTIGATOR/S:	Abosede Alao (Student No: 2282610)
SCHOOL:	Architecture and Planning
DEGREE PROGRAMME:	Master of Urban Studies (Sustain Energy Effic Cities)
DATE CONSIDERED	30 September 2019
EXPIRY DATE:	30 September 2020
DECISION OF THE COMMITTEE:	Approved

CHAIRPERSON [signature]
(Dr Brian Boshoff)

DATE: 7/10/19

cc: Supervisor/s: Gerald Chungu

DECLARATION OF INVESTIGATORS

I/We fully understand the conditions under which I am/we are authorized to carry out the abovementioned research and I/we guarantee to endure compliance with these conditions. Should any departure to be contemplated from the research procedure as approved I/we undertake to resubmit the protocol to the Committee.

Signature [signature] **Date** 8/10/19.

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Appendix 3: Interview schedule

Interview questions for respondents

- The purpose of this interview is to conduct a waste heat assessment and recommend ways of reducing and reusing this waste

INSTRUCTIONS

- Kindly fill in your details below and indicate if you prefer to be anonymous during this research survey
- Proceed to fill up the columns overleaf
- Your participation and co-operation in this survey is fully appreciated
- THANK YOU FOR YOUR TIME!

NAME:
……………………………………………………………………………………

OCCUPATION……………………………………………………………………
………

INDUSTRY TYPE:
……………….………………………………………………………

CONTACT DETAILS
……………………………………………………………………….

CONFIDENTIALITY PREFERRED: YES OR NO (Underline your preference)

Serial No	**Energy-related process**	**Description of the opportunity area**	**Estimated energy available**	**Estimated recovery opportunity**	**Economic benefits if realized**
		Waste heat recovery from exhaust gases, flue gases and air			
		Waste heat recovery from heating processes through steam boilers			
		Waste heat recovery from drying processes			

		Waste heat recovery from cooling processes			